Nora the Dragon

Joyce D'Aprile, Jack Eichenlaub, Freesoul El Shabazz, Jacob Hullings
Michael Beltran
ME 340-2
Winter 2019

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I. Product Description

Nora is a toy dragon composed of a four-part assembly-- two halves of the dragon head, and two interlocking pieces of flame. Over the course of the quarter, Nora went from a rough sketch, to CAD model, to CAM program, to aluminum molds, and finally to an injection-molded polypropylene part. The basis for Nora was a drawing by Nala, a fourth grade student at Lincoln Elementary School in Evanston (Figure 1). We extrapolated our own design sketches from Nala's, with the limitations of our machining and injection molding processes in mind, arriving at the concept seen in Figure 2.

Figure 1: Nala's sketch

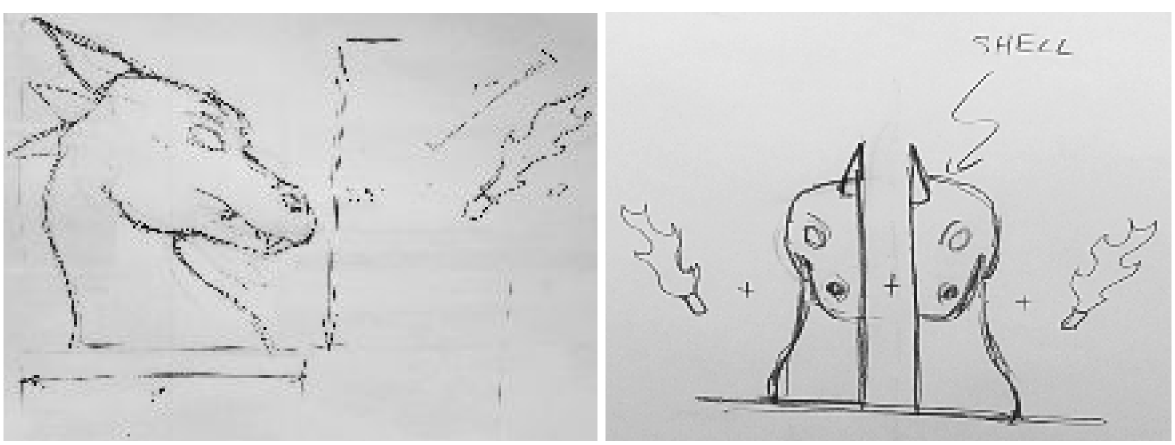
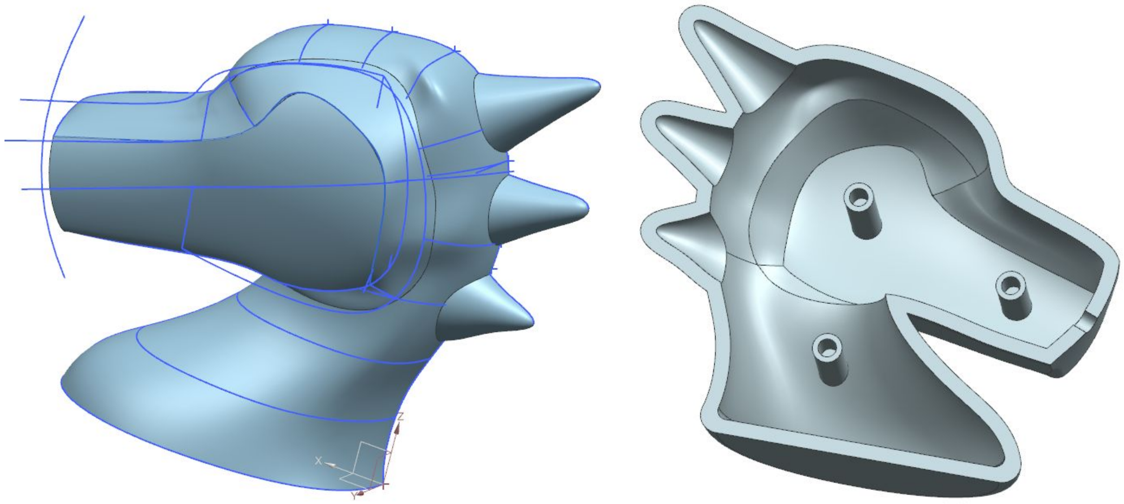


Figure 2: The team's concept sketches for the parts and their assembly

From the sketches in Figure 2, the we to model Nora as 3D geometry in Siemens NX software. Due to the organic form of the parts, the team primarily used surface modelling techniques. We chose to narrow the scope of the project to Nora's head breathing fire, as this would be easier to create given the time restrictions and the limitations of injection molding. Figure 3a displays one half of Nora modelled as a sheet body in NX. This sheet body was scaled down and thickened into a solid before the team mirrored it and added mating geometry to each half to allow for press fit pins to hold the pieces together. Three pins were modelled onto the right half of the dragon (from Nora's point of view), and three corresponding bosses were placed on the left. The right side with its mating bosses is below in Figure 3b.



(a) *(b)*

Figure 3: Surface model of half of Nora's head (a) and thickened solid body with mating geometry (b)

Each half of the fire was a single flat extrusion based on Lego fire, such that the two pieces could slot together to make a three dimensional shape, seen in Figure 4.

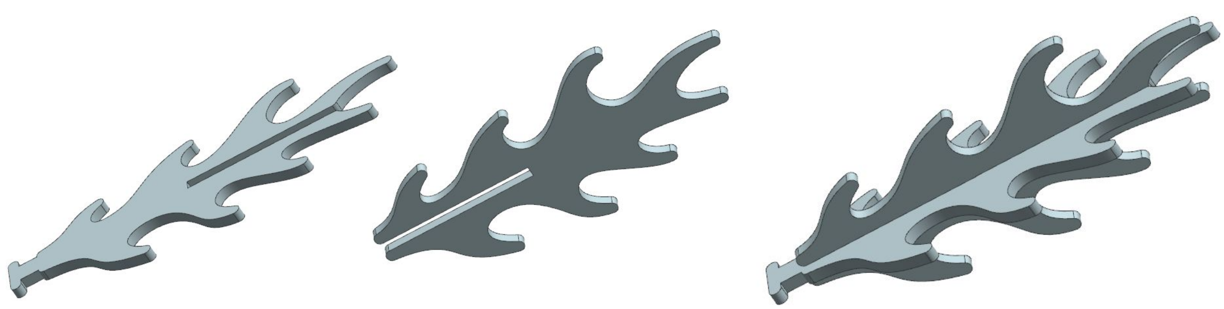


Figure 4: Disassembled and assembled flat fire models.

II. Discussion of Mold Design

The entirety of our product was achieved using three molds total, two for the left and right halves of the assembly, plus a third for the fire parts. The mold design for the two halves are identical in their incorporation of design for injection molding techniques. Due to the complex organic geometries of our parts, thoroughly dimensioned drawings were infeasible, so Figure 5 below shows orthographic views of our five molds on the 4in by 4in mold blanks.

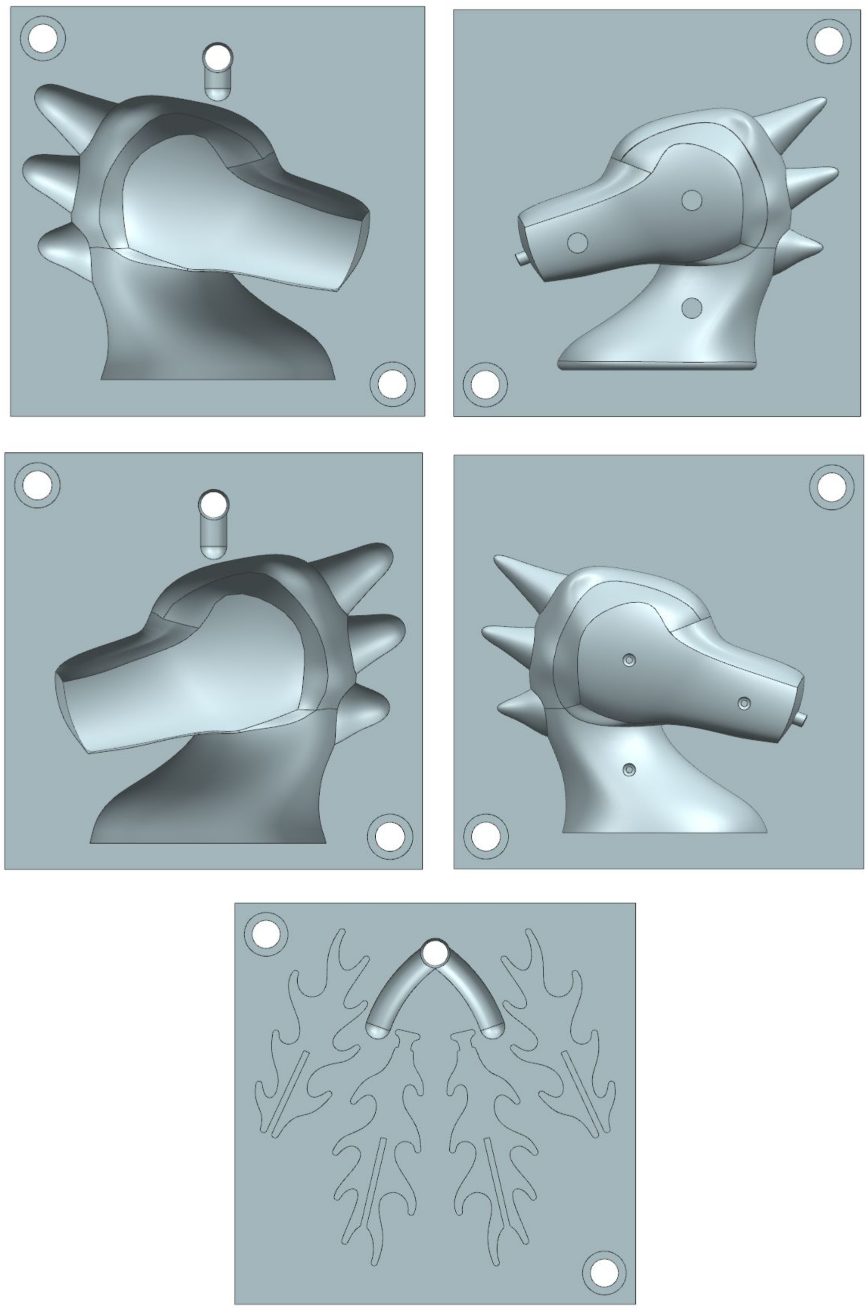


Figure 5: Mold Halves (from top to bottom: left core and cavity, right core and cavity, flames)

By deciding to limit our design to the head of a dragon, we were able to take advantage of the symmetry and split our part down the middle plane perpendicular to the base plane. In doing this we were able to easily place our parting line on a flat surface representing the largest projected area cross section of our part. Due to the relatively steep geometries of the part we suspected that part removal would be a challenge, in order to address this we introduced a 1 degree draft angle at the parting surface of each part during modeling-- this ensured that during shrinkage the part stuck to the core of our mold. Further, because we were able to achieve uniform wall thickness we could expect uniform shrinkage around the cores by about 1-2.5%. The one exception to this uniformity is the pin bosses in the middle of the part. The team decreased the wall thickness of these parts from 0.125 to 0.05 to help mitigate shrinkage as well as allow for an easier fit while assembling. Due to our large part size we used direct ¼" runners around .03" from the part wall with ⅛" gates. Trial and error with the molding machines during the injection process allowed the team to avoid short shots, despite the large size of our parts.

The fire mold, as seen in Figure 5, used a symmetrical layout of the flame parts. This allowed for a naturally balanced runner design with .03" gap between the runner and the wall to allow for ⅛" gates. Additionally, due to the flat nature of the parts, the team was able to only machine a cavity for the fire. The core needed only be a flat surface, so the team used a mold blank. Because the parts were so thin, the fire pieces did not need draft for removal. Instead the team relied on the knowledge that they would shrink away from the cavity.

III. Discussion of CAM Programming and CNC Machining

The general convention we followed for machining was to move from largest to smallest tool, and to perform both a roughing and finishing operation with each tool. For the cavities, we began with cavity mill operations, to generally create the part geometry and remove the bulk of material. Next moving to contour area operations in order to give the geometry more shape and greater surface quality. Separate operations were used for the runners. As for the cores, the process was greatly the same, only that we needed to include drilling operations for pins on both sides of the part. This took a considerable amount of effort, as it was a challenge to successfully drill holes at such a depth. Additionally, the cores feature a small extrusion at the 'snout' of the part in order to interface with the flame pieces-- this required a higher precision cut and thus we used z-level corner and flow-cuts (Figure 9) in order to ensure the feature was present to our design specifications.

MCS_MILL			01:58:39						
WORKPIECE			01:58:39						
CAVITY_MILL_ROUGH	✔	BALL_MILL0.5	00:09:12	WORKPIECE	MILL_ROUGH	.125 in	33 %Flat	16.112 ipm	3056 rpm
CAVITY_MILL_FINISH	✔	BALL_MILL0.5	00:05:05	WORKPIECE	MILL_FINISH	.125 in	33 %Flat	16.112 ipm	3056 rpm
CAVITY_MILL_ROUGH2	✔	BALL_MILL0.25	00:04:48	WORKPIECE	MILL_ROUGH	.075 in	30 %Flat	11.0016 ipm	6112 rpm
CAVITY_MILL_FINISH2	✔	BALL_MILL0.25	00:09:07	WORKPIECE	MILL_FINISH	.01 Scallop	30 %Flat	11.0016 ipm	6112 rpm
PLANAR_MILL_RNNER	✔	BALL_MILL0.25	00:00:28	WORKPIECE	MILL_FINISH	0.0500	33 %Flat	11.0016 ipm	6112 rpm
CONTOUR_AREA_ROUGH	✔	BALL_MILL0.125	01:25:29	WORKPIECE	MILL_FINISH	50 %Tool	.001 Scallop	6.0032 ipm	9992 rpm
CONTOUR_AREA	✔	BALL_MILL0.125	00:03:54	WORKPIECE	MILL_FINISH	50 %Tool	.1 Scallop	6 ipm	9992 rpm

Figure 6: Right Cavity Operation Navigator

MCS_MILL			01:54:47						
WORKPIECE			01:54:47						
CAVITY_MILL_1	✔	BALL_MILL_.5	00:09:21	WORKPIECE	MILL_ROUGH	.125 in	33 %Flat	15.8912 ipm	3056 rpm
CAVITY_MILL	✔	BALL_MILL_.5	00:05:08	WORKPIECE	MILL_FINISH	.01 Scallop	33 %Flat	15.8912 ipm	3056 rpm
CAVITY_MILL_2	✔	BALL_MILL_.25	00:04:49	WORKPIECE	MILL_ROUGH	.075 in	30 %Flat	11.0016 ipm	6112 rpm
CAVITY_MILL_3	✔	BALL_MILL_.25	00:09:12	WORKPIECE	MILL_FINISH	.01 Scallop	30 %Flat	11.0016 ipm	6112 rpm
CONTOUR_AREA	✔	BALL_MILL_.125	01:23:55	WORKPIECE	MILL_FINISH	50 %Tool	.001 Scallop	6 ipm	10000 rpm
CONTOUR_AREA_1	✔	BALL_MILL_.125	00:01:47	WORKPIECE	MILL_FINISH	50 %Tool	.1 Scallop	10 ipm	0 rpm

Figure 7: Left Cavity Operation Navigator

Operation Navigator - Geometry

Name	Path	Tool	Time	Geometry	Method	Depth of Cut	Stepover	Feed	Speed
GEOMETRY			02:37:53						
Unused Items			00:00:00						
MCS_MILL			02:37:53						
WORKPIECE			02:37:53						
SPOT_DRILLING	✔	CENTERDRILL_1	00:00:04	WORKPIECE	DRILL_METHO...			14 ipm	3500 rpm
FULL_DRILLING_0.125	✔	STD_DRILL.125	00:00:18	WORKPIECE	DRILL_METHOD			14 ipm	3500 rpm
CAVITY_MILL_ROUGH	✔	END_MILL0.5	00:41:58	WORKPIECE	MILL_ROUGH	.08 Scallop	33 %Flat	16 ipm	3056 rpm
CAVITY_MILL_FINISH	✔	END_MILL_0.25	00:59:08	WORKPIECE	MILL_FINISH	.02 Scallop	.02 Scallop	12 ipm	6112 rpm
CONTOUR_AREA_FINISH	✔	BALL_MILL0.125	00:47:59	WORKPIECE	MILL_FINISH	50 %Tool	.001 Scallop	6 ipm	10000 rpm
ZLEVEL_CORNER	✔	END_MILL_0.125	00:06:59	WORKPIECE	MILL_FINISH	.01 in		6 ipm	10000 rpm
FLOWCUT_SINGLE	✔	END_MILL_0.125	00:00:15	WORKPIECE	MILL_FINISH			6 ipm	10000 rpm

Figure 8: Right Core Operation Navigator

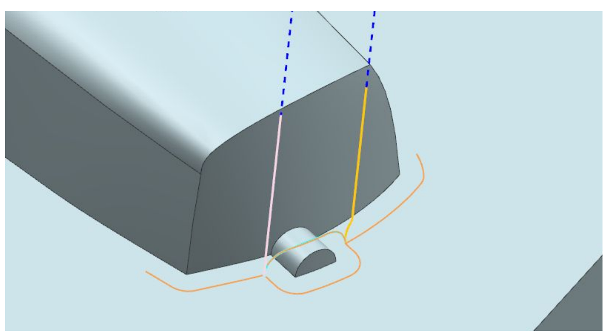


Figure 9: Right Core FLOWCUT_SINGLE Toolpath

MCS_MILL			03:14:25						
WORKPIECE			03:14:25						
SPOT_DRILLING	✔	CENTERDRILL	00:00:04	WORKPIECE	DRILL_METHOD			14 ipm	3200 rpm
DRILLING	✔	STD_DRILL.25	00:00:17	WORKPIECE	METHOD			14 ipm	3200 rpm
CAVITY_MILL_ROUGH	✔	END_MILL0.5	01:12:16	WORKPIECE	METHOD	.08 in	33 %Flat	16 ipm	3056 rpm
CAVITY_MILLFINISH	✔	ENDMILL0.25	00:29:12	WORKPIECE	MILL_FINISH	.02 Scallop	.02 Scallop	12 ipm	6112 rpm
CONTOUR_AREA	✔	BALL_MILL_.125	01:31:25	WORKPIECE	MILL_FINISH	50 %Tool	.001 Scallop	6 ipm	9992 rpm
ZLEVEL_CORNER	☐	ENDMILL0.125	00:00:00	WORKPIECE	MILL_FINISH	.01 in		6 ipm	10000 rpm

Figure 10: Left Core Operation Navigator

Our CAM process was imperfect. We ruined one mold because we forgot to set the MCS coordinate system. This resulted in the tool beginning its cutting operation in the wrong place on the blank. Another difficulty we had was in file management. We ruined another mold, not to mention waisted nearly two hours of our time, by running an earlier version of a manufacturing file. This file was so similar to the one that was wholly correct, other than the fact that it cut a deeper cavity than the tool we were using could sustain, that we did not realize we were running the wrong one until the tool broke. Our third CAM misstep was due to a Z-height misalignment. We did not set one tool height properly, which resulted this tool's operation cutting deeper than intended.

What really allowed us to achieve our manufacturing goals was our adaptability and ability to recognizing our mistakes in process. On several occasions we caught feeds and speeds errors while machining simply by reading ahead a few lines in the G-CODE. Of course this isn't the ideal method of stopping catastrophe, but the scare of almost making a mistake was second only to actually making a mistake in terms of lessons learned. As for design modifications during process we had to touch up a fillet on the left cavity (Figure 11). During our initial injection molding, we noticed that our internal fillets were not producing symmetrical parts at the bottom facing and observed the difference in the molds: one had a more rounded bottom and the other a sharper one. We addressed this problem with the above operation. In order to ensure the surface finish of the remachined part matched the existing half, we matched the toolpath of the right cavity. This made our touch up take longer, as the tool was not always engaged with the fillet to be machined, but our final parts matched well.

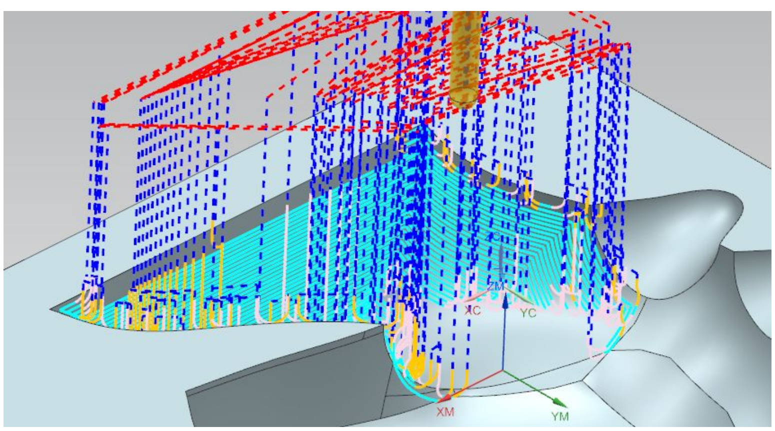


Figure 11: Left Cavity Fillet Touch-Up, which required remachining the bottom face.

Early on we were able to take advantage of our design/engineering intuition in order to generate ridges within Nora's horns. By using a Zig-Zag toolpath, adjusting the path angle, and increasing the scallop size, we created the geometry. The resulting finish would have been unacceptable for a smooth surface, but worked perfectly for this feature, as seen in Figure 12 below.

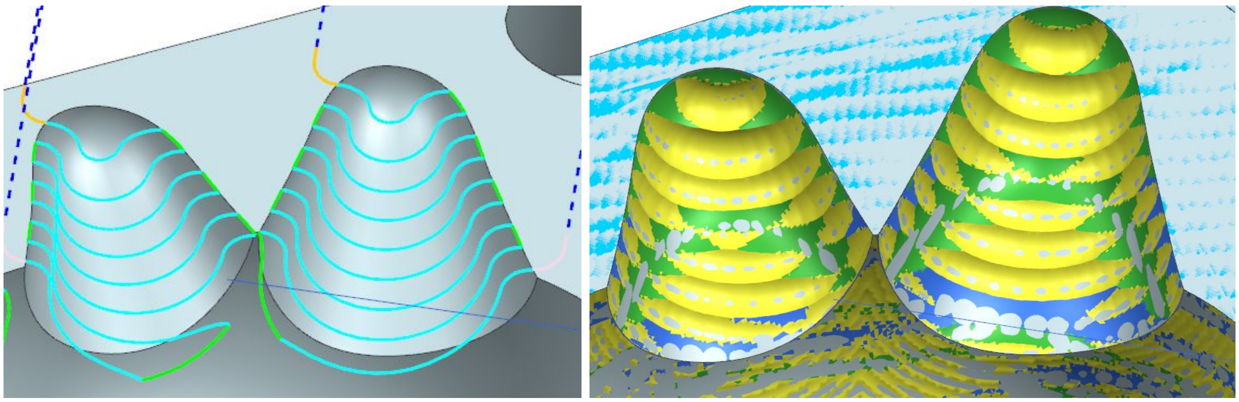


Figure 12: Horn ridge toolpath and resulting geometry.

Through extensive trial and error, and meticulous verification of generated pathways our manufacturing processes ultimately maintained our design intent. In this, our molds were accurate to our specifications within a reasonable tolerance for the tooling used. We believe the majority of our error was generated in the variability of the injection molding process, further discussed in the next section.

IV. Discussion of Molded Parts

In this segment of the report, we will discuss our measurement study results and how well we feel that the parts came out of the injection molding process, in addition to some common pitfalls and things that happened with our parts in terms of shrinkage and varying sizes based on cooling time.

a. Measurement Study

The first thing to discuss is the measurement study that we did on our finalized parts. As Section III mentioned, we chose to remanufacture the inner radius of a cavity mold (the visible base radius on the part), and so we only did the measurement study on the each half of the dragon's head once the radii were corrected. The following table lists all of the values we recorded during the measurement study of our production run for 10 assemblies. We also produced a few more than 10 units of each part, as some of the early ones were dimensionally whacky, and we wanted the dragon to fit together as well as possible. The following data only comes from the 10 dragons we displayed at the design expo. After we collected this dimensional data, we found the average and compared it to the nominal value to find a percent deviation from the expected value. Given that polypropylene is expected to shrink 1.5 to 2% during the injection molding process, we wanted to see if we achieved this expected result for our dragon.

Table 1: List of dimensional measurements of each component for the study

No.	Flame Length (in.)	Left Base Thick (in.)	Right Base Thick (in.)
1	2.35	0.118	0.103
2	2.3	0.116	0.104
3	2.32	0.116	0.104
4	2.35	0.119	0.106
5	2.31	0.125	0.103
6	2.31	0.122	0.103
7	2.3	0.115	0.105
8	2.32	0.113	0.104
9	2.3	0.12	0.103
10	2.35	0.118	0.107

For the simpler flame portion, we definitely hit the tolerance right on the nose; however for the dragon head, our result was more varied. The non-remanufactured side, the right side, was only at 3.9% deviation from nominal size, which is not terrible. However, it was slightly oversize, not shrunk like one might expect. The left side was much more oversize, by almost 20%. At first, we were very confused by this result, but upon reflection realized that this was a direct result of the remanufacturing process of the inner radius. In order to form the radius correctly, wall material was removed from the base of the cavity mold, thereby enlarging the gap between the core and cavity, leading to this larger thickness. We believe that more of that wall was removed than expected due to differences in the zeroing of the CNC machine in the week that passed between our two manufacturing operations.

Table 2: results of comparing measurement data with expected, CAD design values.

Average Deviation from Nominal

	Flame	Left	Right
Average (in.)	2.321	.1183	.1039
Nominal (in.)	2.3511	.1	.1
Deviation (in.)	.0301	**.0183**	.0039
Deviation (%)	1.27	**18.3**	3.9%
Causes		• Excessive flash • Additional Manufacturing to fix fillet	

It is also important to emphasize again that the injection molded parts are only dependent on mold geometry, not CAD geometry, so if there were small errors or imprecisions in the molds, there would be no possible way for the molded part to ever match that geometry.

b. Parts Compared to Molds

One thing that made our team very satisfied was the clear translation of our unique design features from the mold to the parts. We very intentionally textured the horns to give an interesting appearance, and work with the limitations of our tooling, and the final dragon head parts really represented that texture well. We intentionally created the toolpaths to give the cavity surface a somewhat geometric pattern on the finishing pass, and this can be seen on the dragon head when it catches the light and reflects. Another small element that worked super well was our core-side extrusion that pressed against the cavity wall to create the hole in the mouth where the fire would reside. As mentioned in the previous section, this element was very difficult to model and translate to the molds, and we were very happy to see it form very regular openings in the dragon's mouth. Almost no flash was formed in this area, and it (reasonably) hold the fire in proper place and orientation, which is all that we could have asked for!

It is worth mentioning that comparing many of the dimensions of the dragon to the molds would be difficult, if not impossible, given all of the varying radius curves and surfaces. Without lots of time and access to more sophisticated measuring equipment, it would be tough to statistically analyze how accurately we were able to translate the original imagined geometry to the finalized part. From a purely visual perspective, however, the dragon looks exceptionally close to our design intent and all features formed fully, with the exception of the ends of the pins due to air pressure building (as discussed in Section III). We did experience a slight bowing of the bottom of the dragon (the dimension measured in the study) as it is a flat, straight, thick wall that would experience internal forces as it cooled unevenly from the center to the corners. Unfortunately, there was nothing we could do during the injection process to fully alleviate this, as cooling past 35 or 40 seconds did not improve the shape any longer.

While the parts turned out almost exactly as we could have wished, one can clearly see it took much trial and error to arrive at appropriate molds. Even further, it took continual experimentation on the machines to produce repeatable, clean parts. The following **Section V** will dive further into the trials and tribulations of this project, and the many valuable lessons we will take away from our first foray into injection molding.

V. Conclusions and Lessons Learned

It goes without saying, but the team is quite satisfied with the results of the Design Expo this past Friday, and our achievement of first place with Nora the Dragon! It was one of our goals from the beginning of the quarter to create a well executed and ambitious design, and really aim for a high quality finished product. We are quite satisfied with the color scheme of both the head and the fire element as well, they really contribute to the polished look of the product. Obviously this journey was not without hiccups and problems, and these are outlined below starting with the most difficult challenges first.

a. Difficulties, Frustrations, and Learnings

It started all the way at the beginning of the quarter, but **modeling** the dragon head was a very difficult and time consuming process. It was done solely with surface modeling techniques, and then thickened to a hollow solid body at the end of the process. As the shape is so organic and complicated, our NX program file had tens of surfaces and hundreds of operations in the feature tree. Managing these complex interactions was a large challenge, as the body refused to rebuild many times after modifications. We are uncertain if there are strategies we could have taken to avoid these difficulties, but hopefully our interview and conversation with Siemens next quarter will provide some answers to these questions.

Our second area of frustration and stress was actually **manufacturing** the molds from blanks. As a team, we managed to ruin two cavity blanks and one core blank, each from a different error. Some things we were able to catch very quickly, like a mis-set MCS Mill coordinate system in the CAM program, or forgotten feeds and speeds. Others, we still have no certain explanation for. One of our cavities was ruined by a tool that plunged into the blank, and was also offset from its expected location by about a quarter of an inch. We currently believe that there was an issue with the adjust register, so NX believed a different tool was loaded into the spindle and believe the tool to be much shorter and of different diameter than in actuality.

Were we to do this again, we recognize that we could achieve the same injection molded results with a rougher core mold finish, and changing the CAM program to do so would have saved a lot of time. We also could select larger tooling for finishing passes to smooth our curved surfaces, where applicable. Each of our 5 manufactured mold parts took around 3 hours of machining time, meaning we got very accustomed to the buzz and rhythm of the CNC machines.

In terms of **design for manufacturing**, we had a few expectations for what could be changed, and we asked the judges as they came around to our table. They confirmed that a wall thickness of 0.10 inches was little large, but also understood our hesitation to go smaller and risk not filling the large parts. The really interesting suggestions were for pin design and part venting. Like our original mold design, they suggested shorter pins located near the walls. If for some reason we needed the pins positioned as we did, they suggested making ribs radially around the pins to provide extra stability, and only exposing the necessary length.

We mentioned our difficulties getting the pins to fill all the way, as we expected air pressure was building at the bottom. The judges confirmed our suspicions, and that we do not have appropriate tooling here to vent those holes, but in theory one could plunge through the bottom of the pin cavity with a small enough diameter tool that air can escape but not the plastic. They also suggested venting around the pins at the mold surface by carving a tiny channel into the cavity mold and covering it with some sort of cosmetic feature in order to better vent the part and form a structurally even wall.

The last area of issue was **injection molding**. Given the variability of these machines, we had to be certain to set and follow and exact procedure for each part in order to make sure they actually came out similarly. We generally used a top temperature of 515 fahrenheit, lower of 555, and turned the core heater plate almost all the way up. Clamping pressure was at a maximum, and injection pressure at 3 units on the dial, which was only about 30% of the theoretical maximum. By injecting just until the mold halves started visually separating, we guaranteed that the pins filled as much as possible. This was very close to 4.5 seconds of injection time, following by 35 seconds waiting clamped, 20 on an unclamped mold, and then the part was removed. As soon as we unclamped the mold, we pushed more plastic into the barrel loader so it could pre-heat. Following this procedure exactly yielded predictable results, but it was very difficult to arrive at this exact, useful procedure. It took lots of trial and error to say the least.

b. Conclusion

Collectively, we feel that we learned an enormous amount about the entire injection molding process, from part design through finishing after molding. Part of our learning only came because we pushed the boundaries of what we reasonably thought we could do in the 10 week quarter. Having succeeded with such ambition leaves us proud on both a personal and an academic level, knowing we gave it our all and have been recognized by classmates and industry professionals for our work. We hope this report has been a useful glimpse inside our process of triumph and failure, and that Nora the Dragon will remain in the ME 340-2 "Hall of Fame" for years to come.

A Very Special Thanks to:

Mojtaba Mozaffar

Prof. Beltran

UA's

We appreciate your time and guidance.