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# Design and Prototyping of a Variable Geometry Extrusion Die to Exhibit Significant Alteration of Shape

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# **Design and Prototyping of a Variable Geometry Extrusion Die to Exhibit Significant Alteration of Shape**



Honors Thesis

David C. Bell

Department: Mechanical Engineering

Advisors: David H. Myszka, Ph.D. and Andrew P. Murray, Ph.D.

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## Abstract

Extruded parts are conventionally made by forcing melted plastic through a steel die having a fixed opening that matches the shape of the part. Plastic parts made by extrusion include weather stripping, PVC pipe, and composite lumber. Variable geometry dies can change their opening shape during the extrusion process. Developing shape-changing dies technology offers the possibility of making parts with varying cross-sections that currently need to be made through injection molding. This is desirable as, compared to molding, extrusion tends to be faster and less expensive. Variable geometry extrusion dies have been designed and prototyped by the University of Dayton research team that confirms the validity of the concept. This research explores the limits of this new technology by creating a die that has substantial movement of components that form the die opening.

## Acknowledgements

I would like to thank Creative Extruded Products for their assistance in this research for producing and testing all of the dies that have come from the DIMLab.



# Table of Contents

Abstract	Title Page
Background	1
Prior Research	1
Design Process and Segment Creation	4
Assembly and Segment Adjustment	9
Specific Design Requirements	11
The Design	12
Conclusion	16
Bibliography	18

## 1) Background

Over the past 40 years, polymer processing has increased at a rate of 5.6% annually [1]. This growth is more than ten times the growth of steel and more than doubles the growth of aluminum over the same period of time. Extrusion accounts for 40% of all polymer production. Extrusion is such a common method of production because of its low cost and high production rates relative to other methods [2-5]. Because of its production benefits, it continues to grow as one of the most commonly used manufacturing processes.

Extrusion is a relatively simple process in which a polymer is melted and forced to flow through a die which shapes the polymer into the shape of the die [6-8]. After the polymer exits the die it is cooled back to solid form and is cut to the appropriate size [9]. The product has a constant cross section of the shape of the die [10-13]. Although a constant cross section is valuable for many production purposes, a variable cross section would allow for a wider variety of products to take advantage of the cost savings associated with extrusion. Variable geometry dies are currently not being used significantly in manufacturing but research has begun [14, 15]. This research continues the work that has been done through the Design of Innovative Machines Laboratory (DIMLab), within the Department of Mechanical and Aerospace Engineering to determine if the variable geometry extrusion die model works and determine its limitations.

## 2) Prior Research

The difficulties with a variable geometry die are associated with its moving parts. A variable geometry die needs to be designed to minimize or control leakage [16]. Leakage is the polymer that gets in between the moving parts of the die. Leakage that does occur

needs to be removed or addressed so it does not destroy the system [17]. A variable geometry die should have a die exit plane. A die exit plane limits the shape of the extruded product beyond the limitations of the die [8]. Similarly, the die will need to be covered with a face plate to prevent polymer from getting behind the rigid bodies making up the edges of the die. Effectively, the face plate limits the application of polymer onto the die, the die then shapes the polymer, lastly the polymer exits through the exit plane. The face plate's interference with the cross sections of the die should be minimal because it will prevent the polymer from matching the shape of the die and will provide a poor surface finish. Although not a necessary characteristic, having a constant cross sectional area helps to make the design of a variable geometry die easier as the volumetric flow rate does not need to be adjusted to keep the velocity constant. All prior dies have had this characteristic. The final characteristic that needs to be taken into consideration is the actuation of the device. Because it is a moving device, by definition it requires at least one degree of freedom. A single degree of freedom solution would be preferred but is not a necessary component of design [18]. In a previous die, multiple degrees of freedom were used. This created a much larger design space and die land region, making it difficult to protect all of the gaps. In order to create more complex geometries, multiple degrees of freedom will be necessary, but will likely require limitations on the allowable paths. Similarly, these moving parts cannot approach a kinematic singularity, as this would cause the extrusion to fail. Smooth transitions between geometries are necessary.

Based on the design characteristics described, certain joints were determined to be better in the design of a variable extrusion die. The two primary joints are crescent joints and prismatic joints [18]. These two types of joints distinguish themselves because of

surface on surface contact. Surface on surface contact is ideal for limiting leakage. A crescent joint (shown in Figure 1) uses a tongue piece that fits into a groove on the other segment.

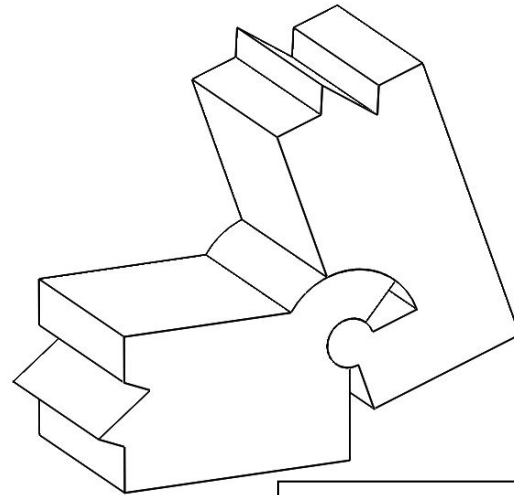


Figure 1: Crescent Joint

Because of the design of a crescent joint, they only work within a range of angles before two planes contact. Using the contact these planes make can help the design stay in the desired arrangement. Crescent joints are also inferior to corner joints because of the required curved area surrounding the joint; they cannot create a sharp

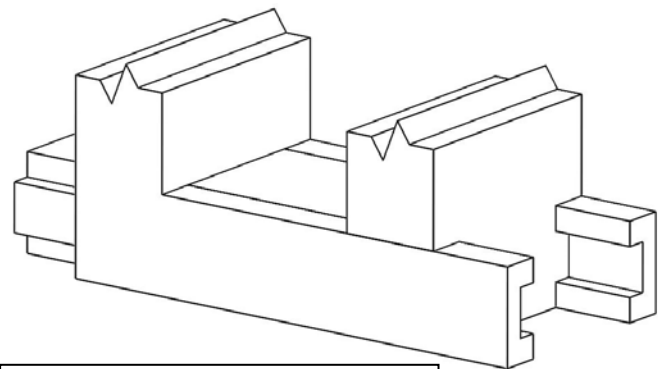


Figure 2: Prismatic/Sliding Joint

angle. Prismatic joints also use surface on surface contact. Sliding joints (Shown in figure 2) will serve as a necessary component in variable geometry dies as they are necessary for any component to have a variable side length; without them possibilities are very limited. A third type of joint that appears to be possible in variable geometry dies (although not used in this research) is corner joints (shown in figure 3).

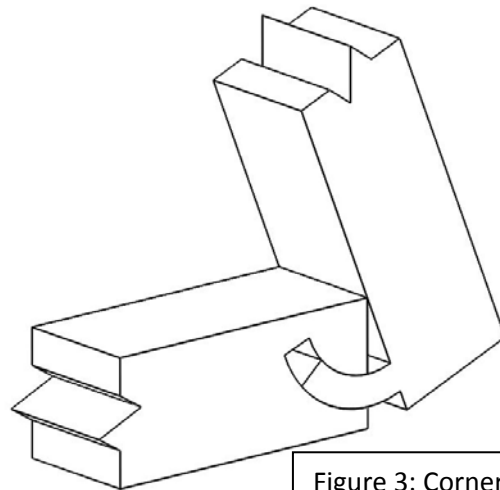


Figure 3: Corner Joint

Corner joints have the advantage of offering a sharp corner to the geometry. Corner joints contain a center of rotation at the corner of the shape. Corner joints rely on edge on edge contact and therefore have more inherent potential for leakage [18]. Corner joints have been used in simple shape changing die prototypes but only under the condition one of the components was grounded. Due to the unknown nature of the efficacy of moving corner joints, they were not used in this research.

The face plate prevents polymer flow from reaching gaps between segments. The face plate at times may need to cover the cross section of the die from which polymer is supposed to flow in order to prevent leakage of the polymer in a different orientation of the die. This should be avoided as much as possible. The interference from the die plate creates very poor surface quality as evidenced by the samples taken from both the crescent-corner-prismatic die and the scraper die. The shape also will not closely follow either the face plate or the die cross section, creating unpredictable results. The face plate still must protect the gaps from leakage. Leaving at least 0.04” space between the face plate perimeter and any gaps was the standard followed in this research.

### **3) Design Process and Segment Creation**

Designing unique variable geometry dies is a new concept. Throughout the design process in this research, the process changed as issues were discovered and solved. The process described will explain the recommended way to create a variable die using only crescent joints and sliding joints. When designing a die, limit the total cross sectional area of the die to a few square inches. The polymer extruder the DIMLab uses, typically, works with smaller parts and does not have the capacity to get much larger.



The first step in making a new design is to design the kinematic system of revolute joints and prismatic joints only (methods for other joint types have not been established). In this research the kinematic design was created in the sketch feature of Solidworks. The kinematic design will not only determine the shape of the final profiles, but will also require important characteristics regarding the plausibility of the design. This kinematic structure will be able to display singularities, die area variability, potential joint interference, and degrees of freedom. These characteristics need to be considered in this step to create a satisfactory design based off specific design criteria. From the kinematic structure, the desired activation limits can be determined. The activation limits will show the range of motion and the initial, final and intermediate cross sectional shapes. The kinematic structure should consist of a set of segments connected consecutively that will never run into each other. The region between these connected pieces will be the die opening. The angles between the segments should be kept fairly large to avoid approaching a geometric singularity which would make it difficult for polymer flow. The limits for how small these angles can get has not been determined.

One possible way to develop the kinematic design is to start with a simple kinematic design (of maybe 3 segments) and repeatedly break segments into more pieces while adding linkages to control the added segments. This allows the design to slowly gain more complexity and to be able to add basic features one at a time. This process will probably struggle creating precise cross sections for functional purposes, but is effective for prototypes.

Once the kinematic design is set, the individual pieces should be created. The following paragraphs will describe how to create a similar design in Solidworks. The first

step for any piece is to create the construction lines to match the dimensions from the kinematic sketch. Once the construction lines are in place, the physical shapes can be determined. Any piece making up part of the perimeter of the die region will require either a crescent or prismatic joint at both ends. To make a crescent joint, start by making two construction circles centered at the corner of the segment that requires a revolute joint. The two circles will be the size of the inner and outer diameters of the crescent joint. In this research, an inner diameter of 0.20" and an outer diameter of 0.60" were used for all crescent joints. Make sure the male and female parts of the crescent joint have the same dimensions. Add these construction circles to all of the crescent joints on a part. Also add circles to any point that will be attached to a segment not making up the perimeter. After this begin adding the complexities to the crescent joint. If the segment in question is a male piece, add three lines connecting the two circles, drawn radially from the center. The first segment will mark the end of the male segment or tongue. The second will mark the beginning of the tongue and should be a construction line. The third will mark the direction of the rest of the piece. The third line is only necessary if a geometric constraint is desired apart from the tongue and groove contact. Each of these line segments should be dimensioned as angles relative to the construction lines. The dimensions of these angles are unknown at this time and will require adjustment later; this is why it is imperative to dimension these relative to the construction lines, so they easily can be changed without distorting the rest of the part. Once these construction line segments are added, two arcs can be made. The first arc will follow the larger construction circle, starting at the first line segment and ending at the second line segment. The second arc will follow the smaller construction circle, starting at the first

line segment and ending at the third line segment.

This setup shown in figure 4 provides the contour of the male crescent joint. The rest of the part can be designed starting at the end of the outer arc and the end of the third radial line segment.

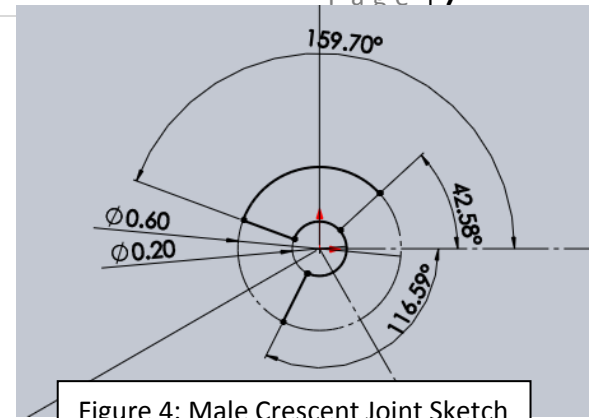


Figure 4: Male Crescent Joint Sketch

If the corner of the segment is female a similar process is used. There should already be two construction circles in place. Connect these construction circles with three line segments. The first will mark the beginning of the female part or groove and should be a construction line. The second will mark the end of the groove. The third line will mark the direction the part will face, again only necessary if a hard stop or geometric constraint is desired apart from the tongue and groove interaction.

Two arcs should be made. The first arc follows the larger construction circle and connects the first line segment to the second. The second arc follows the smaller construction circle and connects the second

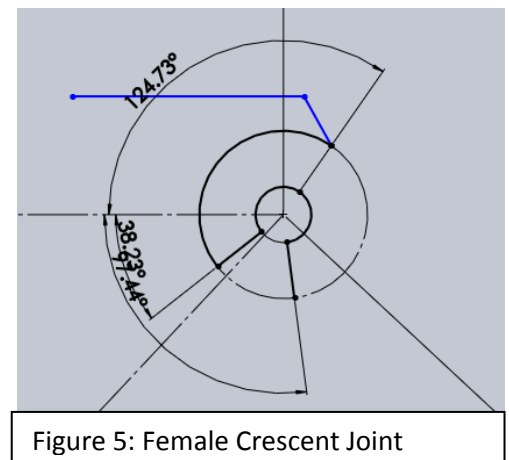


Figure 5: Female Crescent Joint

line segment to the third line segment going through the first line segment on the way.

Each of the line segments should be dimensioned relative to the initial construction geometry to allow the dimensions to be easily adjustable. This setup for the female crescent joint is shown in figure 5. The rest of the part can be designed starting at the end of the outer arc and the end of the third radial line segment.

With the structure of the crescent joints, the two structures can be attached. This contour can be adjusted to create the features of the perimeter of the die. When

dimensioning these lines, keep in mind, the dimensions of the crescent joint angles will need to be adjusted later. Any geometry referencing these features will change as the angles are adjusted. The part of the segment not making up the perimeter of the die also needs to be connected. If there is another joint interacting with this part, include the circle marking this joint drawn earlier in the area connecting the two crescent joints. The shape of this side at this point only needs to consider maintaining enough thickness to not break when force is applied and making the shape look reasonable.

If a segment includes a sliding joint, at this point, the line of action will need to be set back in the kinematic diagram so the sliding joint does not interfere with the crescent joints. Once this kinematic issue is resolved, draw a construction line along the line of slide. This line can be straight or curved. In this design a straight line of slide was used. On the female half of the joint, this line does not need to be a construction line. Start by making this line significantly larger than it needs to be, about three times a typical side length. This will be shortened later. At the end of this line draw a perpendicular line away from what will be the perimeter of the die. This line needs to be long enough to contain the size of the groove desired. Once this line is complete, it can be connected to the crescent joint used on the other end.

If the sliding joint is to be the male part or tongue, the construction line will become a solid line connecting both sides of the crescent joint together. Most of this feature will be added in a later extrusion. Make sure there is a face that is perpendicular to the line of slide to create this feature.

At this point, the shape of every segment is complete. Extrude the 2D sketch out a fixed distance. If the piece includes part of a sliding joint, add the features now. The male

and female parts of a sliding joint require the same sketch for them to interact. If the piece is the female part of a sliding joint, draw the sketch into the face perpendicular to the line of slide. Make an extruded cut of this shape through the whole part. Make sure this sketch does not interfere with any other features. If the piece is the male part of a sliding joint, draw the sketch on a plane perpendicular to the line of slide off of the part. This sketch will be extruded creating a new feature with added material. This extrusion should be about three times a typical side length, it will be shortened later.

Use the process described above to create all of the segments. Once all of these pieces are created, make a plate that will act as the back piece. This back piece should be large enough to fit the entire assembly. On this piece create circular features at all of the fixed references in the kinematic design. Extrude this piece out (about 0.1”) to create a large plate. This will be the fixed piece in the assembly. If it has not already been done, create any segments attaching pieces not involving the perimeter of the die. At this point, they can all be straight lines or solid shapes with circular features centered at the joints.

#### **4) Assembly and Segment Adjustment**

At this point, the assembly should be able to be constructed. The first piece added should be the back piece or face plate. Fix this piece in place. Then start adding other pieces. The primary mating tools should be concentric circles and concentric planes. These mates emphasize the surface on surface contact requirement. Do not add limits on the range of motion into these constraints. Once all of the pieces are attached, the basic assembly should be complete. Confirm the current assembly is the desired arrangement for these pieces. A kinematic diagram when assembled can have many configurations; make sure the configuration in place is able to smoothly transition to the desired configurations. Once this is confirmed, go back and fix the angular dimensions of the

crescent joints to make the tongues and grooves appropriate lengths to avoid interference. For most joints, the minimum and maximum will occur at the two extremes. Make the groove and tongue pieces contact at one of the extremes. The faces created by the third line segments in the crescent joint section above can also often be made to interact at either the minimum or maximum. Once the crescent joints are appropriate sizes, shorten the male and female parts of the sliding joints to reasonable length. In this research, no geometric constraints were included in the sliding joint. At this point analysis is required. There are many scenarios where geometric interference could have occurred. Through reshaping the parts, remove these flaws. Each flaw will require a different solution.

In this research, the idea of covering crescent joints with a washer to prevent leakage was considered. Washers can be added by recessing the outer circle of both parts of a crescent joint. A washer of the same size should be made to fit into this space. The washer will be able to rotate freely, but this is not a problem. Adding washers allows the face plate to be much more open.

If washers are applied to all of the crescent joints, the face plate can allow through polymer almost anywhere the die region desires. Using the sketch tool (in Solidworks) and the convert entities tool sketch the perimeter of the die region. This sketch will change if the assembly is moved and then “rebuilt.” Copy a number of these sketches onto the back piece, making sure to fix one of the ground pieces to its respective fixed pivot. Add a number of these sketches on top of each other. The outer most region will be the opening in the face plate and should be cut out. This region depending on the design could allow for gaps in the die. These gaps need to be covered. Enlarging the face plate or back piece is a last resort. Often making certain features of the segments larger can

accomplish this, but the solution is not fully formed yet. Using a technique of copying traced sketches onto the face plate has been an effective process for accomplishing this.

Once the gaps are covered, the segments not forming the perimeter need to be redesigned to be able to interact with the other segments geometrically. The face plate should be sized appropriately, trying to minimize the overall size of the die. The face plate then should be built up vertically to act as a container for the die. Other finishing touches should be made as necessary to make the die functional.

### **5) Specific Design Requirements**

The primary purpose of this research was to discover the plausibility of creating a variable geometry die with significant shape change. The orientations were allowed to be designed not for any particular function, but rather just to show significant change. Previous dies created for polymer extrusion have all been simple in geometric change and kinematic complexity. This research looked into creating a die with at least six different segments making up the perimeter. In order to prove the concepts plausibility, some of the features were controlled by using techniques already discovered. For this reason, only crescent joints and sliding joints were used. Also, multiple degree of freedom systems have run into difficulties with the size of the region from which the die can flow. This research limits designs to single degree of freedom solutions. From previous dies it has been discovered that face plate interference creates poor finished quality. For this reason it was avoided. The die was limited to about 1 square inch of total area. This is a requirement for being used in the polymer extruder intended to be used. The die itself will use as many positive stops or geometric limits intended to increase the stability of the design. Finally, the design was to be one inch thick. The possibility of a longer die

including heating along the die was discussed, but ultimately thrown out because of the unnecessary added complexity. The die was designed to contain no sharp corners. All of the angles making up the perimeter of the die were designed to have smooth transitions. This was a request to allow the results from this die to be used in other research.

## 6) The Design

The design developed in this research shown in figure 6 is the current design of what will be a prototype for variable geometry extrusion. The extreme orientations are shown in figures 7 and 8.

From these views, it can be seen that the profiles do not serve a functional purpose. The profiles were intended to vary greatly and the actual shape of these profiles was unimportant. The design will transition between these two profiles while going through intermediate profiles along the way. The final extruded polymer part will

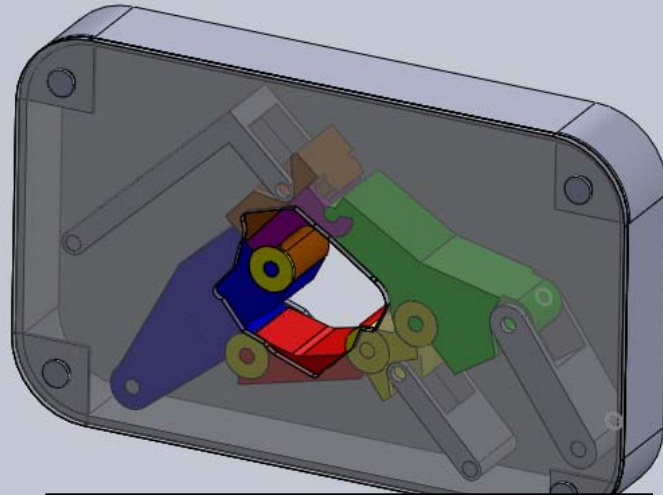


Figure 6: Variable Geometry Die Assembly

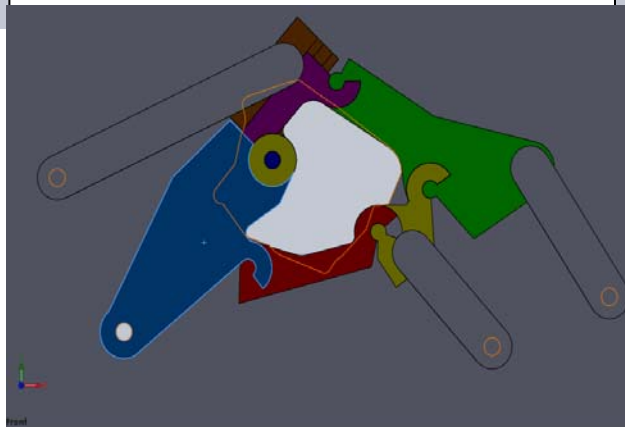


Figure 7: Variable Geometry Die Extreme Profile 1

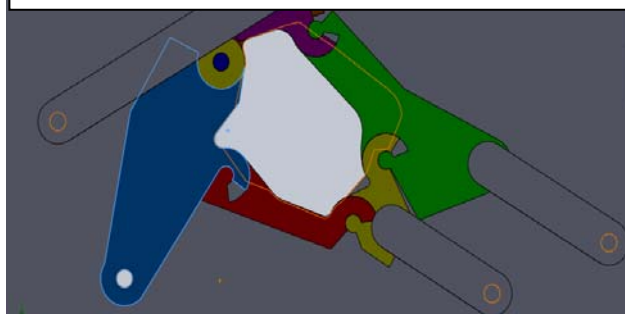


Figure 8: Variable Geometry Die Extreme Profile 2



look similar to the part shown in figure 8.

The design created is a one degree of freedom system driven by the blue segment shown in figure 6, 7 and 8. The design has six segments

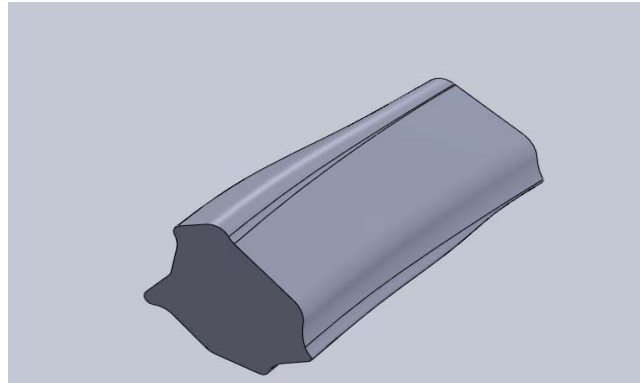


Figure 9: Variable Geometry Die Contour Model

making up its perimeter. The design includes five crescent joints and one straight line sliding joint. The design is 1 inch thick. All of the Crescent joints are the same size. All of the crescent joints are covered with washers. Using washers should eliminate the concern of the gap created between the tongue and groove of the crescent joints. To add washers and keep the necessary constant flat surface for the polymer to contact, the tongue and groove of crescent joints need to be recessed. In this design, the crescent joints were recessed 0.05 inches and a washer of the same size fills the hole. One problem with the current design comes from this added feature. The purple segment requires this cutout for the washer to prevent a geometric constraint, but because it is part of a sliding joint this cutout will not always be

fully covered by the washer. This flaw is shown in figure 10. Figure 10 is a close up of the die shown in figure 6. This creates a gap through which polymer can flow. This gap will need to be addressed before this die will be

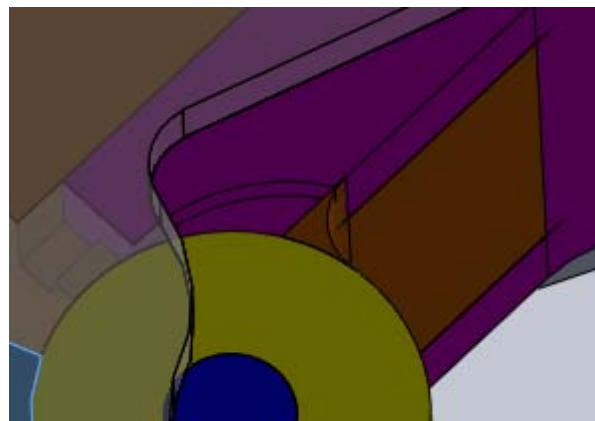


Figure 10: Washer Indent Leakage Flaw

usable. One possible solution would be to once again move the sliding joint to a parallel line of slide farther away from the revolute joint.

The washers allow for the face plate to be larger because the face plate does not need to cover the gaps the crescent joints create. The face plate in this design is the perimeter of all of the area the polymer would flow. This face plate is ignoring the gaps created behind the segments.

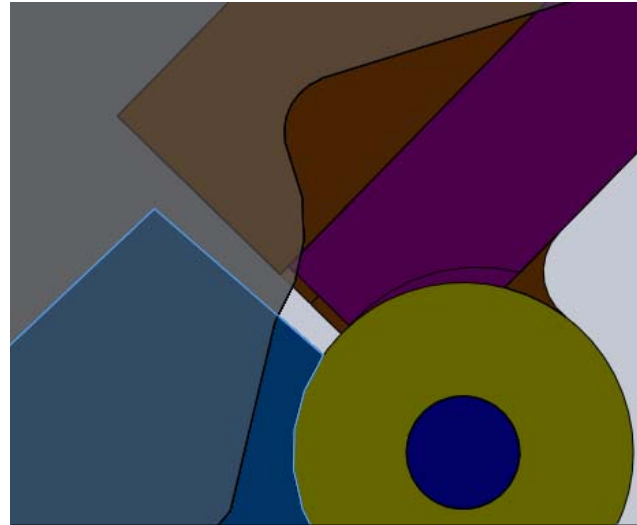


Figure 11: Leakage gap Behind Crescent Joint

This current design will allow for leakage between the blue and brown segments. This gap is shown in figure 11. This gap occurs because of how much the position of the nearby crescent joint physically moves. One potential solution to this problem would be to make the crescent joint at this point larger, allowing for a larger washer that would cover this point. A larger crescent joint would impose more of its geometry on the die exit shape which could be undesirable in certain situations. The allowable movement of the location of revolute joints appears to be related to the size of the crescent joint used.

The face plate blocks polymer flow slightly near the yellow segment. Some of this material is unnecessary with the addition of the washers protecting the areas this material was intended to block. The yellow piece moves significantly and some of the face plate may be needed to cover the gaps in some of the intermediate orientations. This unnecessary material is shown in Figure 12.



Figure 12: Unnecessary Face Plate Material

The yellow segment is the smallest piece included in the die perimeter. The size of the portion of this segment included in the perimeter is about 0.81 inches. Connecting the two crescent joints in this segment was difficult because of the limited amount of space

to work. The minimum size of a segment appears to be limited based off the size of the crescent joints used. Both of the crescent joints have an outer radius of 0.3 inches. Because these circles cannot overlap and will need to be attached, the smallest segment involved in the perimeter of the die needs to be larger than the sum of the radii of the two crescent joints it uses. It is recommended the segment is a substantial amount larger than this limit.

The sliding joint was a requirement for this design. The sliding joint in this design moves within a relatively small range. This limited range may not display all of the information that it could. Only one previous die included a sliding joint. Difficulties resulting from sliding joints are currently unknown and this die is intended to display. This is not an easily fixable problem. In order to make this feature move a greater distance the entire design would need to be remade.

Within Solidworks, with the current design fully constrained, the die sometimes will move into a different orientation with the same input angle from the blue piece. This could represent a kinematic singularity. This possible singularity could be simply a glitch in the software that would not occur in the physical world. The number of positive stops in this design should make the kinematic singularity impossible to reach. If this kinematic

singularity is determined to be a significant concern, the kinematic design would need to be edited.

## 7) Conclusion

This research looked into the design of a prototype of a variable geometry extrusion die. The primary findings of this research involved the method and limitations of variable geometry dies. The largest design factor when creating a die appears to be the size of the crescent joints used. Assuming crescent joints are the only way revolute joints will be represented, the size of the crescent joints has a large impact on the amount of shape change and types of segments used. The use of washers to cover crescent joints seems to be a very good method of preventing leakage. The prototype once built will be able to confirm the feature as a plausible solution.

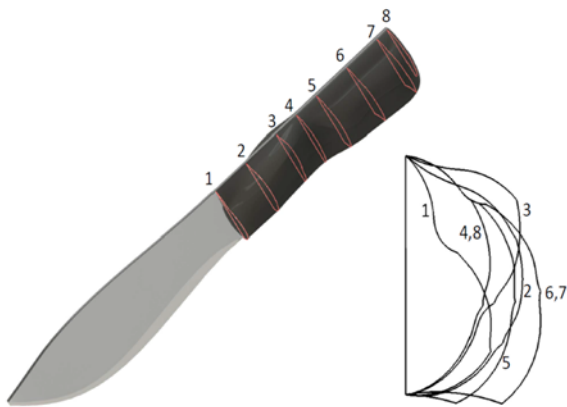


Figure 13: Knife Handle Extrusion Die Prototype

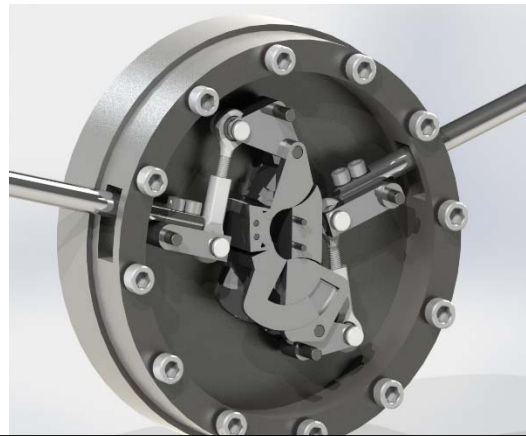


Figure 14: Knife Handle Extrusion Die Prototype

The prototype once built will help further define the possibilities and limitations of variable geometry extrusion. A variable geometry die designed for functionality will have features requiring a greater number of segments and joints more similar to this die than previous dies. Discovering the limitations of the design will help further clarify the types

of items that could eventually use variable geometry dies for manufacturing. The die shown in figure 14 is an example of a die with a valuable function. This die creates the profiles necessary to create the knife handle shown in figure 13. This shows the potential of shape changing dies.

The next steps for advancing this research require completing a die with the flaws that were mentioned addressed and then creating that die. This die has features previous dies have not included; these features need to be shown to be possible. Long term, when looking at potential future dies, the biggest concern appears to be being able to deal with all of the limitations surrounding crescent joints. Crescent joints if too small can allow for leakage behind them if the particular piece moves significantly, but limits the size of segments and the possible shapes of the profile. These profiles are forced to contain the circular portion created by crescent joints, adding a shape that might not be desirable. The smaller the crescent joints, the smaller this feature. To try to make the crescent joints smaller, exploring the possibility of adding a flexible material to cover the gap behind the crescent joint (like the one shown in figure 11) could allow for better finished profiles. The knife handle die shown in figure 14 has multiple degrees of freedom; most dies created for functional purposes will likely use multiple degrees of freedom. Solving the problems surrounding multiple degrees of freedom seems to be important research to discover for the future of the field.

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