Edge Design for Performance

A Major Qualifying Project Report

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by

Evan Bossio

Sophia Leitzman

Riley Lopez

Amanda Rodriguez

Professor Christopher A. Brown, Advisor

Abstract

This project examines the relationship between knife surface features and food sticking to the side of the blade. Since no existing literature was found on the subject, we developed original blade designs and testing procedures. Our designs focused on limiting potential contact area by pushing food away from the blade. After testing 5 different knives, we found that the curved chip-breaker design resulted in the best performance.

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1. Introduction

1.1. Objective

The objective of this project is to learn what blade surface features perform best to prevent sticking by designing and creating prototypes of several knife blades and testing their performance.

1.2. Rationale

Tens of millions of knives are sold in the United States each year; 46.9 million according to Riedel (2013). A common issue with the kitchen knife is foods with a high water content sticking to the side of the blade (Dusoulier, 2018). We believe consumers should have access to knives that increase ease of use by preventing unwanted stickage. While there is little information on the correlation between a blade's topography and its performance regarding food sticking to the blade, it is something we have personally experienced. Research on this correlation was performed using Google Scholar; the phrases used to conduct these searches can be found in Appendix A. Understanding this relationship will allow us to design a knife blade with features that prevent stickage.

1.3. State of the Art

1.3.1. Definitions and General Concepts

There are many different features to consider when describing the components of a kitchen knife. For the purpose of our project, we defined a knife to be a handle attached to a sharpened blade. The components of the blade itself include the following:

- Cutting edge
- Non-cutting edge
- Thickness of the blade
- Blade length
- Blade width
- Edge angle
- Tip radius

Figures 1.3.1 and 1.3.2 show these components on a diagram of a kitchen knife.

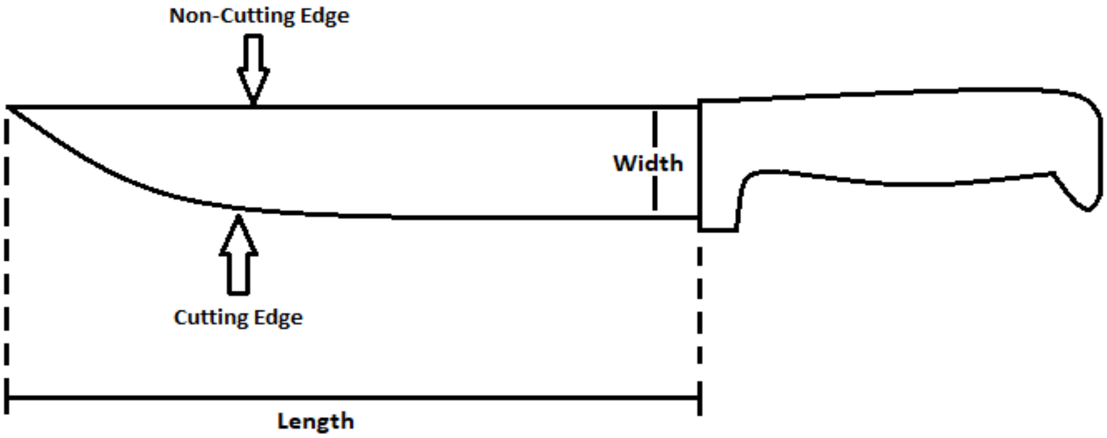


Figure 1.3.1 **- Side View of Kitchen Knife with Labelled Parameters (Hainsworth et al., 2008)**

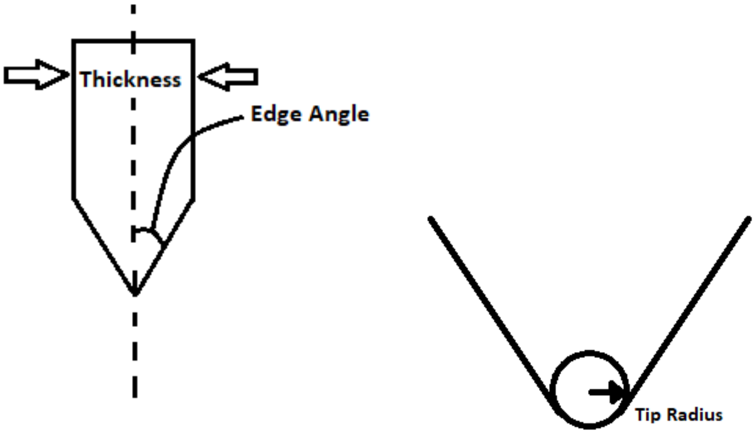


Figure 1.3.2 **- Front View of Kitchen Knife with Blade Edge & Angle Nomenclature (Hainsworth et al., 2008)**

It is important to note that the cutting edge of a knife blade may not be exactly circular as seen in Figure 1.3.2. In this case, several points on the tip radius should be measured to create an accurate characterization (Denkena and Biermann, 2014).

The edge angle, as shown in Figure 1.3.2, is the angle measured from the center of the blade to the external side of the blade. Increasing the edge angle will increase the cutting force with the usage of higher cutting speeds and specific energies (Singh et al., 2016).

Common household kitchen knives typically feature flat grinds since the sharpness acquired using this type of grind eases the slicing process (Comeau, n.d.). However, a knife featuring a convex grind can help prevent food from sticking to the side of the blade by reducing the area of contact between the sliced food and the blade itself (Dusoulier, 2018). In opposition to a convex grind, concave grinds are common in hunting and sport knives because of their sharper edge. A fourth grind - the S grind - is popular for high-end kitchen knives. It combines the features of other grinds, with a convex tip that reduces contact area at the cut and a concave area that creates a pocket, limiting the area on the blade face for food to stick to. The geometry of different grinds can be seen in Figure 1.3.3.

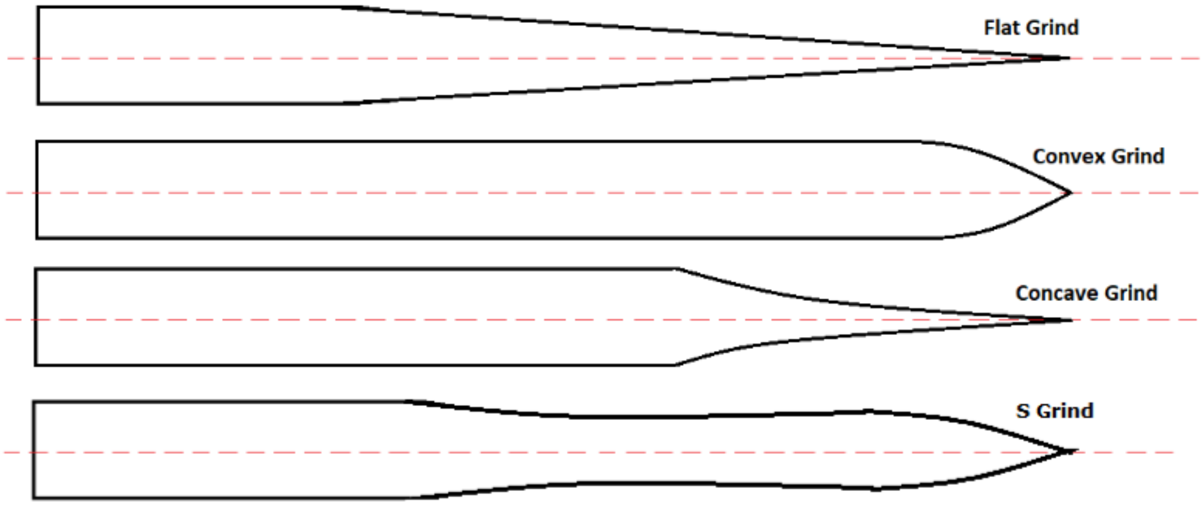


***Figure 1.3.3* - Front View of Different Knife Grinds (Comeau, n.d.)**

1.3.2. Machining and Bioinspired Designs

A chip-breaker is a common feature used in the machining process. When a machining tool is removing material from an object, a strand of the cut material continues to grow in size and can wrap around and cause damage to the machining tool. Chip-breakers prevent this from happening by forcing the chip to bend in such a way that the chip material breaks and falls out of the way machining path (Thompson, 2014).

Although chip-breakers could be effective to prevent sticking, the utilization of shark scales can provide an additional solution. A shark's scales help them glide through water with ease by utilizing a hydrodynamic function that helps reduce friction and resistance to forward motion (Cavanihac, 2001). These functions are what make sharks one of the fastest aquatic animals. Magnifying shark scales reveals a tooth-like shape that can reduce drag by disrupting water flow (Choi, 2014). These scale shapes are highly sought after to improve the speed of swimmers and divers; however, no one has been able to make these unique shapes successfully (Cavanihac, 2001). The repelling of water by these types of scales can be applied in a culinary setting to prevent knife stickage.

1.3.3. Capillary Adhesion vs Surface Roughness

The sticking encountered when using a knife to slice foods such as tomatoes or onions is due to capillary adhesion. This adhesion occurs because the presence of water molecules at the interface between two solids form capillary bridges that create attraction between the solids (Persson, 2008). Increasing the surface roughness can provide a solution for this adhesion, similar to the effects of chip-breakers or scales.

However, large asperities can contribute to the adhesion, so it is advised to use smaller roughness features for this purpose (Liu et al., 2007).

1.3.4. Materials

When looking for what material to use in the design of our knives we wanted to see what was already available on the market. The most commonly used material for kitchen knives according to Ranieri is stainless steel, due to its resistance to corrosion and its clean, slick appearance (2007). Type 316 is a type of stainless steel that is frequently used in food and surgical applications (KnifeCenter Inc, n.d.).

1.3.5. Professional Manufacturing Process

The basic process of professionally manufacturing knives begins by laser-cutting the basic shape of the blade out of a sheet of stainless steel. The blades are heat treated to set the structure of the material, making the steel both hard and elastic ("Kitchen Knife Process", 2016). To begin this process, the blades are heated up to 1000°C and then quickly quenched in oil. This results in a harder, stronger, but more brittle steel. To reduce the brittleness, the metal is heated over a period of two hours at a lower temperature (around 175˚C for maximum hardness). It is then allowed to cool at room temperature ("Purpose of Hardening and Tempering of Knife Steel", n.d.). After heat treatment, the blade edges are leveled and straightened, and the blade's shape is further defined with grindstones. Features like the bolster and handle are added, and then the whole knife is polished and given a professional finish. Finally, the blades are hand-sharpened to give them a quality cutting edge ("Kitchen Knife Process", 2016).

1.3.6. Axiomatic Design

Axiomatic design is a design theory and method used to analyze the relations between functional requirements (FR) and design parameters (DP) and how they address the customer needs. The design process focuses on the relation between a set of FRs and DPs through the use of a design matrix. This design method uses two axioms, independence and information axioms, in order to analyze how the components of a design effect the quality and efficiency of the overall product. The independence axiom stresses the importance of keeping the FRs independent from each other by making sure that each DP only impacts one FR. The information axiom focuses on minimizing the total information content going into the design by analyzing the likelihood that a DP will satisfy the FR (Suh, 1990). A system that can maintain independence and reduce the amount of information going into the design has a higher probability of success and is considered a better quality design.

1.4. Approach

A combination of several research aspects from the state-of-the-art were integrated in our designs.

1.4.1. Anti-Stick Features

We used a convex grind for one of our designs since it has been proven to help prevent stickage of certain foods by reducing the total area of contact (Dusoulier, 2018). In addition to the convex grind, we paired a flat grind with enlarged shark scales on the side of the blade in order to further limit the flat surface area (Choi, 2014). We cross-examined the scales' dimensions against research done by Liu et al. on roughness versus adhesion to ensure that these features would not be counterproductive (2007). On other designs, we used a concave grind in order to mimic chip-breaker geometry near the blade edge (Thompson, 2014).

1.4.2. Fabricating

We drew inspiration from commercial knife processes by using whetstone grinding as our primary sharpening technique and chose Type 316 Stainless Steel as our blade material (KnifeCenter Inc, n.d.) (Ranieri, 2007). However, due to limited equipment and materials, we altered the manufacturing process to accommodate what was available to us. First, we did not have access to strong enough laser cutters. Even with access to strong laser cutters, they would not have been able to cut the shapes of our blade features ("Kitchen Knife Process", 2016). Second, we decided not to apply any heat treatment because we did not need to alter the physical or chemical properties of the material ("Purpose of Hardening and Tempering of Knife Steel", n.d.). Lastly, the handle feature was not of interest to our design because it has no relation to stickage ("Kitchen Knife Process", 2016).

1.4.3. Testing

We were unable to find any published testing for both knife blade stickage and moisture, so we developed our own testing procedure.

2. Methods

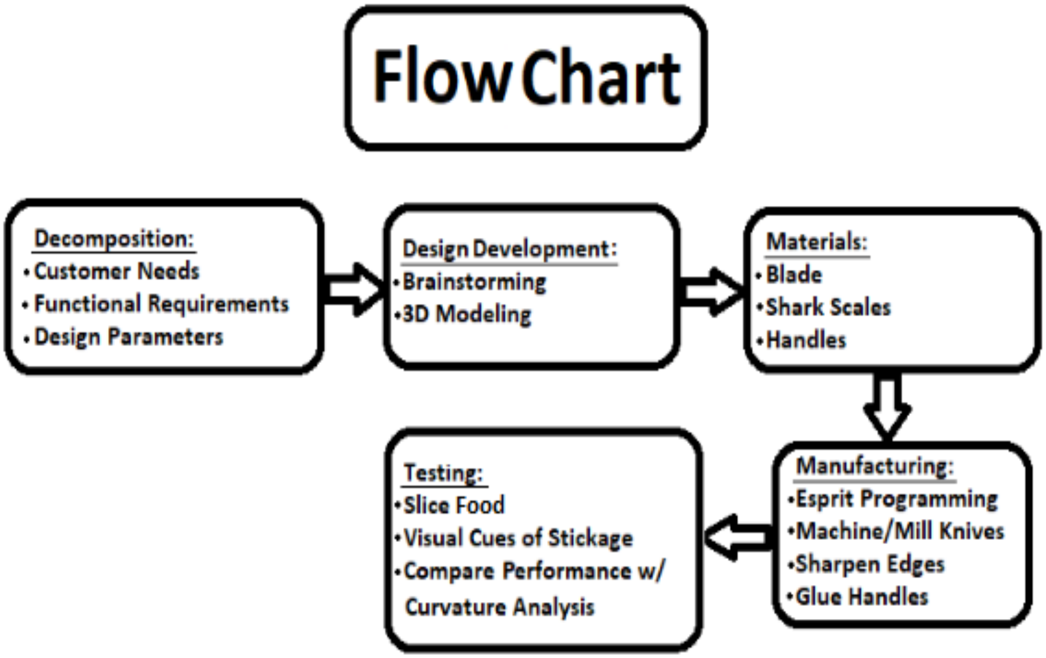


***Figure 2.1* - Flowchart detailing our methods process**

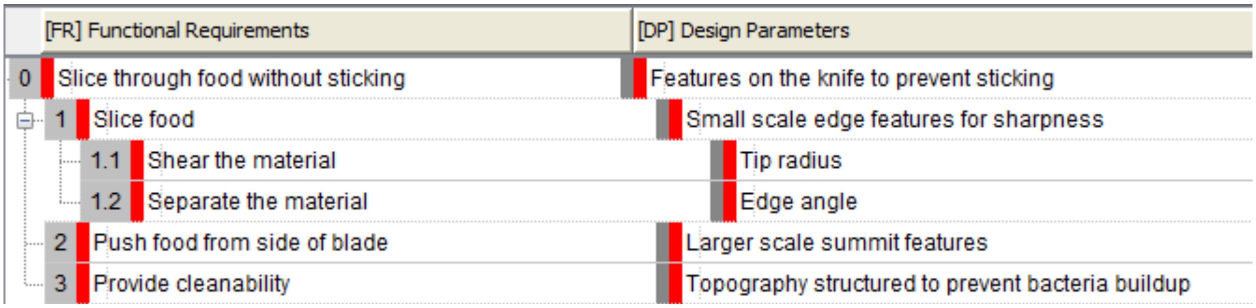
2.1. Decomposition

We first determined the attributes a kitchen knife should have to satisfy the customer needs (CN) and established a basis for the functional requirements (FR) that our knife designs needed to address. The FRs we chose focused on ensuring the following: that the knives could slice through food, that sliced food was prevented from sticking to the blade, and that the knives could be used and cleaned properly. Then, we selected specific design parameters (DP) that would accomplish each FR individually while limiting performance risks with conflicting parameters.

For the first DP, we concluded that the blade's sharpness directly impacted the knife's ability to slice the food. The tip radius is a key parameter for the knife's ability to initially break through the food, as a larger radius would make the blade too dull (Meissner, 1997). Additionally, we found that the edge angle of the blade is important for slicing through the food after the initial shearing (Singh et al., 2016). The second DP concentrated on design aspects of a blade that works to avoid stickage. Lastly, we looked at how certain topographies affect the ability to properly clean the blade.

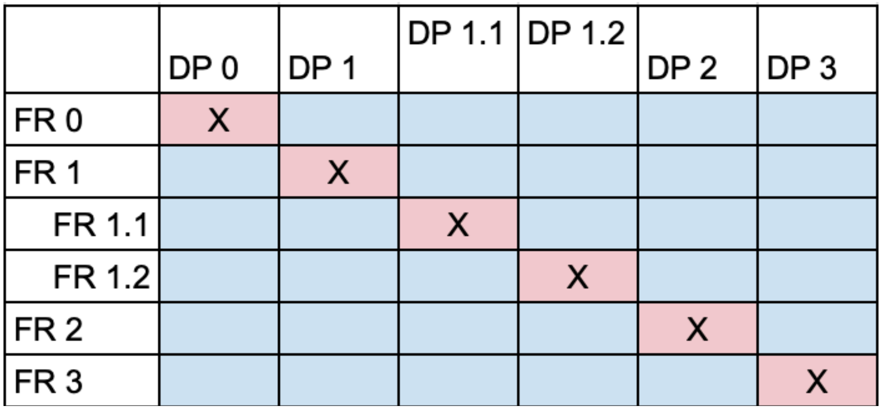
We developed design equations that exemplify how the variables in the DPs affect the FRs. After gathering all of the CNs, FRs, and DPs, we organized them in a design matrix showing the relationship between DPs and FRs. The equations and matrix provide quantitative and visual confirmation that each DP only had an impact on one FR, meaning FRs are not coupled. The FRs, DPs, and design matrix can be found in the following tables, while the design equations can be found in Appendix B.

Table 2.1 - FRs and DPs



	[FR] Functional Requirements	[DP] Design Parameters
0	Slice through food without sticking	Features on the knife to prevent sticking
1	Slice food	Small scale edge features for sharpness
1.1	Shear the material	Tip radius
1.2	Separate the material	Edge angle
2	Push food from side of blade	Larger scale summit features
3	Provide cleanability	Topography structured to prevent bacteria buildup

Table 2.2 - Design Matrix



	DP 0	DP 1	DP 1.1	DP 1.2	DP 2	DP 3
FR 0	X					
FR 1		X				
FR 1.1			X			
FR 1.2				X		
FR 2					X	
FR 3						X

2.2. Design Solutions

Our design development process began by taking inspiration from our research and finding ways to incorporate these ideas into a knife. Similar to its real-world application, a chip-breaker feature was added to push excess material out of the blade's way (Felix, 2018). Furthermore, we decided to have two different chip-breaker designs. One design included a smooth, rounded finish as seen in Figure 5.2, while the other included a sharp, flat finish as seen in Figure 5.3. Both knives were designed asymmetrically to avoid damaging the unsliced food.

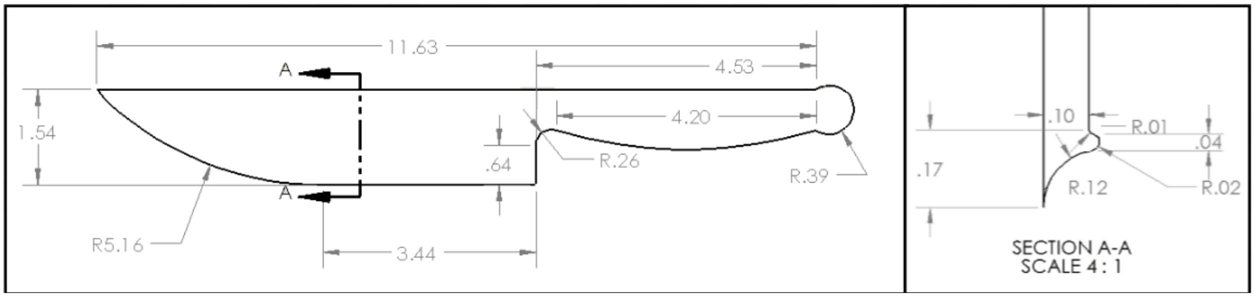


Figure 2.2 - Computer Aided Design (CAD) model of Left: isometric view of curved chip-breaker design, and Right: cross-section A-A

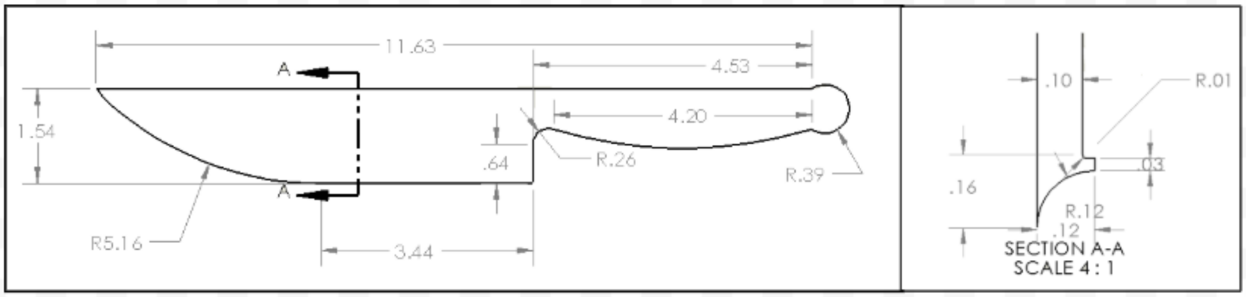


Figure 2.3 **- CAD model of Left: isometric view of flat chip-breaker design, and Right: cross-section A-A**

We developed another unique design by incorporating enlarged shark scales on the blade. Adding the shark scales' complex geometry to our blade design limits potential points of contact, thus reducing the likelihood of food sticking to the side of the blade. Initially, we wanted to feature the scales as a permanent part of the knife, however, the geometries of the scales were too small and complicated for traditional machining. Therefore, we manufactured them separately by 3D printing and gluing them to the side of a standard kitchen knife blade. These designs can be seen in Figure 5.4.

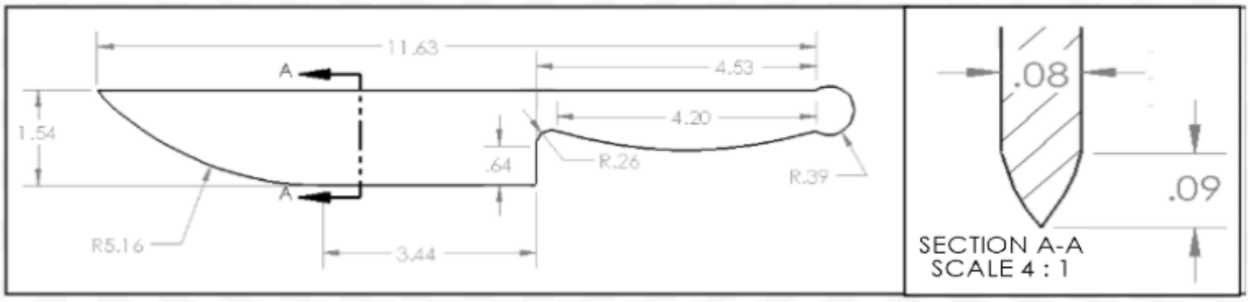


Figure 2.4 **- CAD model of Left: convex knife, and Right: cross-section A-A**

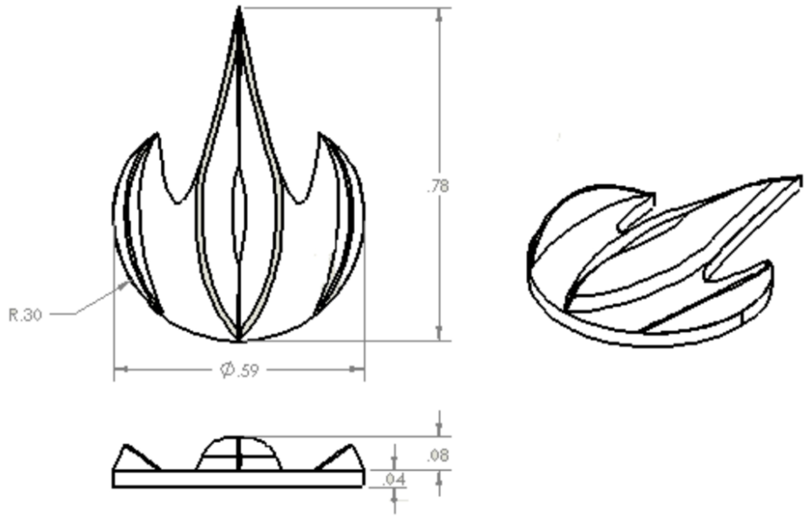


Figure 2.5 **- CAD drawings of the shark scales (top, front, and isometric views)**

2.3. Materials

Our knives were made of Type 316 Stainless Steel, a material commonly used in kitchen knives due to its resistance to corrosion and “clean” look (KnifeCenter Inc, n.d). Professionally manufactured knives are commonly coated with non-stick coating; however, we did not use any coatings, allowing us to focus specifically on the geometric effects on sticking (Russell, n.d.). We additionally used 3D printing material for the handle of the knife rather than wood composites because the filament was more accessible.

2.4. Manufacturing

We began the manufacturing process by 3D printing, using the SLA method, the shark scales and the knife handles. The knife models into ESPRIT, a Computer-Aided Manufacturing (CAM) system used for Computer Numerical Control (CNC) programming. We found that the best way to machine the proper geometries was to use milling operations on a HAAS mini mill. After setting up the CAM programs, plates of Type 316 stainless steel were machined into our knife designs. The edge features were machined using a ⅜” endmill entering from the side and cutting the curve with a 0.0001 inch step height.

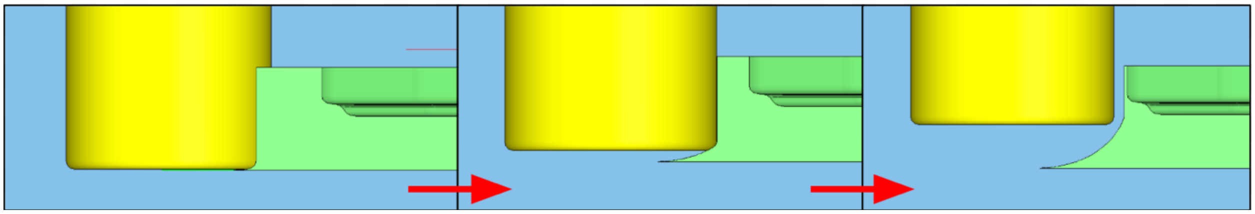


***Figure 2.6* - Snapshot progression of CAM simulation machining of the concave edges**

The machining was followed by grinding the edge of the blade by hand using whetstones ranging from 240 to 10,000 grit. The last remaining steps were to secure the handles to the knives and attach the shark scales to a purchased knife featuring a flat grind.

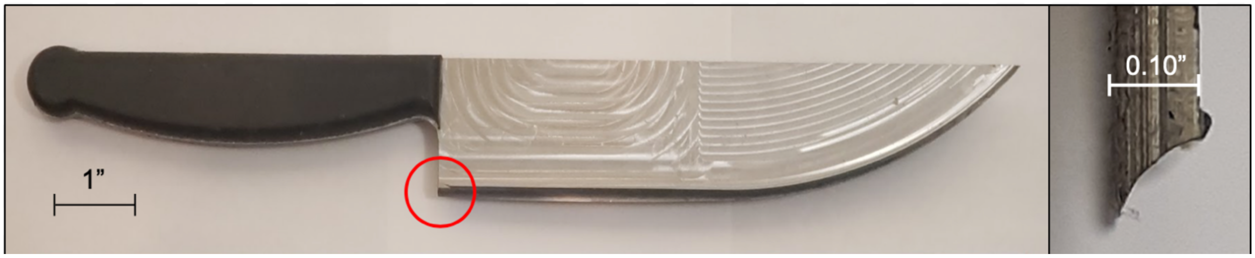


***Figure 2.7* - Machined curved chip-breaker blade; Left: front view, and Right: top view of edge feature**

Figure 2.8 **- Machined flat chip-breaker blade; Left: front view, and Right: top view of edge feature**

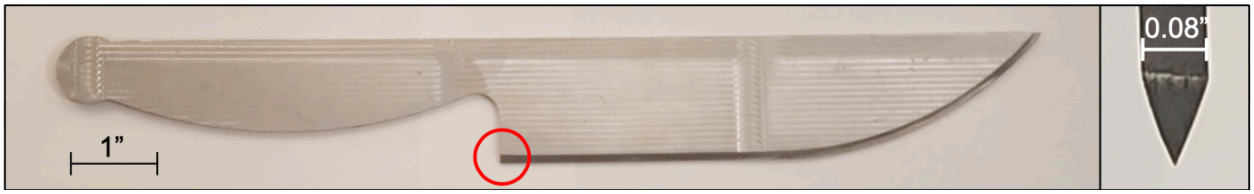


Figure 2.9 **- Machined convex blade; Left: front view, and Right: top view of edge feature**

Figure 2.10 **- Purchased knife featuring a flat grind**

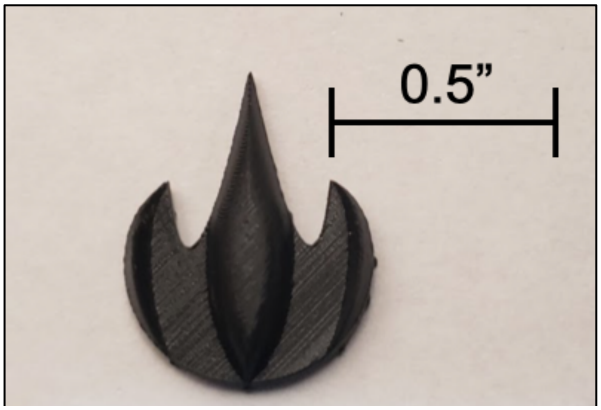


Figure 2.11 **- 3D-printed shark scale**

2.5. Testing

We developed our testing procedures according to the customer needs established in the decomposition. Visual cues were the primary source of measuring the success of our knives. Several preliminary tests were performed to decide on the best testing procedure for examining the performance of each knife. During preliminary testing, we compared slicing through several different types of foods and different slice thicknesses. We found that slicing food about ⅛ inch thick gave us the clearest and most consistent results for determining the magnitude of stickage.

List of the knives tested:

1. Standard kitchen knife with a flat grind (control knife)
2. Convex knife grind
3. Curved chip-breaker knife
4. Flat chip-breaker knife
5. Control knife with shark scales glued to it

The final testing procedure is listed below. Each test had multiple trials performed by each team member for controlled, varying forces and slicing techniques.

1. Sharpen knife with Whetstone.
2. Make sure knife is completely dry before moving on to the next step.
3. Place grid on cutting board.
4. Using the grid, slice food ⅛ inch thick.
5. Leave knife stationary and wait 5 seconds before next step.
6. Record whether or not the food slice visibly stuck to the side of the blade during the 5 second interval.
7. Record any other applicable notes or observations.
8. Repeat Steps 1-7 five times for each knife.

3. Results & Discussion

3.1. Control Knife

The control knife rarely sliced without having the food stick to the blade. All cuts were clean slices and did not have damaging effects to the sliced foods. These results were expected for a standard, flat grind kitchen knife because there were no special features that would reduce the sticking. Table 3.1 shows the testing data for this knife.

***Table 3.1* - Results from control knife testing**

Control Knife				
Slices that stuck (out of 5 slices)				
Operator	**Bananas**	**Onions**	**Cucumbers**	**Tomatoes**
1	4	2	2	3
2	5	2	2	3
3	5	2	2	3
4	5	2	2	3
avg %	95%	40%	40%	60%

3.2. Convex Knife

The convex knife performed better than the control knife, but still had experienced food sticking to the blade. Similar to the control knife, all of the cuts were clean and did not have damaging effects on the sliced foods. These results show that solely reducing flat surface areas can limit sticking. Table 3.2 shows the testing data for this knife.

***Table 3.2* - Results from convex knife testing**

Convex Knife				
Slices that stuck (out of 5 slices)				
Operator	**Bananas**	**Onions**	**Cucumbers**	**Tomatoes**
1	2	1	0	1
2	0	0	0	1
3	1	2	2	1
4	0	1	2	1
avg %	15%	20%	20%	20%

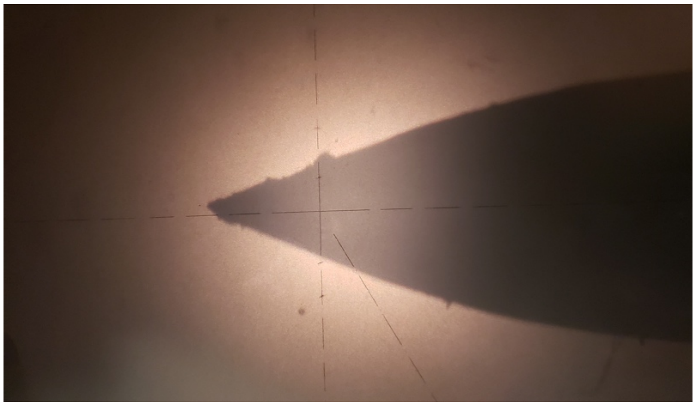


***Figure 3.1* - Optical comparator image of convex knife**

3.3. Shark Scale Knife

The shark scale knife performed significantly better than the control knife, as seen in Table 3.3 below.

***Table 3.3* - Results from shark scale knife testing**

Shark Scale Knife				
Slices that stuck (out of 5 slices)				
Operator	**Bananas**	**Onions**	**Cucumbers**	**Tomatoes**
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
avg %	0%	0%	0%	0%

These results show how the shark scales were beneficial in preventing stickage. However, since the shark scales had significant thickness, we cannot confidently determine whether it was the scale thickness pushing the food away from the blade or the scale topography preventing stickage.

Two downsides to this design were the scales causing some deformities to the sliced foods and the knife being difficult to clean. Its difficulty in cleanability was due to its geometry featuring small, sharp valleys that were consequently unable to satisfy DP3 for cleanability.

3.4. Flat Chip-Breaker

The flat chip-breaker performed considerably better than the control knife by successfully preventing food from sticking to the side of the blade. While testing, we noticed food accumulating in the concave edge of the knife, underneath the chip-breaker feature. The abrupt change in geometry also caused small deformations in the sliced food. These deformations were not nearly as noticeable as those caused by the shark scales in Section 3.3. These results (Table 3.4) proved that design features pushing food away from the side of the blade is a viable option for the prevention of sticking.

***Table 3.4* - Results from flat chip-breaker knife testing**

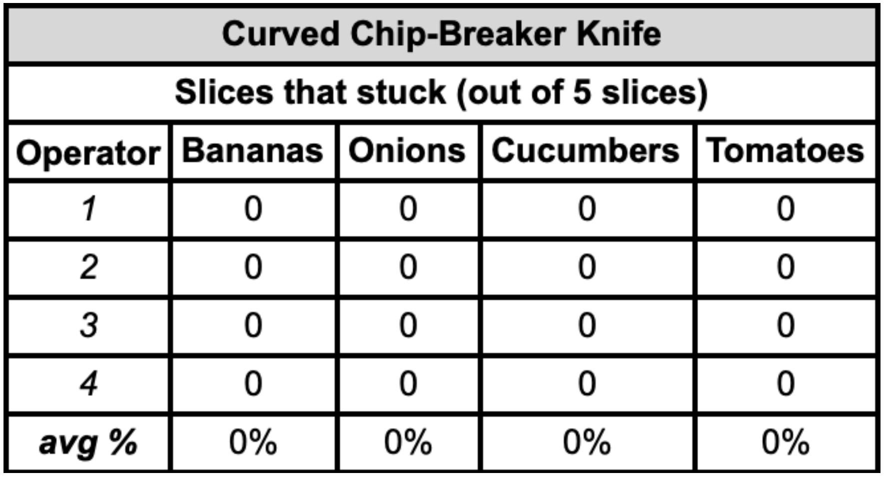
Flat Chip-Breaker Knife				
Slices that stuck (out of 5 slices)				
Operator	**Bananas**	**Onions**	**Cucumbers**	**Tomatoes**
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
avg %	0%	0%	0%	0%

***Figure 3.2* - Optical comparator image of (slightly damaged) flat chip-breaker knife**

3.5. Curved Chip-Breaker

The curved chip-breaker also performed significantly better than the control knife. As seen in Table 3.5, none of the tested foods stuck to the blade. Compared to the shark scales and flat chip-breaker, the smooth, curved geometry of this knife better prevented deformation of the sliced foods. Due to its similar edge design to the flat chip-breaker, the curved chip-breaker also had food accumulate in the concave edge of the knife. This design successfully showed the viability of the chip-breaker feature in preventing stickage.

***Table 3.5* - Results from curved chip-breaker knife testing**



Curved Chip-Breaker Knife				
Slices that stuck (out of 5 slices)				
Operator	**Bananas**	**Onions**	**Cucumbers**	**Tomatoes**
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
avg %	0%	0%	0%	0%

***Figure 3.3* - Optical comparator image of curved chip-breaker knife**

3.6. Summary

Overall, we found that, while the convex knife performed better than the control knife, the curved chip-breaker, flat chip-breaker, and shark scale knives vastly outperformed the control knife. While the flat chip-breaker and shark scale knives had damaging effects on the sliced food, we ranked them above the convex knife due to their lack of stickage. This led us to choose the curved chip-breaker knife as the best performing design with no stickage and no damaging effects on the sliced food.

Table 3.6 **- Summary of testing results**

Slices that stuck (out of 20 slices)					
Food	**Control**	**Convex**	**Curved C-B**	**Flat C-B**	**Sharks**
Bananas	19	3	0	0	0
Onions	8	4	0	0	0
Tomatoes	12	4	0	0	0
Cucumbers	8	4	0	0	0
avg %	59%	19%	0%	0%	0%

4. General Discussion

4.1. Axiomatic Design

Axiomatic design provided a foundation of methods and theories in which we were able to build our testing procedures, FRs, and DPs upon. Our FRs and DPs have seen many variations and adjustments throughout the project. When first starting our decomposition, we intended to have an FR focusing on sharpenability. However, since our knives would not be made for public use, we focused more on the knives' geometry and surface topography. Additionally, the final decomposition included an FR that focused on cleanability. While we were not able to reliably test for the presence of bacteria after cleaning, we did not get rid of this FR because it had more of an effect on the surface topography design process than sharpenability.

4.2. Testing Methods

The testing methods were largely based around slicing different foods and visually determining whether or not they stuck to the side of the blade. Originally, we had planned on applying moisture tape before and after each test to detect changes in moisture, using the tape beforehand to ensure the knife was completely dry. During our testing of the procedure, we found that the moisture tape was too difficult to remove from the knife side without getting the blade wet again, therefore negating the purpose of testing for dryness before slicing. Additionally, we found that the moisture tape was ineffective in detecting the moisture present in foods; there was no color change when applied after slicing.

4.3. Testing Results

The results of our testing showed how each knife performed when cutting several different foods. The control knife did not prevent food from sticking to the blade as expected. The convex knife performed slightly better than the control knife but still had some slices stick. We found that the chip-breaker feature was effective at preventing stickage, however, the knives featuring chip-breakers were unable slice through hard or thick foods. Although the shark scales were successful in prevent stickage, we were unable to determine if this was due to the overall shape of the scales or the thickness of the scales deflecting the food away from the blade.

4.4. Sharpenability

We found that the knives, being hand-sharpened, were not sharp enough to cut through foods that were too thick or hard. The concave blades could only be ground on one side, due to the chip-breaker, and applying too much force to the other side resulted in bending their thin tips. For the convex knife, the biggest issue was consistency. Due to our inexperience with whetstones, the forces we applied and the angles we applied were not constant. Only grinding one side and grinding inconsistencies prevented us from getting the finely tuned, sharp tip needed for slicing harder foods.

5. Conclusions & Recommendations

5.1. Conclusions

5.1.1. Axiomatic Design

The axiomatic design approach helped define the problem and led to designs that offered effective and efficient solutions. Our designs addressed the main problem of preventing food from sticking to the blades, however, they did not address problems related to cleanability or sharpenability.

5.1.2. Testing Methods

Testing methods were developed to examine whether or not the design successfully solved the issue of stickage by slicing several different foods that have tendencies to stick to commonly used kitchen knives. These testing methods proved effective for determining the effectiveness of each knife blade.

5.1.3. Testing Results

Our testing process showed that features can be added to kitchen knife blades in order to push food away and therefore prevent stickage. The curved chip-breaker design performed the best to prevent stickage while not causing damage to the sliced foods. Aside from the standard kitchen knife with a flat grind, the convex grind performed the worst in terms of stickage. While the shark scales prevented stickage, they caused damage to the sliced food and their small, sharp valleys made it harder to clean.

5.1.4. Sharpenability

A problem we encountered in the testing process was sharpening the knives by hand with the whetstones. Sharpening the knives by hand made it more difficult to make each knife edge sharp enough to slice through thick or hard foods.

5.2. Recommendations

Two problems should be addressed when building upon this project’s research: the first being the limited ability of manual hand sharpening and the second being damaging effects caused by the knife features. In order to address the sharpening issue, there are two adjustments that could be made in the design process as well as one in the manufacturing process. One possible design adjustment would be to make the knife with a flat grind on the non-cutting side of the edge along with a concave grind on the cutting side. The other design change would be to extend the tip farther away from the side of the blade which would reduce the edge angle, thus allowing space for sharpening on the cutting side of the edge. Issues related to sharpening by hand could be reduced by using a belt grind to sharpen the blade during the manufacturing process. As for the shark scales causing damage to sliced food, decreasing the size of the scales could be implemented to prevent the scale thickness from inflicting damage.

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Appendix A

The following search terms were used in our research process that ultimately did not lead to relevant information regarding blade's topography and its performance regarding adhesion:

- "blade topography and adhesion"
- "food sticking to knife blade"
- "ASTM knife test"
- "the role of surface features in adhesion"
- "knives and capillary adhesion"
- "surface features to prevent adhesion"
- "capillary adhesion on blades"

Appendix B

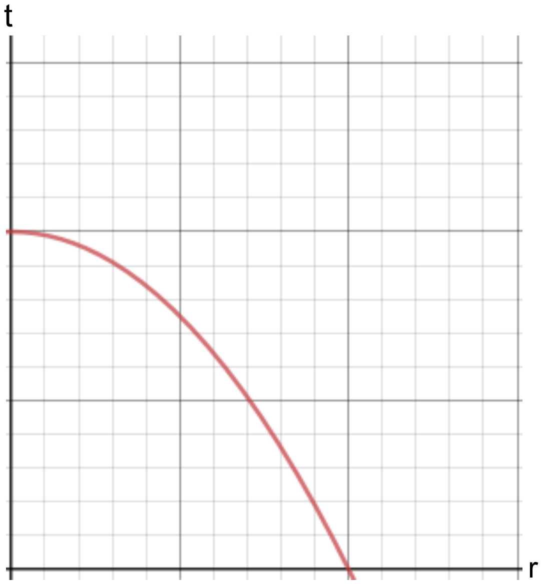
FR1, DP1.1, & DP1.2

FR1 = DP 1.1 + DP 1.2

DP1.1 = $t = -(r-2)^2 + 100$
DP 1.2 = $\lambda = \angle$

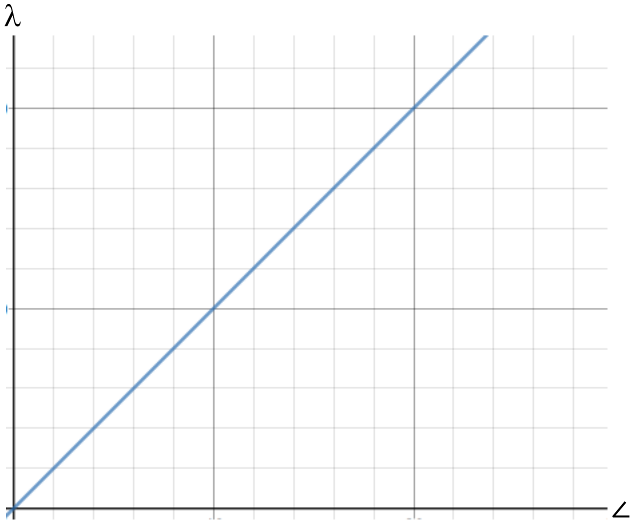
FR1= $-(r-2)^2 + \angle + 100$

DP 1.1 Graph



t = Shearing of Material (N/mm^2)
r = Radius of Curvature (mm)

DP 1.2 Graph

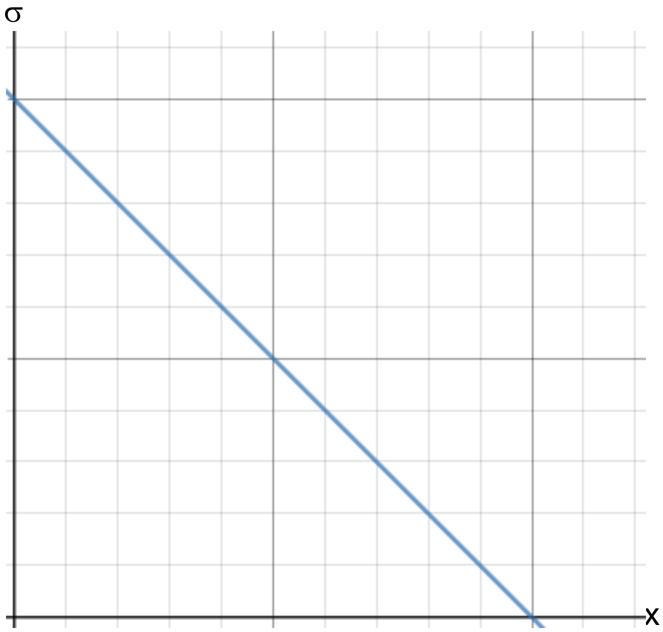


$\angle$ = Edge Angle (degrees)
λ = Ability to Separate Material

FR2 & DP2

DP 2 = $\sigma = -x + 100$ = FR2

DP 2 Graph

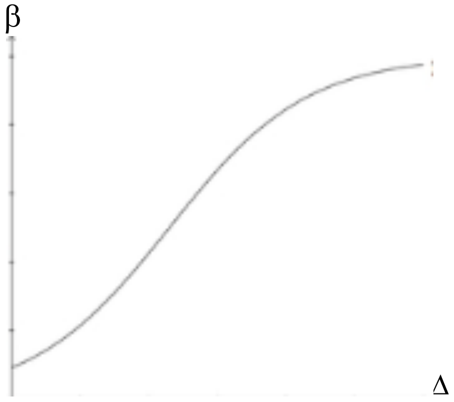


σ = Adhesion (%)
x = Surface Area Not in Contact with Food (cm^2)

FR3 & DP3

DP 3 = $\beta = 100 / [1 + 99(0.63)^{\Delta}]$ = FR 3

DP 3 Graph



Δ = Volume of Non-Flat Surface Topography (mm^3)
β = Percent of Removable Bacteria