Manufacturing of the Tetons on a CNC Mill

Hannah Huang

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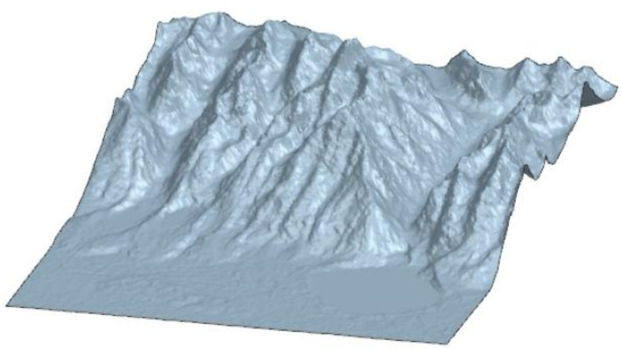
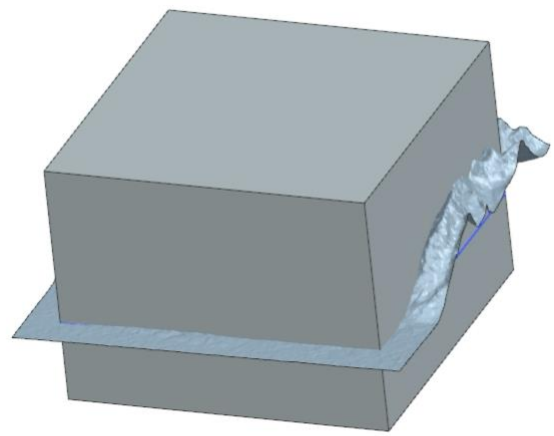
CAD Model Description

I decided to CNC the Jenny Lake portion of Grand Teton National Park. I chose this because this is one of my favorite parks, but also because it has mostly organic, complex surfaces that would be practically impossible to machine on a manual or conversational mill. I found a surface model of these mountains on Sketchfab made by “WVU Volcanology and Petrology Lab.” The steps I took are outlined in Figure 1, which Figure 1d being the final part. I ended up extruding a section to essentially flatten the grass and lake geometry. While this reduces the fidelity of the final product, this will greatly quicken the process in the flattened areas.



(a)



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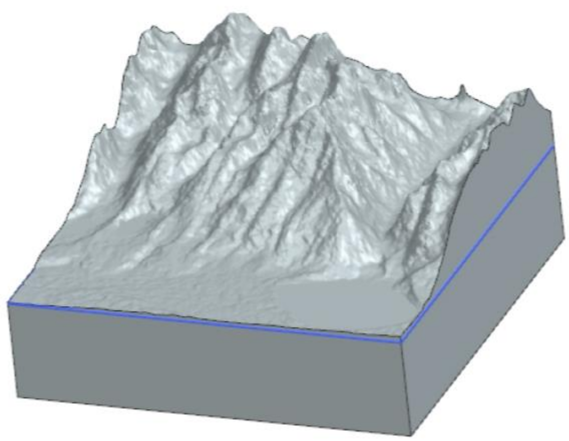
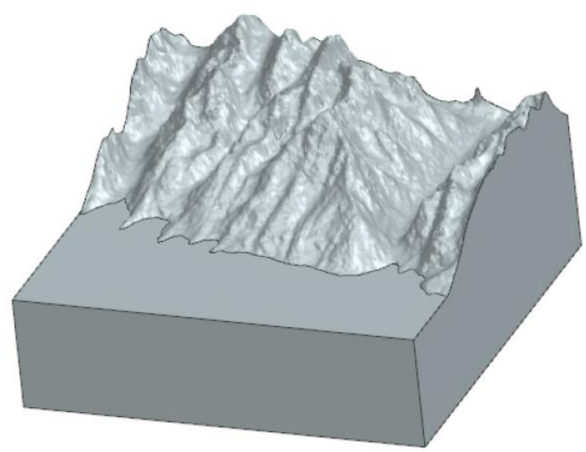


(c)



(d)

Figure 1. CAD process of (a) importing surface into NX, (b) extruding a 4”x4” sketched square, (c) trimming the extruded body with the surface, and (d) extruding another 4”x4” sketch to create a flat area.

CAM Operations

The machine coordinate origin was set at the front left corner on the top face of the stock, and there was a clearance plane of ½" from the top of the stock (see Figure 2). The operations are summarized in Table 1 and further elaborated on within this section. The feeds and speeds are directly from the recommendations posted on Canvas, and the stepover and depth of cut follow the 1/3" step rule.

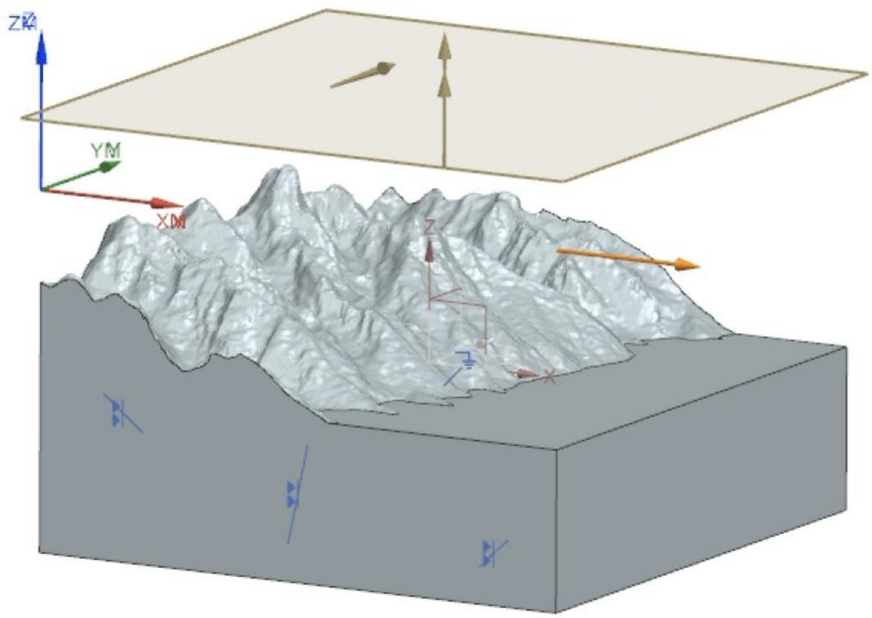
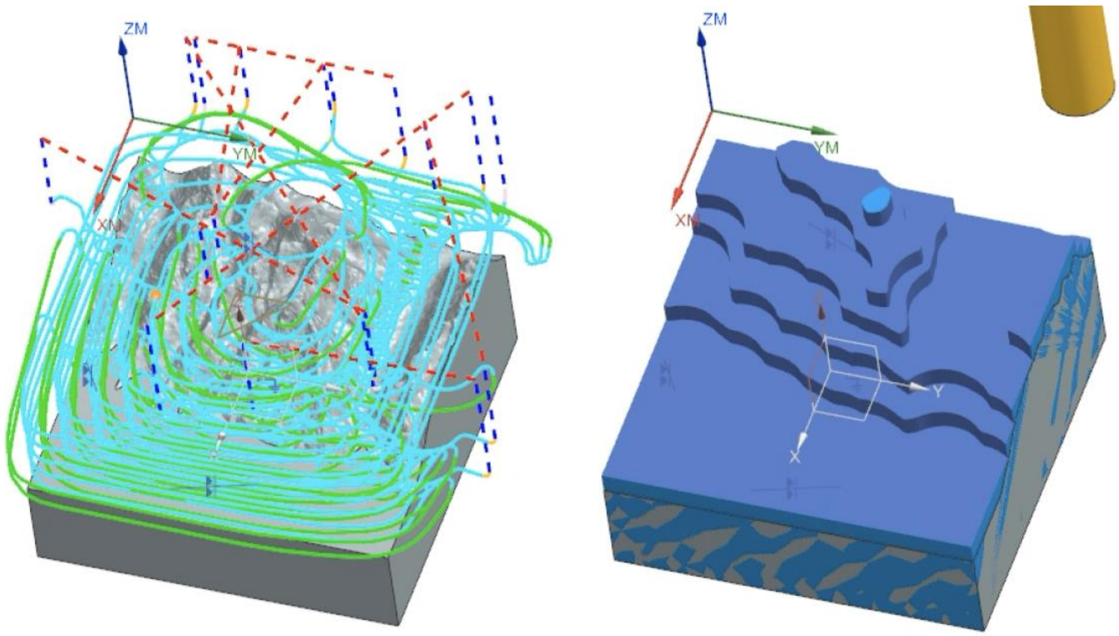


Figure 2. MCS and ½" clearance plane.

#	Type	Method	Tool Dia. (")	Feed (ipm)	Speed (rpm)	Stepover (")	D.O.C. (")
1	Roughing	Adaptive	0.75	18	2,037	0.2500	0.2500
2	Roughing	Cavity	0.5	10	3,056	0.1667	0.1500
3	Roughing	Area	0.25	12	6,112	0.0833	0.0833
4	Finishing	Area	0.25	12	6,112	0.0833	0.0833
5	Finishing	Planar	0.75	18	2,037	0.2500	0.2500
6	Finishing	Planar	0.25	12	6,112	0.0833	0.0800

Roughing 1 – Adaptive Milling ¾" endmill

In the first roughing step, I used adaptive milling to full-width cuts in quick bulk material removal. This method utilizes a lot of circular motions, which allows the endmill to easily mill through breakthrough regions while maintaining very low chip loads. This is useful for my geometry because the mountain valley is a location where milling directly through would be much quicker than slowly outlining the profiles until the two regions intersect. The tool path and in-process workpiece (IPW) are shown in Figure 3. In Figure 3a, we can see that there are a high concentration of circular cutting lines that go through the valley.

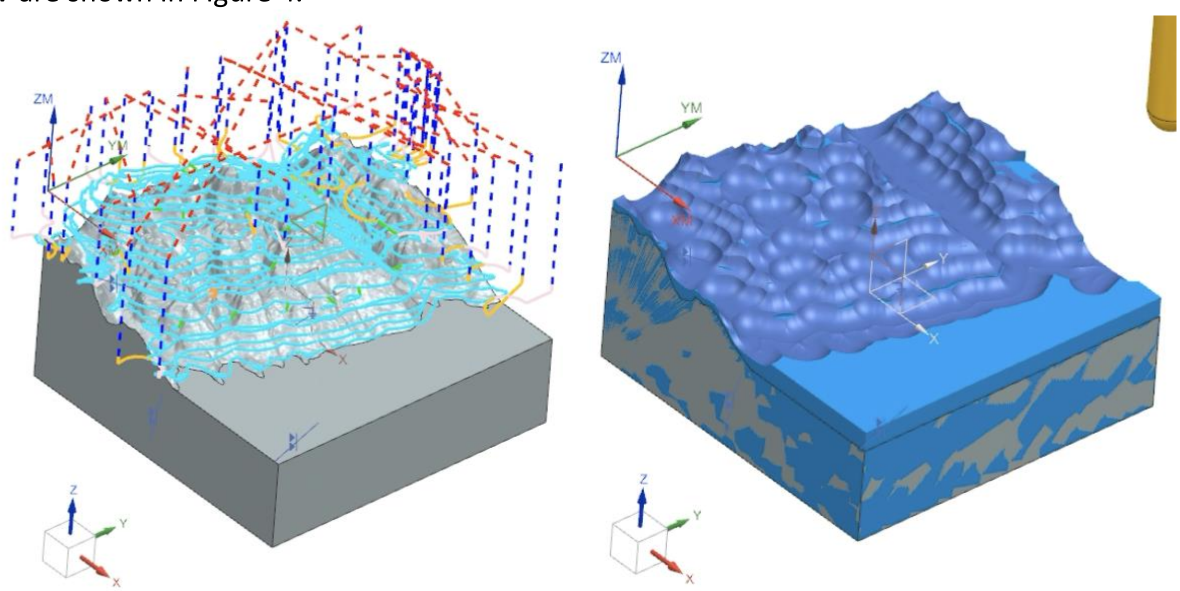


(a) (b)

Figure 3. Roughing 1 – Adaptive Milling ¾” endmill (a) tool path and (b) IPW.

Roughing 2 – Cavity Milling ½” ballmill

In the second roughing pass, I go down in tool diameter by a ¼” to get more detail, but still aimed at large material removal. I chose to use a ball mill so that I can begin to get the sloping surfaces of the mountains. This would also have been a good place to use the adaptive milling technique; however, a ball mill cannot be used with adaptive milling, so I chose to use a traditional cavity mill instead. Additionally, this path is restricted to the mountain region, because the flat region can be easily taken care of with a planar milling step later. The path and IPW are shown in Figure 4.

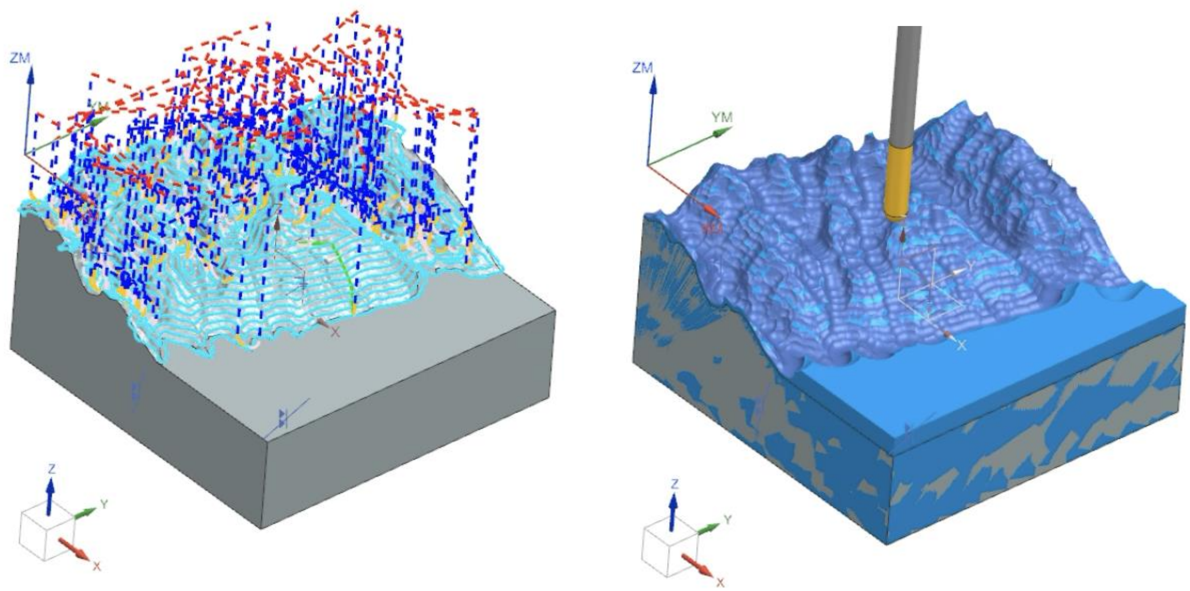


(a) (b)

Figure 4. Roughing 2 – Cavity Milling ½” ballmill (a) tool path and (b) IPW.

Roughing 3 – Area Milling ¼” ballmill

Next, I stepped the tool diameter down by another ¼” to get even finer details. This time I used the are mill tool which follows the contour of the part to result in a much more consistent surface finish. This is shown in Figure 5a, in which we can see that the tool path loops around the entire contour of the surface very evenly. We can see that the resulting IPW in Figure 5b has smooth lines wrapping around the contours, instead of the jagged and sharp points produced by the cavity milling in Figure 4b. Even though this is only a roughing step, the subsequent finishing step should further refine this surface in the same way. Additionally, I found that area milling saved around 8 more minutes when compared to cavity milling. Again, this step is contained to the mountain region.

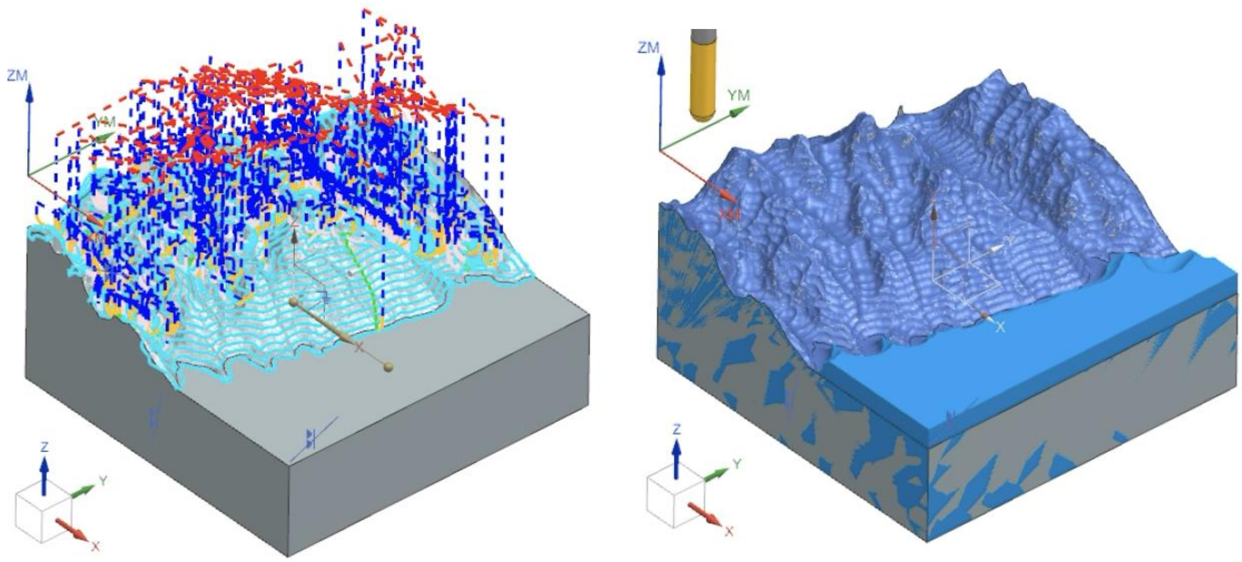


(a) (b)

Figure 5. Roughing 3 – Area Milling ¼” ballmill (a) tool path and (b) IPW.

Finishing 1 – Area Milling ¼” ballmill

This is the first finishing step, in which I finish the surface of the mountain region with another area mill of a ¼” ballmill. As explained in Roughing 3, the area mill gives a smooth, consistent surface finish. After milling this section, the geometry is surprisingly not sharp to touch at all. The tool path and IPW are shown in Figure 6.

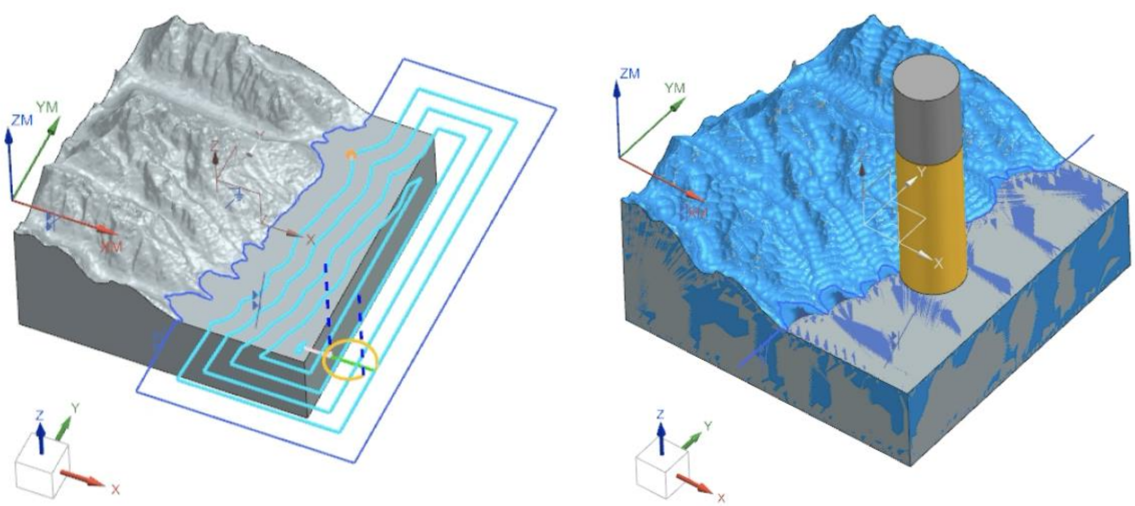


(a) (b)

Figure 6. Finishing 1 – Area Milling ¼” ballmill (a) tool path and (b) IPW.

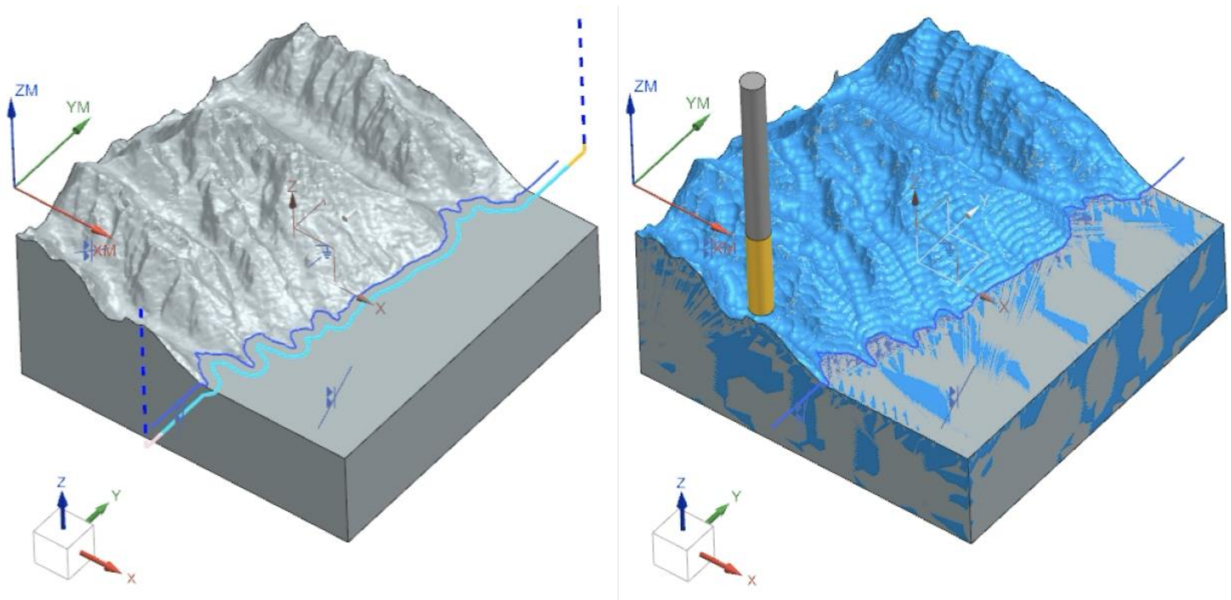
Finishing 2 – Planar Mill ¾” endmill

The second finishing step is on the flat part. The toolpath shown in Figure 7 is not actually the original toolpath, but had to be modified after breaking a tool which will be explained in a later section. I attempted to use many other planar milling techniques, including the floor mill, but NX threw errors about these methods not supporting “convergent boundaries,” which appears to be the complex boundary between the mountain and the flat area. Thus, I had to do a workaround by sketching the boundary between the mountains and the flat area, then enclosing that in a box which can be milled by the Planar Mill operation. You can notice that there is a lot of “wasted” tool path, where the end mill is milling air. This was necessary to get the tool to begin outside of the part, such that it does not take a full diameter plunge into the material. This is further explained in the next section.



(a) (b)

Figure 7. Finishing 2 – Planar Mill ¾” endmill (a) tool path and (b) IPW.



(a) (b)

Figure 8. Finishing 3 – Planar Mill ¼" endmill (a) tool path and (b) IPW.

Manufacturing Process

When putting tools into the holders, I had to account for the necessary stickout distance based on the maximum vertical distance between features. This was important to pay attention to for the ¼" endmills, where the flute length was only about 1", but the necessary stickout was 1.27" (see Figure 9).

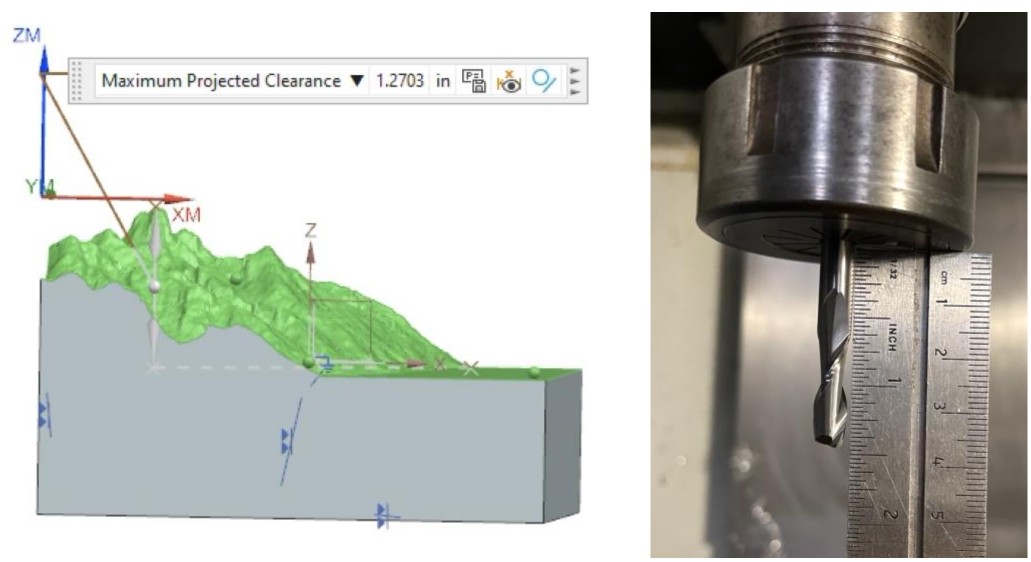


Figure 9. Setting stickout length based on extreme vertical distances from the model.

Figure 10 show how I set my MCS and tool offsets. Notice in Figure 10c that the top of my stock ended up being super uneven. I was not worried about this because none of my final part utilizes the top surface, meaning that all of this surface would get milled away. To make sure my tool offsets were consistent with each other, I kept the offset tool in the exact same spot for all 4 tools, making sure that I did not move the table in the x or y direction during the process.


(a) (b)

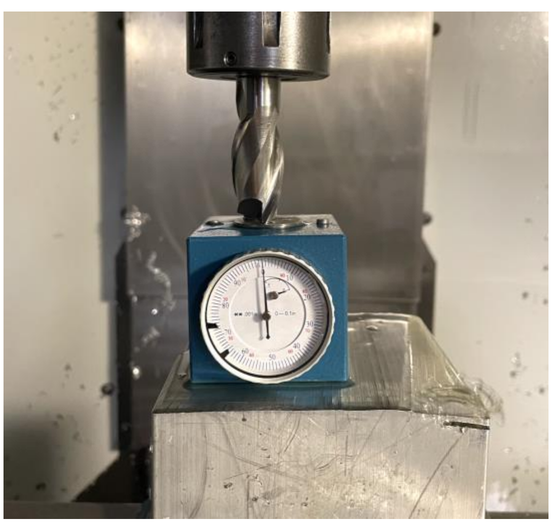
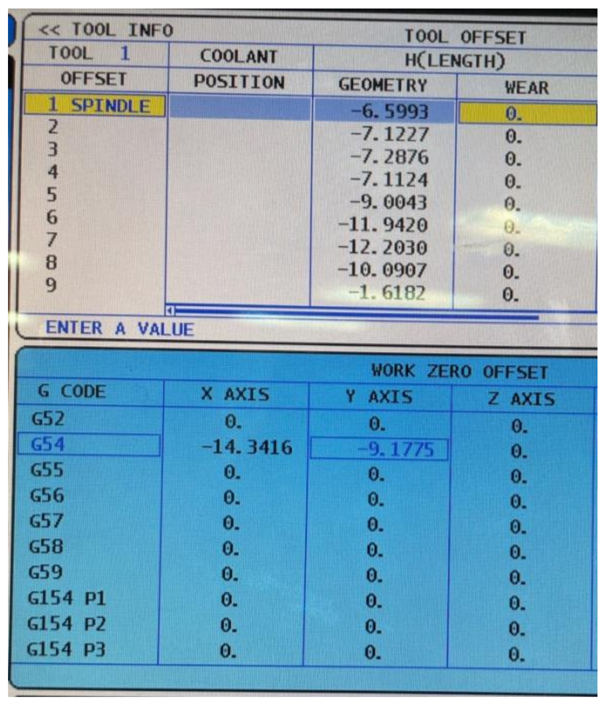
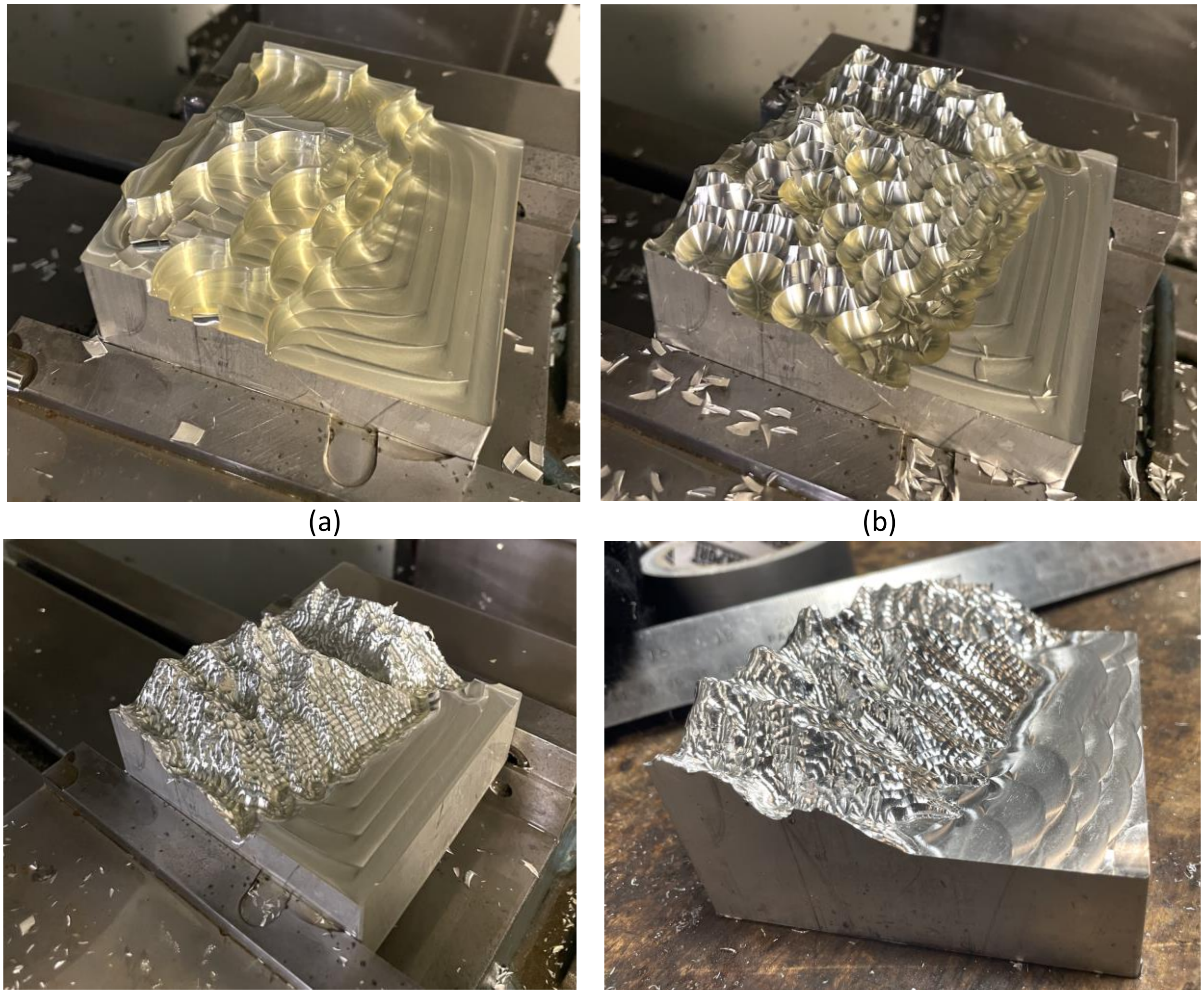



Figure 10. Setting (a) x and (b) y zeroes, as well as (c) tool offsets. Final values are shown in (d).

Process shots are shown in Figure 11.



(a) (b) (c) (d)

Figure 11. In-process workpieces after (a) first roughing pass (op #1), (b) second roughing pass (op #2), (c) first finishing pass (op #4), and (d) the finished part.

Problems Encountered

During the first pass of the first operation, I heard a loud noise and realized that my stock was vibrating in the clamp. This led to gouges in the stock (see Figure 12). I was lucky this happened so quickly because my top surface was still there, meaning I could safely reset all my zeros and tool offsets. Additionally, none of the gouges would make it to the final part, since all the material around it gets milled away in subsequent steps. I made sure to really crank on the handle the second time around.

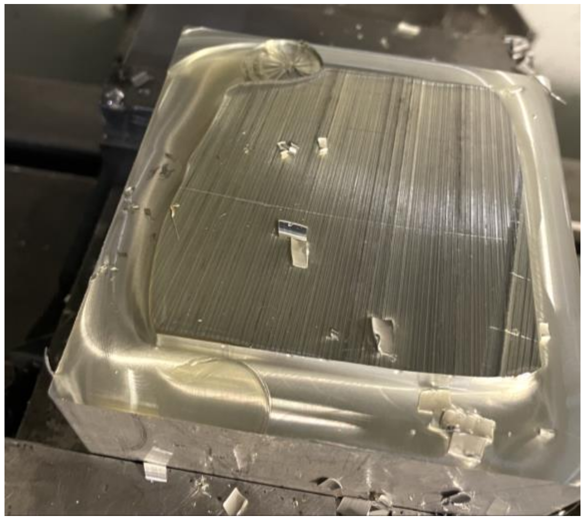
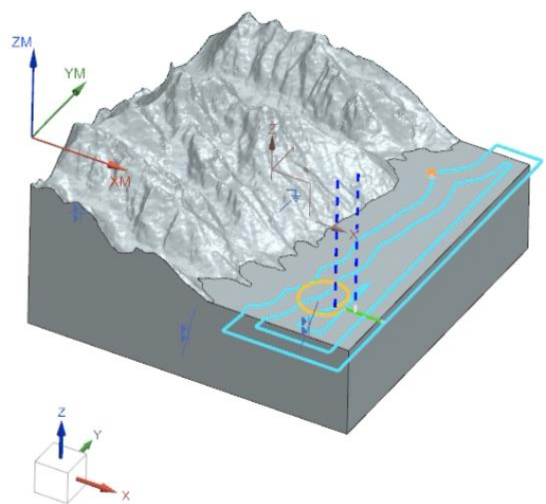


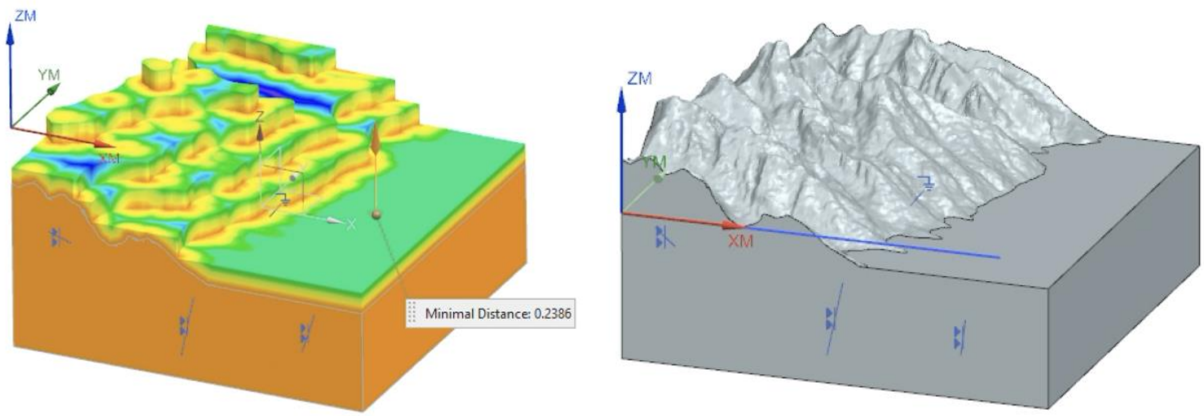
Figure 12. Gouging in part after stock shakes loose.

In the second to last op, the ¾” endmill began by plunging into the stock and chipping the tool (see Figure 13a). This was because of my improper use of a planar operation. As shown in Figure 13b, the original path shows the tool plunging directly into the part. I expected it to make a winding helical motion into the part, like a cavity mill would do; however, it does not have this 3D information like contour operations do. Thus, I changed the path to that shown in Figure 7 to alleviate this issue. The modified path only took about 1 more minute longer than the original path, so I did not really care about the tool milling air a third of the time. At this point, I no longer had the top plane that I used for my zero offsets. The only flat surface I had was from the first roughing operation. Therefore, I analyzed the IPW after the first roughing operation and found that the flat roughed face sat 0.2386” above the actual part surface (see Figure 14a). Then, I sketched lines in the x and y direction at the front left corner of the stock, which were 0.2386” above the flat surface and used those lines as my new MCS (see Figure 14b). Then, I reset my tool offsets from the remaining flat surface (see Figure 15).



(a) (b)

Figure 13. (a) Chipped tool and (b) original tool path for op #5.



(a) (b)

Figure 14. (a) Finding the distance between the roughed surface and part surface, and (b) using this distance to define a new MCS.

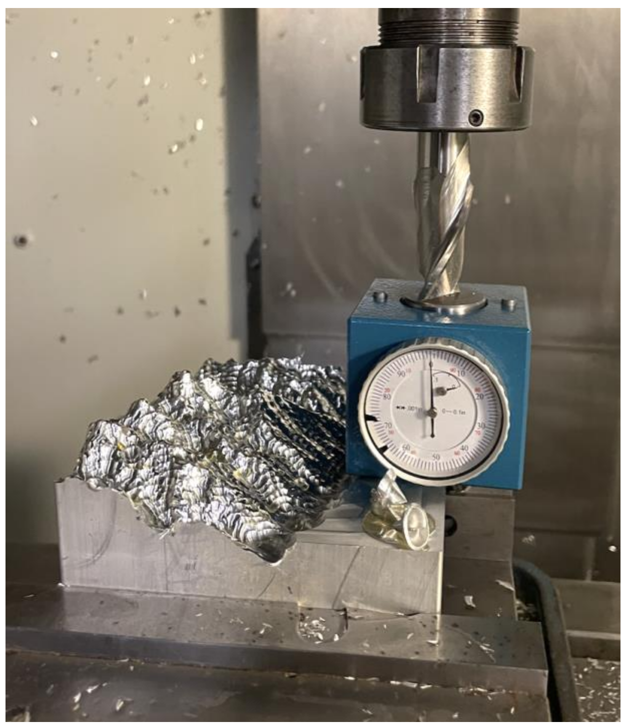
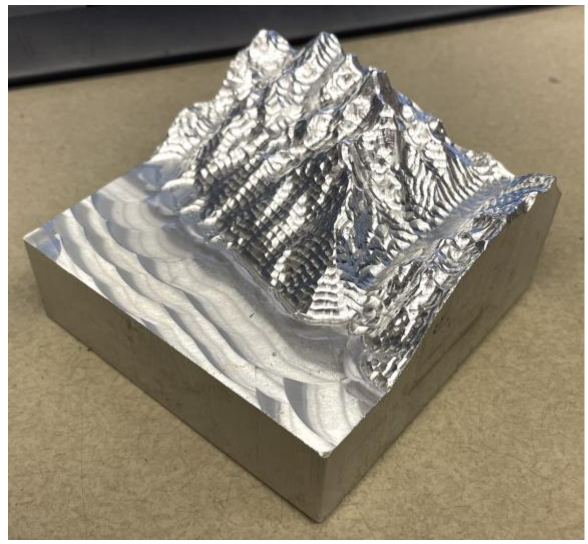


Figure 15. Resetting tool offsets from roughed surface.

Results and Reflection

Despite the difficulties I ran into, I consider the final part a success. While the surface does not look exactly like my model, it is relatively smooth and consistent (see Figure 16). I could have added more detail by including a smaller ball mill, but at that point the stickout to diameter ratio was bigger than I wanted to risk. Additionally, the transition from the contoured region to the flat region is almost smooth, showing that my method of resetting tool offsets was pretty accurate (see Figure 16c). In retrospect, I would definitely take my time more with setting up, making sure that small errors that lead to large amounts of work to fix it don't occur again (such as not properly tightening the workpiece). Additionally, I should have caught the plunging action in NX, as the CAM clearly shows the endmill rapid-ing straight into the workpiece. I should be more wary about using planar milling, since it does not have 3D information of the workpiece that the contour operations do.

(a)



(b)

(c)

Figure 16. (a), (b) Different views of the final part, and a (c) closeup on the transition region.