Overview

This document explains how computer aided manufacturing (CAM) was implemented to create a unique aluminum part using NX 11.0 and the Haas Super Mini Mill 2 (**Figure 1**).

Figure 1: The Haas Super Mini Mill 2 in use

Part Component Design

Blank | A 4” x 4” x 1.8” aluminum block (**Figure 2**). This part was modeled in NX 11.0.

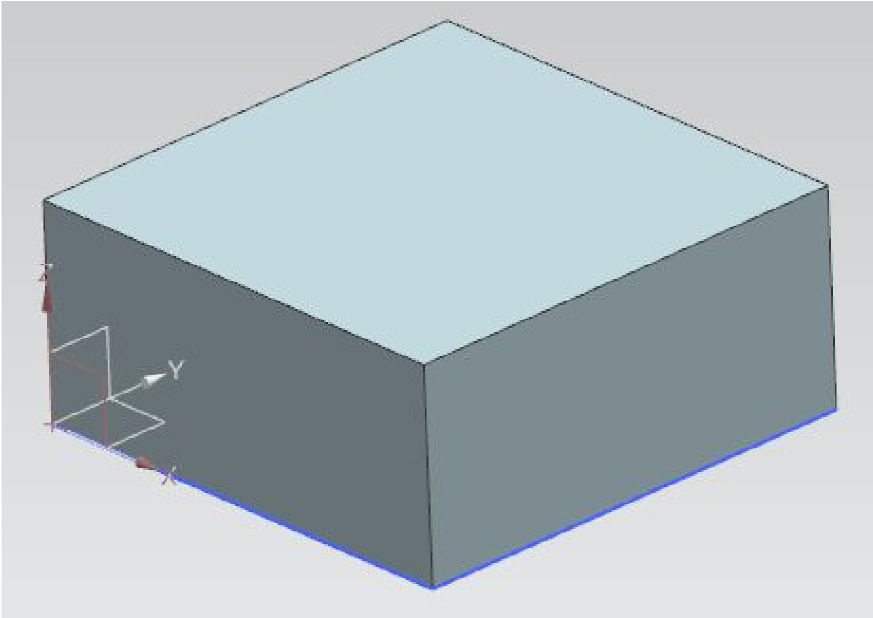

Figure 2: The blank component as shown in NX

Stock | A decorative art piece which honors the film My Neighbor Totoro by Studio Ghibli (**Figure 3**). In the middle of the eponymous protagonist's raised silhouette, a raincoat-clad child is depicted hanging from a leaf. The stock was first modeled in Solidworks 2017-2018 then converted to an NX .prt file. To ensure the part could be machined, all sharp edges were modified with fillets that, at the very least, can accommodate a tool with a 0.0625" diameter; this is the smallest tool available in the Northwestern machine shop.

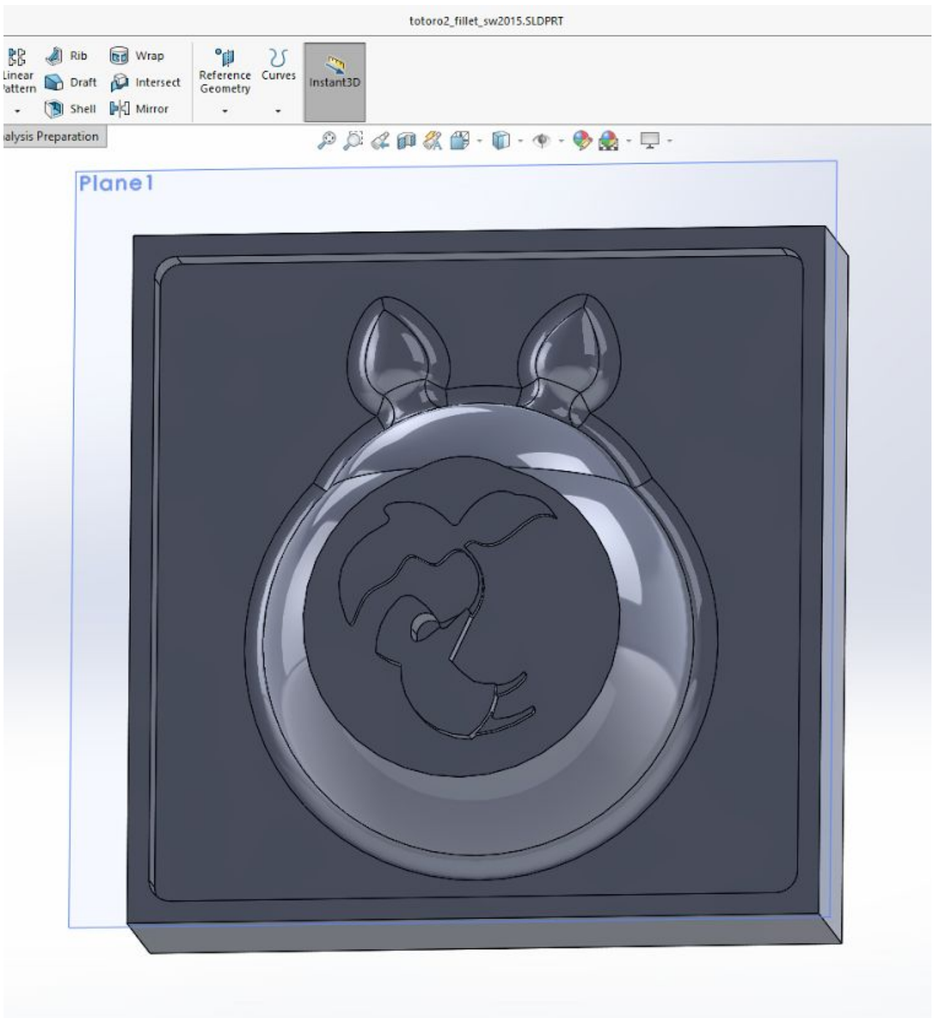

Figure 3: The stock component as shown in Solidworks

NX Manufacturing

In CAM, a manufacturing program organizes the operations needed for a CNC machine to fabricate a desired stock piece from a blank. To set up a manufacturing environment, first the blank and stock .prt files must be imported into an assembly file. For this project, a fixed constraint was used to fasten the stock in place. Two touch align constraints were subsequently used to adhere the edges of the blank to those of the workpiece. The origin of the machine coordinate system was defined using a point inferred from the bottom left corner of the blank's top face. Lastly, the rapid clearance plane was positioned 0.25" above the blank's top face.

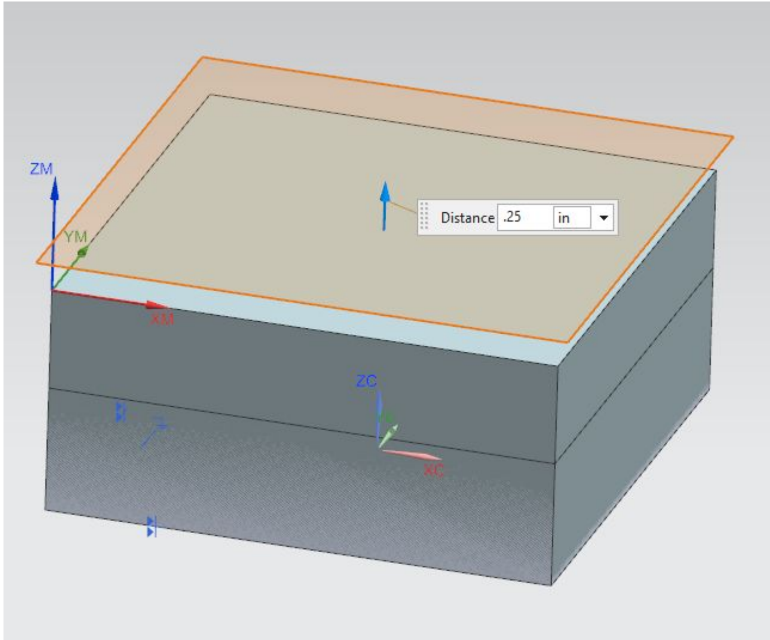

Figure 4: Manufacturing initial setup with constraints, MCS and clearance plane definitions

The operations included in the manufacturing program are shown in **Table 1**. They are listed in chronological order. The tools used in each operation are described in **Table 2**. Excluding the first cavity milling and the contour area operations, the rest of the procedures reference the in-process workpiece to generate tool paths which circumvent areas that have already been trimmed.

Table 1: Operations used in NX manufacturing program

Name	Subtype	Method	Tool Num.	Stepover	Feed (ipm)	Speed (rpm)	Cut Depth (in.)
BULK_CUT_1	Cavity mill	ROUGH	1	33% Flat	12.224	3056	0.16
BULK_CUT_2	Cavity mill	FINISH	1	33% Flat	12.224	3056	0.16
INSIDE_1	Cavity mill	ROUGH	2	33% Flat	12.224	6112	0.05
INSIDE_2	Cavity mill	FINISH	2	33% Flat	12.224	6112	0.05
INSIDE_3	Cavity mill	ROUGH	3	33% Flat	7.8	10K	0.04
PLANAR_PROFILE_1	Planar profile	FINISH	3	50% Flat	7.8	10K	0.035
INSIDE_4	Cavity mill	SEMI FINISH	3	33% Flat	7.8	10K	0.04

BODY_CONTOUR	Contour area	FINISH	4	0.0005 Scallop	7.8	10K	N/A
L_EAR_CONTOUR	Contour area	FINISH	4	0.0005 Scallop	7.8	10K	N/A
R_EAR_CONTOUR	Contour area	FINISH	4	0.0005 Scallop	7.8	10K	N/A
KID_DEFINE	Cavity mill	FINISH	5	33% Flat	2	10K	0.02

Table 2: Tools created in NX

Tool Number/ Adjust Register	Tool Name	Diameter (in)	Number of Flutes
1	EM_0.5	1/2	2
2	EM_0.25	1/4	2
3	EM_0.125	1/8	2
4	BALL_MILL_0.25	1/4	2
5	EM_0.0625	1/16	2

Operation Set 1 | BULK_CUT_1 and BULK_CUT_2 | Tool 1

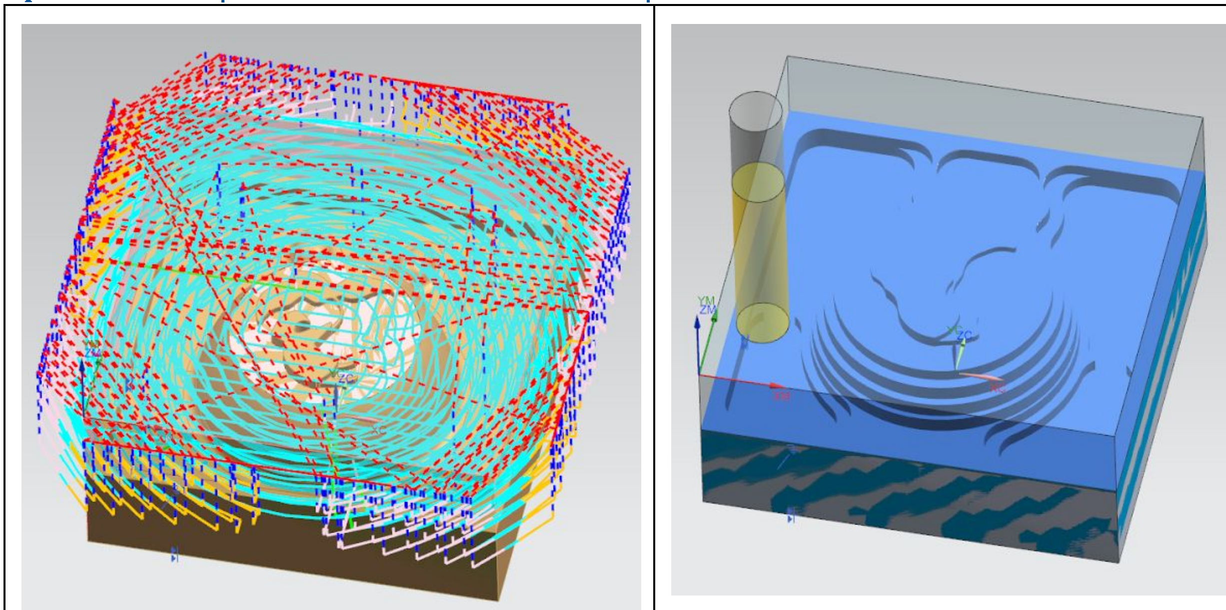

Figure 5: Tool path (L) and 3D simulation (R) for BULK_CUT_1

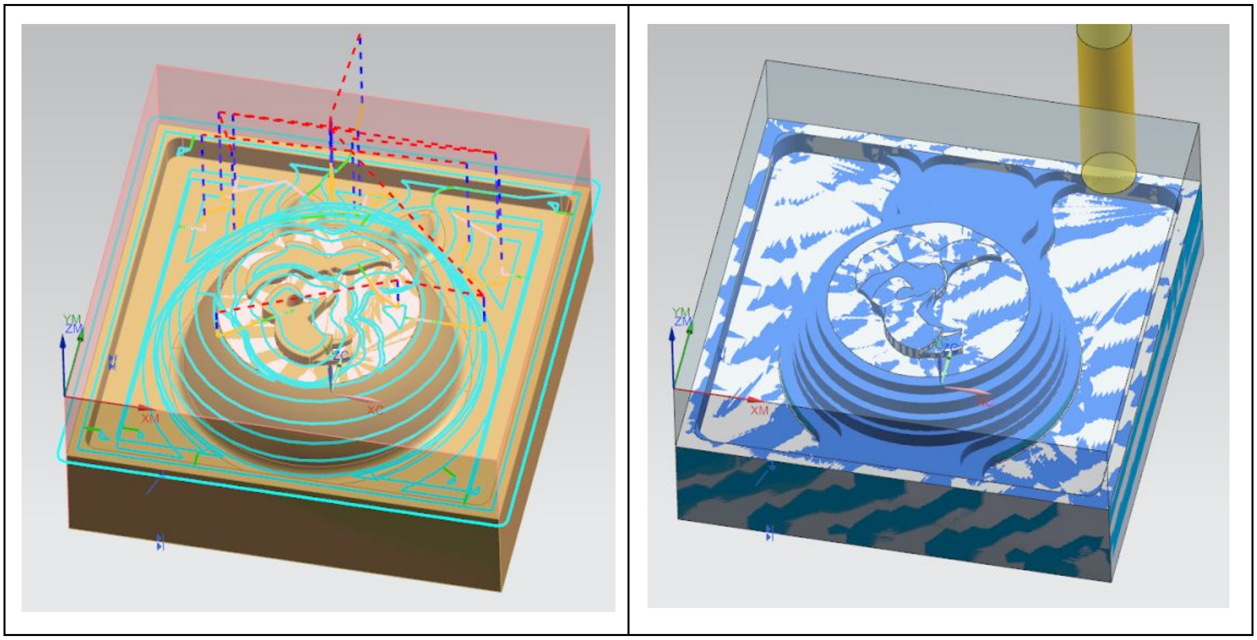

Figure 6: Tool path (L) and 3D simulation (R) for BULK_CUT_2

The manufacturing program begins with back-to-back roughing and finishing cavity milling operations which use a 0.5” flat end mill tool. These operations are performed first to minimize the time needed to eliminate excess aluminum. A flat end mill is required to ensure the top face of the extruded border, the bottom of the square background, and the middle of Totoro’s stomach will be parallel to the bottom face of the workpiece. A 0.5” diameter is specified because tools of this size can remove large amounts of material yet are slim enough to squeeze between the revolved ears - thus reducing the time subsequent operations will need to shape these features.

Operation Set 2 | INSIDE_1 and INSIDE_2 | Tool 2

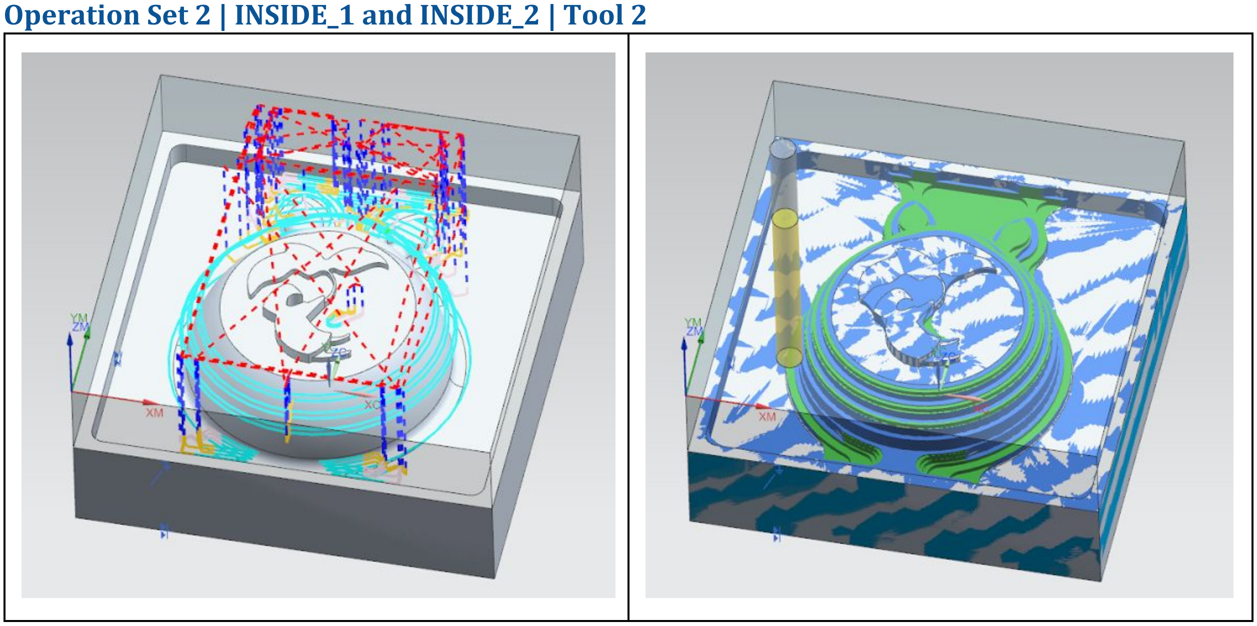

Figure 7: Tool paths (L) and 3D simulation (R) for INSIDE_1

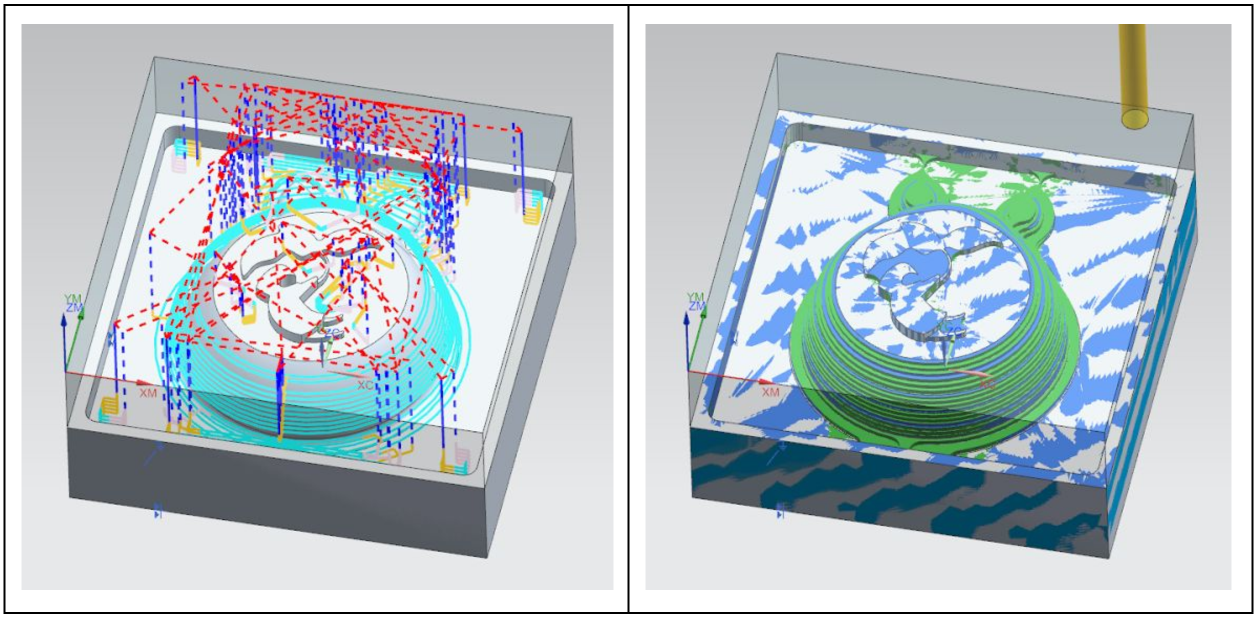

Figure 8: Tool paths (L) and 3D simulation (R) for INSIDE_2

Consecutive roughing and finishing cavity milling operations are performed with a 0.25" flat end mill to clean surfaces sculpted by tool 1. A flat end mill is employed to ensure the bottom of the extruded cut and the middle of Totoro's flattened stomach remain level with the base of the workpiece. A 0.25" diameter is used because tools of this width can slip inside corners where tool 1 cannot reach.

Operation Set 3 | INSIDE_3, PLANAR_PROFILE_1, and INSIDE_4 | Tool 3

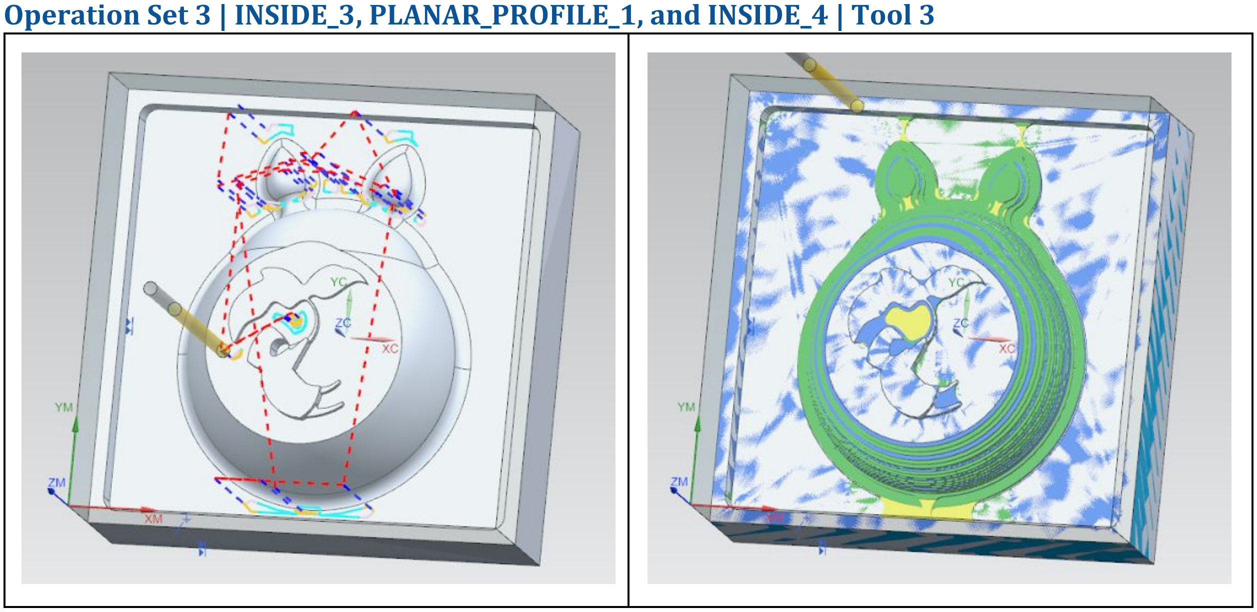

Figure 9: Tool paths (L) and 3D simulation (R) for INSIDE_3

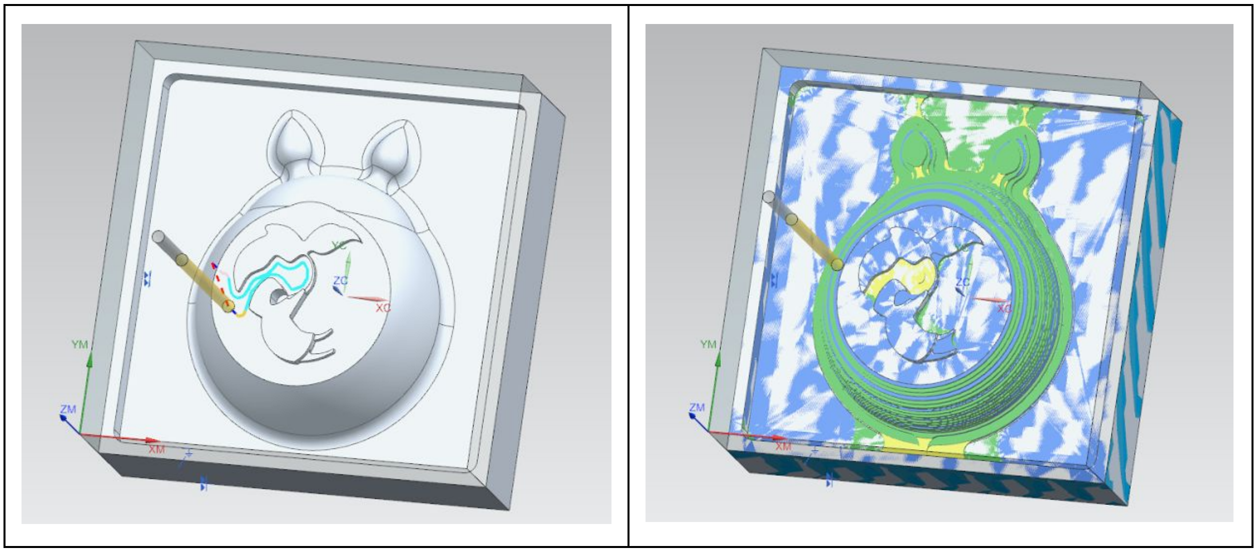

Figure 10: Tool paths (L) and 3D simulation (R) for PLANAR_PROFILE_1

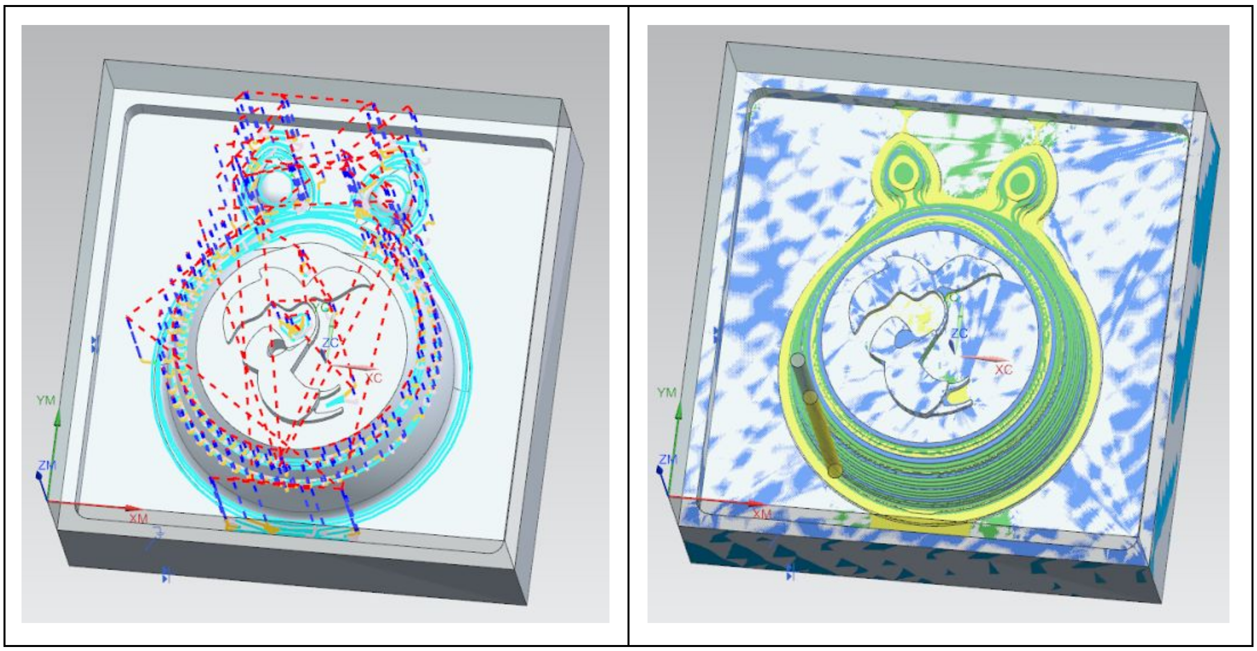

Figure 11: Tool paths (L) and 3D simulation (R) for INSIDE_4

To tidy up the silhouettes of the child and the leaf, a roughing cavity milling operation is performed with a 0.125” flat end mill. This is followed by a planar profile operation which uses tool 3 to carve the nonlinear channel separating the hood of the raincoat from the blade of the leaf. A semi-finishing cavity milling operation picks up where INSIDE_2 left off and refines the coarse steps that encircle Totoro’s protruded body. Semi-finishing is implemented in place of finishing to provide residual material for succeeding contour area operations to remove. Continuous cutting is generally encouraged to prevent the edges of a tool from unnecessary wear. It also promotes uniform trimming across linear surfaces, and produces sleek complex contours.

Note, in **Table 1**, PLANAR_PROFILE_1 has a stepover size of 50%. It is the only operation which violates the ⅓ cut rule. This is an inherent property of planar profile operations which cannot be changed by the user. As a result, the cut depth of the operation is set well below $\frac{1}{24}$ ".

Operation Set 4 | BODY_CONTOUR, L_EAR_CONTOUR, and R_EAR_CONTOUR | Tool 4

Although the shape of Totoro's body is recognizable, the sides are not smooth. Noticeable steps wrap around curved surfaces because, up until this point, only flat end tools have been utilized. To file these ridges down, contour area operations with a small scallop size are performed over sloped features with a ball mill tool. A ¼" diameter is specified to accommodate the ⅛" radius fillets which anchor the bottom edge of Totoro's body to the floor of the extruded cut.

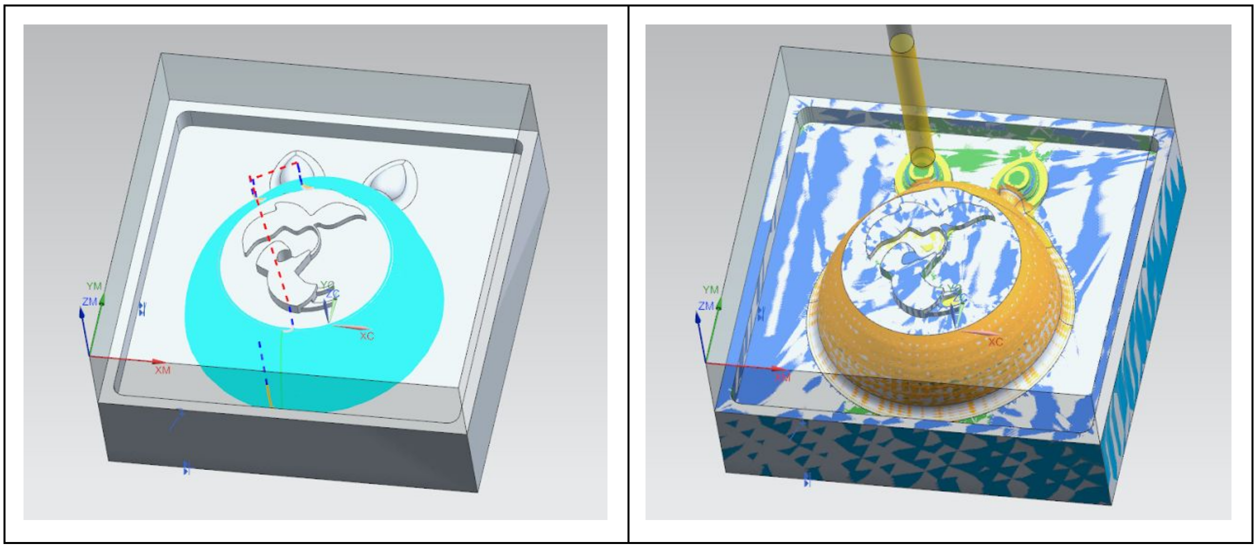

Figure 12: Tool paths (L) and 3D simulation (R) for BODY_CONTOUR

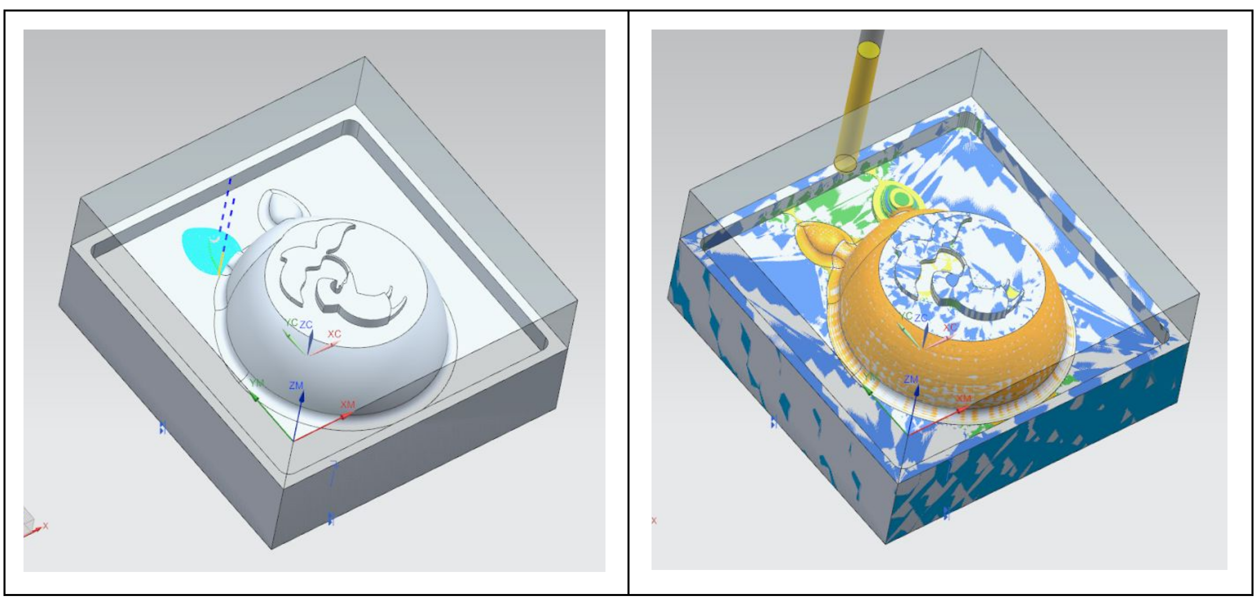

Figure 13: Tool paths (L) and 3D simulation (R) for L_EAR_CONTOUR

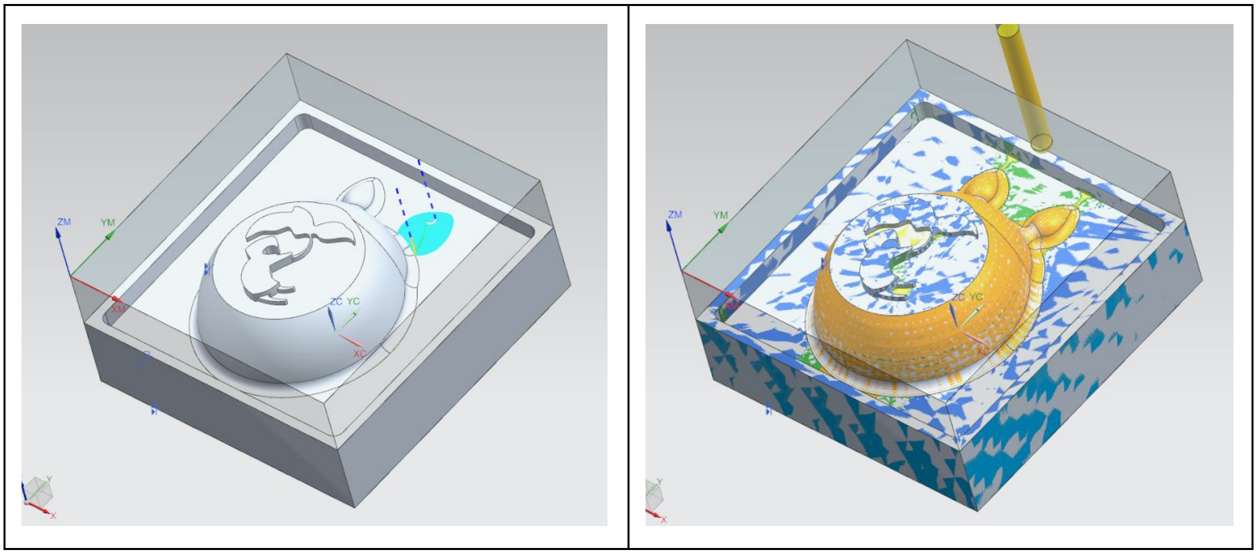

Figure 14: Tool paths (L) and 3D simulation (R) for R_EAR_CONTOUR

Operation Set 5 | KID_DEFINE | Tool 5

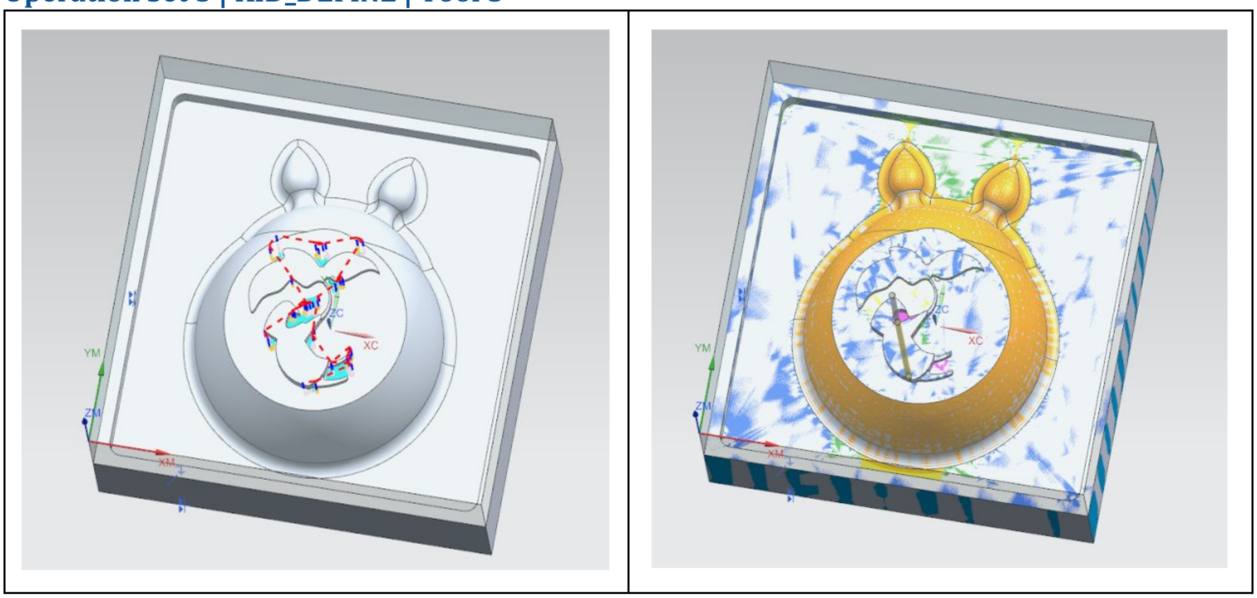

Figure 15: Tool paths (L) and 3D simulation (R) for KID_DEFINE

Before the program can end, delicate details like the child's face and inner thigh and the curve of the leaf must be defined. To do this, a cavity finishing operation with a 0.0625" flat end mill is performed. A flat end mill is assigned to ensure the circle cut across Totoro's stomach as well as the vertically extruded images of the child and leaf remain horizontal to the underside of the workpiece. A 0.0625" diameter tool is used because these intricate features were designed specifically with the smallest tool available in mind. This operation is limited by a cut level defined from the floor of the cut circle to the upper face of the extruded child. The height of the operation was restricted because it is not safe to use the 0.0625" tool for cuts deeper than $\frac{3}{16}$".

Post Processing

After the manufacturing program is created, a HAAS VF3 postprocessor must be used to translate the resulting script into G-code. This last step is important because CNC machines read G-code to determine the tools, speeds and movements needed to execute operations correctly.

CNC Manufacturing

Setting Up the CNC

Before touching the CNC, a bandsaw was used to sever a 4" x 4" x 1.8" blank from a larger block of aluminum. This blank was then secured to a mill with a pair of parallels and a vice. To level the raw material for manufacturing, a face milling cutter was manually jogged over the top of the aluminum to create a horizontal surface. Afterwards, an edge finder was used to determine the x- and y-coordinates of the MCS. Calibration was performed by misaligning the tip, running the spindle at 1000 rpm, and repeatedly jogging the clamped blank (left or right in the x-direction and forward or backward in the y-direction) towards the edge finder until the tip clicked into place. In the offset menu, a value of 0.1" was subsequently added to the zeroed xy-coordinates to account for the radius of the edge finder. These values were verified by raising the edge finder above the block and translating the tool to the numbers saved in the G54 work coordinate system. Fortunately, the resulting position matched the location of the MCS indicated in **Figure 4**.

As shown in **Table 2**, the manufacturing program requires five tools. Each tool was assembled by fastening the appropriate mill bit to a conical tool holder. **Figure 16** shows which cutting tools were selected and how they were assembled on the day of manufacturing. Because tools 2-4 are involved in operations which circle tightly around Totoro's body, their lengths were adjusted to extend 1" out from the holder. This task was necessary to prevent the holder from smashing into the blank.

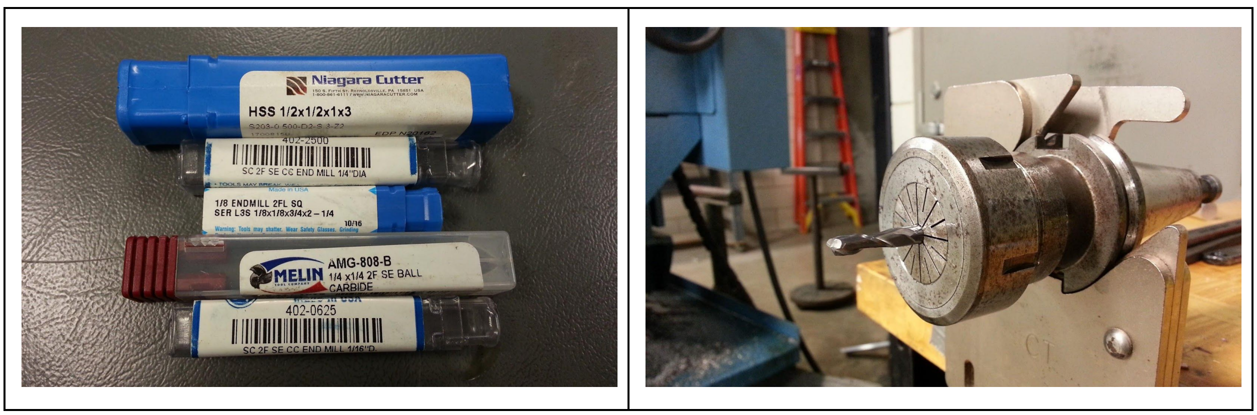

Figure 16: Cutting tools selected (L) and an assembled tool with a flush collate and nut (R)

A 1" gage box was used to find the z-offset of each tool. Calibration was performed by systematically decreasing the tool height and swiping the gage box underneath the cutting edge. Once the top of the box contacted the underside the blade, the spindle was dialed back up by one increment and a smaller handle jog magnitude was selected. This process was repeated until a handle jog magnitude of 0.0001" was used. After locking the zeroed z-coordinate into the tool offset menu, 1" was subtracted from the height entered to account for the size of the gage box. These offset values were verified by dropping the tools to a height 1" above the z-positions previously measured. If a gage box was able to just pass under the mill bit, then the zero position was approved.

The Manufacturing Process

Due to time constraints, the milling process occurred over a period of two days. On October 19, INSIDE_2 was suspended at 10:49PM and resumed at 8:15AM the following morning. Between tool changes, the rapid speed was reduced to 5% and single block mode was employed to evaluate whether the z-offsets of each tool were set correctly. During operations 2-5, high-pitched chatter was heard. This happened because the lengths of tools 2 and 3 were intentionally set to 1" to prevent the holder from accidentally shearing off parts of the blank.

The photographs below show how the aluminum block transformed between tool changes. As seen in **Figure 17 L**, the bulk cavity operations successfully used tool 1 to carve out the outline of Totoro's body as well as the general form of the child and leaf. In **Figure 17 R**, the first two inside cavity operations created smaller steps around the extruded body and were able to scoop out residual material connecting Totoro's ear tips and underbelly to the extruded wall.

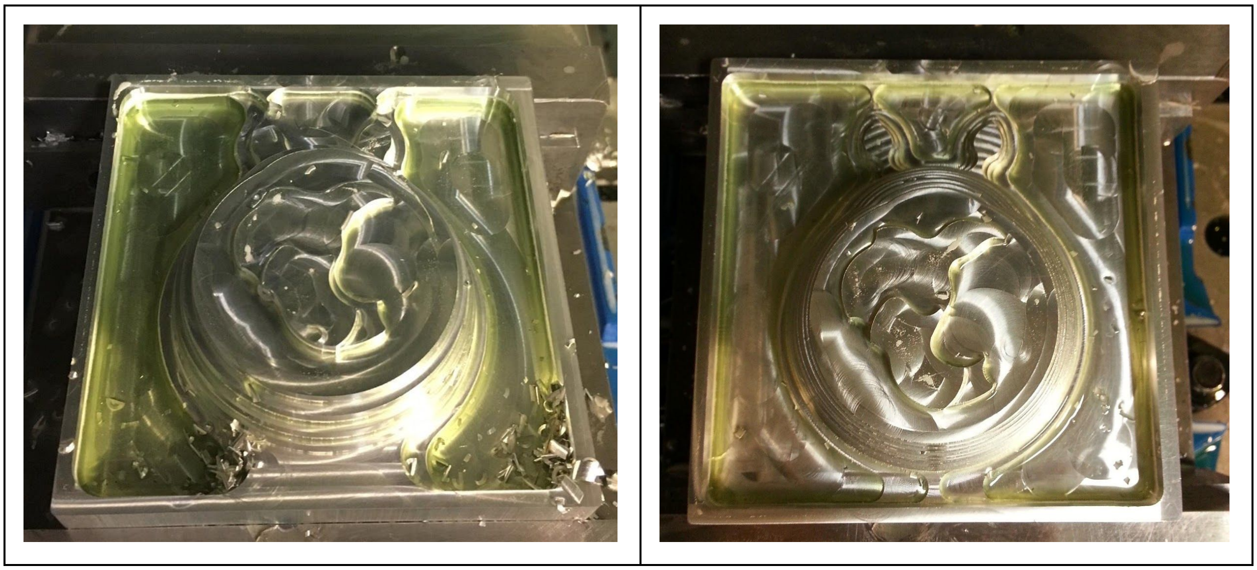

Figure 17: Blank after first tool change (L) and blank after second tool change (R)

Figure 18 L shows that touch up operations INSIDE 3, PLANAR_PROFILE_1, and INSIDE_4 successfully used tool 3 to shape the petiole of the leaf, the channel above the child's head, the space between the dangling legs, and further reduced the ledges surrounding the revolved body. In **Figure 18 R**, it is apparent that the contour area operations were able to buff the rounded curves of Totoro's ears and body to a glossy finish. During manufacturing, these contouring procedures were performed with a 650% feed rate. This was done to accelerate the program and help the tool shave aluminum continuously - since the scallop size for all three processes is 0.0005".


Figure 18: Blank after third tool change (L) and blank after fourth tool change (R)

Figure 19 shows the result of the last finishing operation. As depicted, the 0.0625" end mill was able to sculpt dainty features like the facial opening of the child's hood and the edges of the leaves. The total program took 4 hours, 13 minutes and 43 seconds to complete. This is significantly longer than the 3 hours, 29 minutes and 58 seconds predicted by NX but expected - because of picture taking, intermittent cleaning, and single block verification between tool changes.

Figure 19: The freshly-cut, final result

Results and Final Observations

Figure 20: The cleaned but unpolished final aluminum part

As shown above, the final part resembles the original piece modeled in Solidworks (**Figure 3**). Upon closer inspection, however, there are a few minor differences. In the small spaces between the ears and the upper wall, the bottom of Totoro's body and the lower wall, and along the crescent of the child's stomach, razor-thin ledges exist. These areas may have been missed because I changed INSIDE_4 from a finishing operation to a semi-finishing operation.

While I was revising my program, I was informed that contour area operations should be preceded by a semi-finishing operation to maximize the amount of time the tool stays in contact with the blank material. This, in turn, prevents the blades from dulling and produces a smooth surface. Unfortunately, I failed to realize that INSIDE_4 is also a cleaning operation which I originally intended to use to perfect the outline of the child and refine small areas inside the extruded cut left untouched by INSIDE_2 and INSIDE_3. Heavy reliance on NX's verify path feature also contributed to this oversight. Although the 3D dynamic simulation does display faint ridges above and below Totoro's body when zoom is employed, the crescent plateau adjacent to the child's stomach does not show up at all (**Figure A1**). To rectify this mistake, another cavity milling operation with tool 3 should have been set up after the contour area operations.

Appendix A

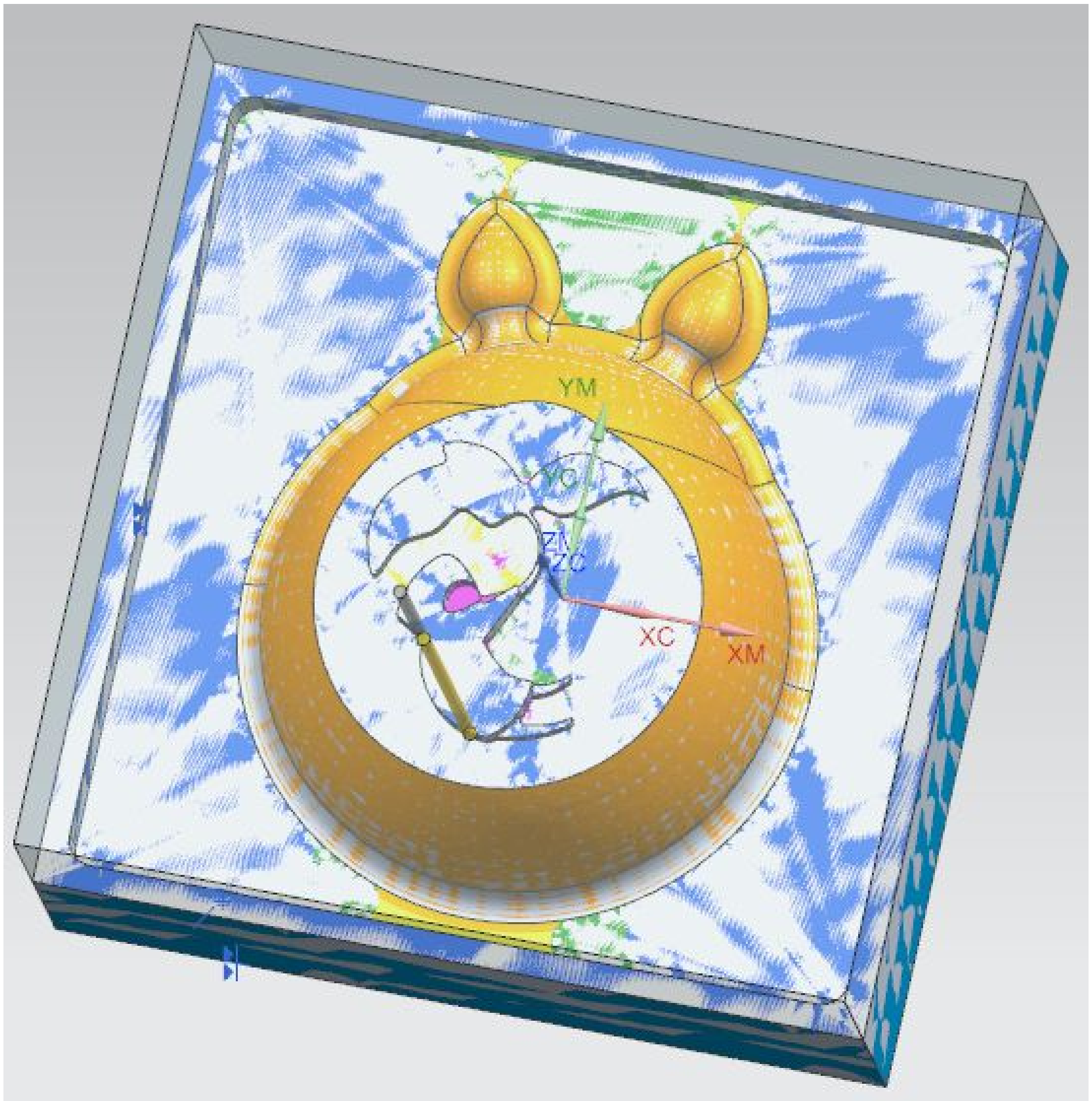

Figure A1: A zoomed in image of the simulated final part generated in NX

Although the yellow ledges do show up, the area between the arm and stomach of the child looks clean. This deviates from what was seen after the milling program terminated.