An Analysis of Through-Hole Punching in PMMA With Varied Process Parameters

by

Stuart Graham Rossen

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Signature of Author ....
Department of Mechanical Engineering
May 9, 2008

Certified by ....
David Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Thesis Supervisor

Accepted by ....
John H. Lienhard V
Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

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Abstract

The ability to combine through-hole punching with a surface patterning during microembossing would greatly enhance the production of a variety of microfluidic devices. In support of that goal, a series of theoretical simulations and physical tests were performed to investigate the effect of clearance, shear speed and temperature in creating through-holes. A better understanding of the effects of these parameters in through-hole punching has useful implications in the development of better tools for hot-embossing.

Theoretical simulations modeling the punch and die mechanics for various punch sizes and clearances were performed using ADINA finite element analysis (FEA) software; similar simulations were done for a straight shearing situation for comparison. A special straight-line punch and die set with a movable was then machined for use with an existing hot-embossing machine. Tests were done while varying the temperature of the sample, the clearance of the shear and the shear speed.

From the finite element analysis, we gathered data about the shear stress distribution in the samples during the shearing process. The physical experiments gave us information about the peak stress for each test, allowing for some quantitative analysis. The parts were also assessed qualitatively under 10x magnification and classified accordingly. Ultimately, we were able to see some signs of shear quality degradation with increased clearance, but the differences were less pronounced at small clearances (25 microns or less).

Thesis Supervisor: David Hardt
Title: Ralph E. and Eloise F. Cross Professor of Mechanical Engineering

Acknowledgements

I would like to thank Professor Hardt for all his guidance along the way and the opportunities he has given me since I first joined his lab group as a UROP student in early 2007. I would also like to thank Aaron Mazzeo for all his help and guidance—his recommendations and assistance have been invaluable. Finally, thank you to Matthew Dirckx for his suggestions and development of material models critical for the finite element analysis done in my work.

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Chapter 1

Introduction and Background

The manufacturing process of hot embossing has been demonstrated as a useful process for the production of various products [1], especially microfluidic devices. Many of these devices require microfluidic channels to be embossed on both sides of the part. To connect these channels, clean and effective through-holes need to be produced. Producing through-holes is different from the typical process of hot embossing because instead of imprinting a pattern part way into a plastic wafer, material must be removed by shear and the tooling must go all the way through the part.[1] This creates more concerns about burrs and other imperfections as a result of the shearing process. While much has been done over the years in terms of research regarding the creation of through-holes in elastic-perfectly plastic, isotropic materials such as aluminum, not as much exists in the way of practical suggestions for such processes when done with polymers like PMMA. For basic elastic-perfectly plastic materials, the theory on shearing and punching is well

[1] It is also possible to make holes by pure plastic deformation with a microscale piercing operating, but initial tests by Mazzeo [3] proved very difficult.

established. For example, the approximate force needed to shear a piece of sheet metal can be calculated as

$$F = 0.7 \cdot T \cdot L \cdot (UTS) \tag{1}$$

where F is the force, T is the sheet thickness, L is the total length of material being sheared and *UTS* is the material's ultimate tensile strength [2]. In addition, many tables have been created for different materials to help machinists pick appropriate clearances (how much greater the radius of a die is than the radius of its corresponding punch) for sheet metal based on thickness, punch diameter and material properties. Unfortunately, because thermoplastics do not respond to shearing in the same way that materials like aluminum do, the theoretical and experimentally derived suggestions for metals cannot be used for thermoplastics.

The need for research into the effects of certain basic variables in the through-hole punching process (primarily, clearance) was also evident from previous research done on the subject by member's of MIT's Center for Polymer Microfabrication [3].[2] In a paper published in ICOMM in 2007, through-hole punching with various shapes and sizes of punches was tested with interesting results. While some holes appeared to be punched cleanly with minimal defects (left image of Figure 1-1), others appeared to have serious issues. The right-hand image of Figure 1-1 shows a hole with an extremely large burr, more of a "deep-drawn cup." This seems to indicate the potential dominance of tensile yielding of the material instead of pure shear.

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[2] See http.://web.mit.edu/cpmweb

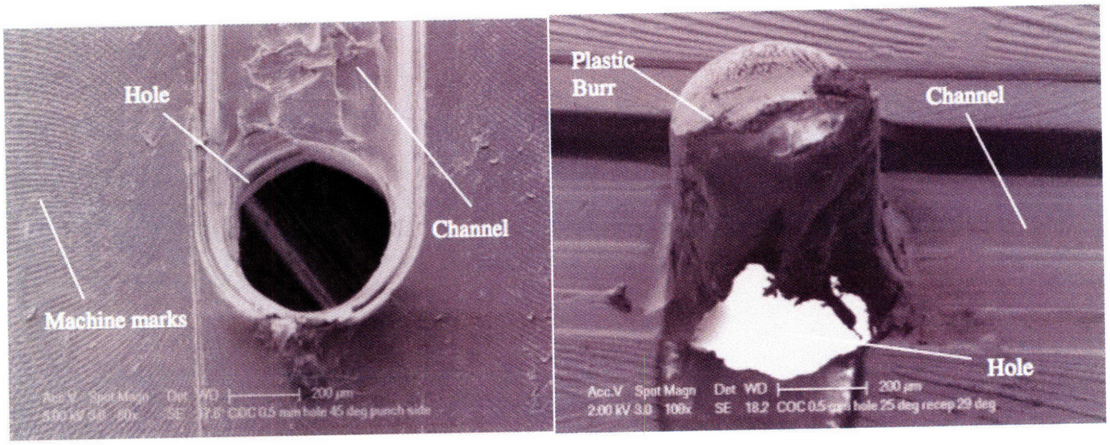


Figure 1-1: The left-hand image shows a cleanly punched through-hole from research done at MIT's Center for Polymer Microfabrication. The right-hand image shows another hole punched during research at the Center, but with indications of tensile failure instead of shear yielding.

The aforementioned research brought up many questions about what parameters were most critical to optimal through-hole creation, and about what critical values they might have. The research presented in this thesis attempts to go beyond recent studies of through-hole punching in PMMA and look at how some of the basic variables in the process affect the process and the quality of the end result.

Because the existing theoretical material on shearing and using punch and die sets to create through-holes in sheet metal is not appropriate for the situation we have at hand, we took a different in our attempt to qualitatively and quantitatively assess the different parameters in punching a thermoplastic. First, a computer model was developed to mimic the punch and die and shearing situations (with parameters such as thickness, punch diameter and clearance varied), with a thermoplastic material models being used for the simulations. To assess the validity of the results of these simulations, an experimental setup was developed for use with an existing hot embossing machine. A new punch and die set capable of adjusting the clearance to known values was built for these experiments. Because of its common use in microfluidic applications and its availability in our lab, PMMA was used in all simulations and experimental tests.

Chapter 2

Modeling of PMMA Shearing

Because simple standard mechanical models of shear are not appropriate for predicting quality punching parameters for materials like PMMA, the main portion of theoretical analysis was done using the finite element analysis (FEA) package ADINA. (This is in stark contrast to shearing and punching information of linear elastic materials, on which there is a significant database of information regarding best practice [4].) The goal of the ADINA modeling was to see how the shear stresses developed in situations with different shearing and punching parameters (such as temperature and clearance).

One critical reason for the use of ADINA to model the shearing of PMMA was because of our physical experimentation limits. What we ultimately want to understand is the situation seen in Figure 2-1 where a circular punch (and corresponding circular die cavity) is used to create a through-hole in the polymer.

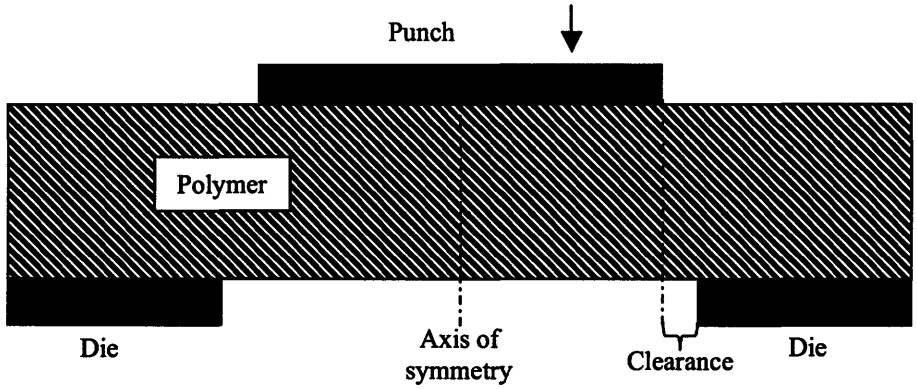


Figure 2-1: This is a simplified diagram of a circular punch and die setup; note the axis of symmetry and the clearance (which is equal to the difference in the radii of the die and punch).

While this situation can be modeled in a FEA program, it would be extremely difficult to develop a corresponding physical test capable of varying the punch-die clearance (accounting for the centering of the punch and die was a possible pitfall of such a test as well). It is much more feasible to instead create a straight-line shearing (see Figure 2-2) experiment with the ability to vary clearance. ADINA was thus used to help us assess the theoretical differences between the circular punch-die and straight-line shear situations without needing to develop a circular punch-die experiment.

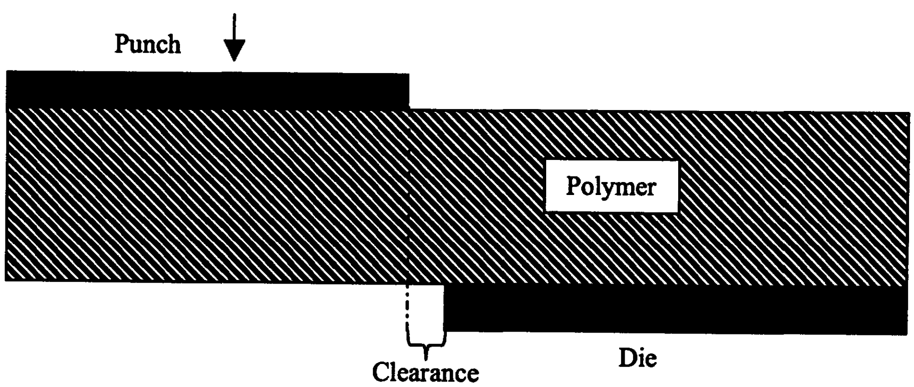


Figure 2-2: This is a simplified diagram of a straight-line shear setup. In this case, the clearance is equal to the horizontal distance between the punch and the die.

First to be modeled was the straight-line shearing. The model was created using six points and two meshed surfaces as seen in Figure 2-3. Line 5 (L_5) was modeled to have a set downward displacement (simulating the punch), while line 2 (L_2) was set to be a boundary (simulating the die). As a result, the horizontal distance between point 1 (P_1) and point 2 (P_2) is the clearance for this model. The material model used for the simulations was a visco-elastic model for PMMA with parameters derived by Matthew Dirckx (based on his own collected data and previous research done on the development of relevant material models [5, 6, 7]; the full material model can be seen in Appendix A). Simulations were performed at 110°C. The clearances modeled ran from 6.35 microns (0.00025") to 100 microns (0.004").

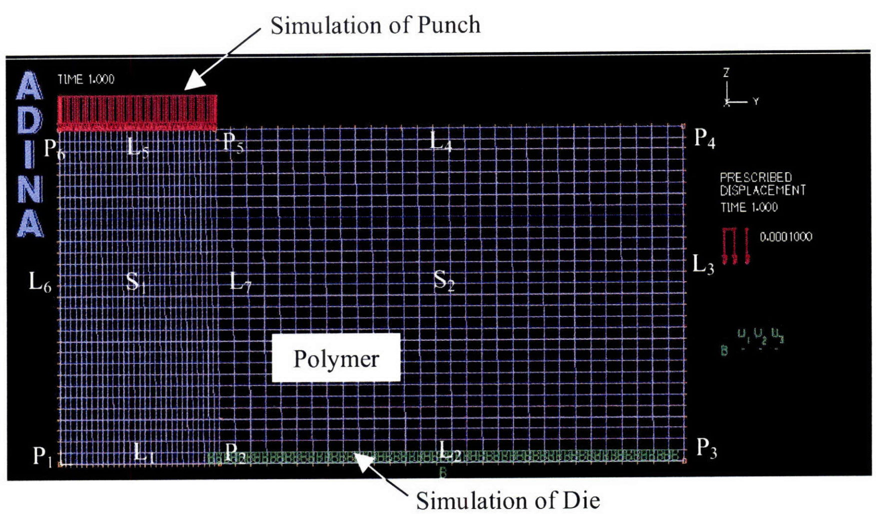


Figure 2-3: ADINA model for straight shearing simulation with clearance of 6.35 microns. Circular punch-die simulations were done with L_5 as the punch radius and L_6 as the axis of symmetry.

Unfortunately, one of the limitations of the FEA software is its ability to model failure of the material—being able to completely model the shearing process was out of the question. When we tried to model extreme displacements (e.g., 50% of the material thickness), we encountered additional issues with the software and were not able to produce useful simulations. At these displacement levels, the mesh had a tendency to wrap in on itself in a way that did not accurately simulate the actual behavior of the material. As a result, the simulations were ultimately all run with a 10% displacement of the punch (line 5 in Figure 2-3). This allowed us to have enough displacement to begin to see the material's behavior in shear, but not too much to induce inaccurate material behavior.

The second main situation modeled was the case of the circular punch and die (the situation seen originally in Figure 2-1). The same points and meshed surfaces were used as in Figure 2-3, except with line 6 (L_6) being the axis of symmetry. As in the previous straight shear models, simulations were run with the same variations in clearance. The size of the punch was also varied for this set of simulations. Punch diameters of 500 microns, 740 microns, 1000 microns and 2000 microns were selected because of their use in previous studies of through-hole punching.

One of the goals of these simulations was to see if there were some critical values for clearance that indicated a potential drop off in shearing quality. To identify such a demarcation, we first attempted to compile some quantitative data from the simulations to assist us. For each of the many simulations, a color-coded image was created detailing the shear stress levels of the piece in different areas (see the images on the next page in

Figure 2-5). From these graphs, we were able to identify the location and value of the peak shear stresses—something we thought might be a clue to some sort of critical clearance.

Unsurprisingly, the maximum shear stress was consistently seen at the edge of the punch, where the shearing of the PMMA would begin. This maximum shear stress was negatively linearly correlated with the clearance; as seen in Figure 2-4, from the 500-micron punch simulations, the maximum shear stress goes down as the clearance goes up. No clear demarcation that would indicate tearing instead of shearing is evident from these values.

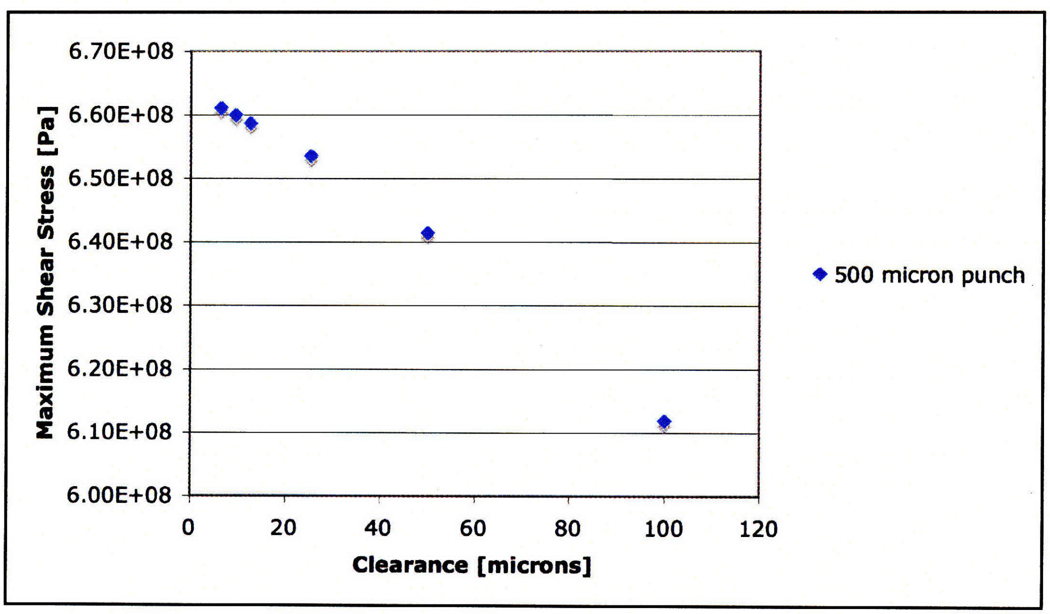


Figure 2-4: A graph of the Maximum Shear Stress versus Clearance for the 500-micron-diameter punch ADINA simulations.

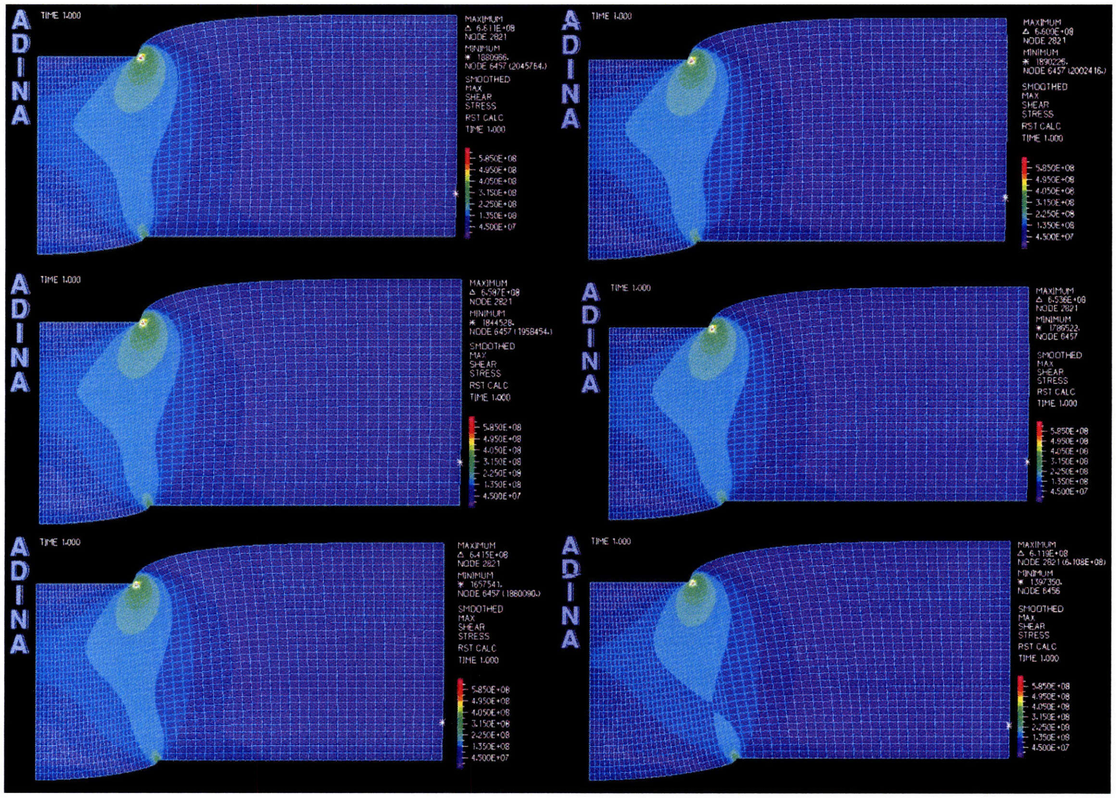


Figure 2-5: Maps of the shear stress distribution in the ADINA simulations for the 500-micron punch situation. From left to right and top to bottom, they are in order of increasing clearance: 6.35 microns, 9.525 microns, 12.7 microns, 25.4 microns, 50 microns and 100 microns, respectively.

Because these maxima are not necessarily the best indicator of the quality of the total shear, the next aspect of the finite element analysis that we examined was the general distribution of shear stresses within the part. We will focus on the area directly below the punch edge since that is where the actual shearing should occur. Figure 2-5 shows, for the 500-micron punch displacement simulations, the shear stress distributions for simulations with increasing clearances. In the simulations with clearances ranging from 6.35 microns (.00025") to 25.4 microns (.001"), we do not see a very large difference in the shear stress distribution in the part. However, as we begin to look at the simulations with much greater clearances (the bottom two images in Figure 2-5), it is clear that there is noticeably lower amount of shear stress in the area of interest. In the image sequences for the larger punch diameter and straight shear simulations, this held true as well. While it was not quite as extreme for the straight shear, it tends to have the same trends and behavior, so the corresponding straight-line shear physical experiments we performed have some significance in a discussion of punching circular through-holes. Looking at principle stresses in all directions for each of the simulations (for the straight-line punch and the circular punch and die) yielded the same conclusions.

Chapter 3

Straight-Line Shearing Experiments

In order to test some of the predictions from the theoretical simulations, an experimental test was created. The physical tests relied on a unique punch and die set with an adjustable punch-die clearance. Figure 3-1 shows a top view of the punch and die, and notes where the polymer blanks were placed for shearing. As this diagram shows, a trapezoidal punch and similarly shaped die were used. To position the punch for each test, a shim was placed on the shortest wall of the die (noted as the A_D in Figure 3-1 and as "shim wall" in Figure 3-2) and the movable punch was slid towards it until the shim was sandwiched tightly in between the die's "shim wall" and the "shim wall" of the punch. Because of the trapezoidal design, by placing shim stock as shown in Figure 3-1, a clearance of half the width of the shim is created for our angled shearing edge (also note, in Figure 3-1, the location of the polymer to be sheared on this edge). This allowed for us to create clearances even smaller than the thickness of the shim stock we used (.0005"—12.7 micron—thick shim stock was used for these tests; multiple layers were used as necessary to produce greater clearances).

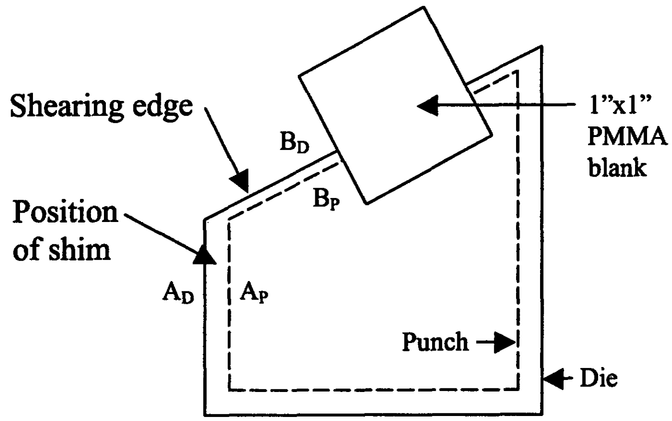
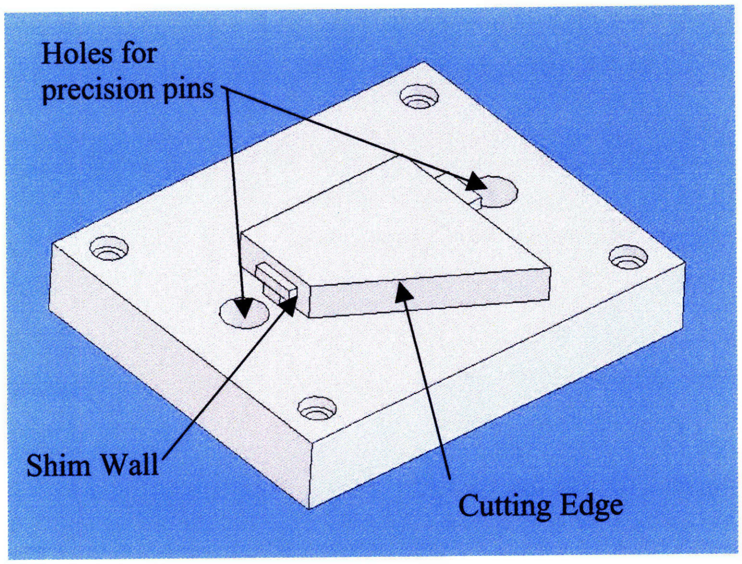


Figure 3-1: *Top view of Punch-Die set.* The solid line is the die wall, with the dotted line being the punch edges. Shim stock is placed in between A_D and A_P, generating clearances in between B_D and B_P (the shearing edge) of half the shim thickness. The polymer to be sheared is also shown; it is sheared along edge B.

For optimal alignment, the punch and die set machined for this purpose was designed for use with an existing die set. The existing die set (seen in Figure 3-3) had two precision pins on top and bottom for alignment. The holes for these precision pins can be seen in Figure 3-2 on either side of the punch and die. To secure the movable punch's position (after the clearance has been set), there are three setscrews opposite the shearing edge that keep it in place (also visible in Figure 3-3).



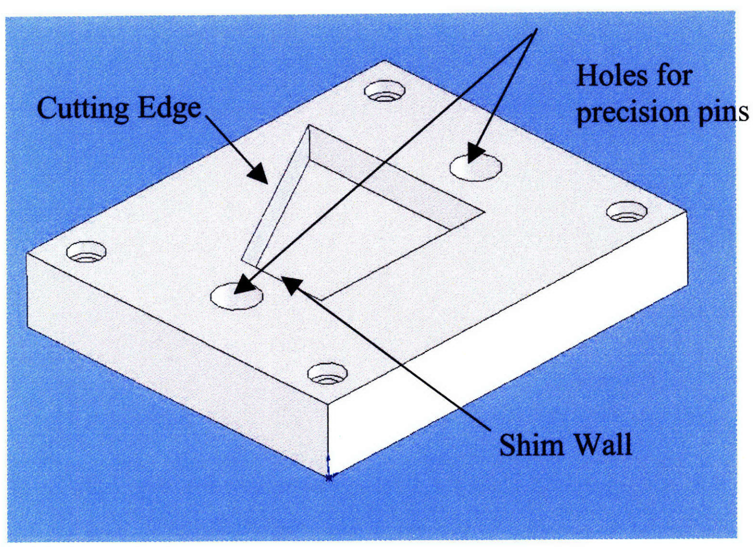


Figure 3-2: The top image shows the movable punch on its track; the set screws to keep it in place are on the back left side that is not visible. The bottom image is the die. The shim was placed in between the noted walls in the images above. The cutting edges are also noted. The two holes on both the punch and die are for the precision alignment pins.

The punch and die set was machined out of steel to provide durability and repeatability for the shearing tests. After being bolted into the existing die set, it was placed in the hot embossing machine (Figure 3-4). The hot embossing machine (designed and built by Matthew Dirckx [8]) relies on a modified Instron machine to provide the necessary pressure and a large hot oil system to heat up the upper and lower platens in Figure 3-4 to the required temperatures. The image in Figure 3-4 shows the full setup ready for testing.

To perform the individual tests, one-inch-by-one-inch blanks of 1.57 mm thick PMMA was used. The blanks were placed with slightly more than half of the piece on the die side of the cutting edge. The punch was then lowered slowly until it made contact with the piece, securing it in place for the test.

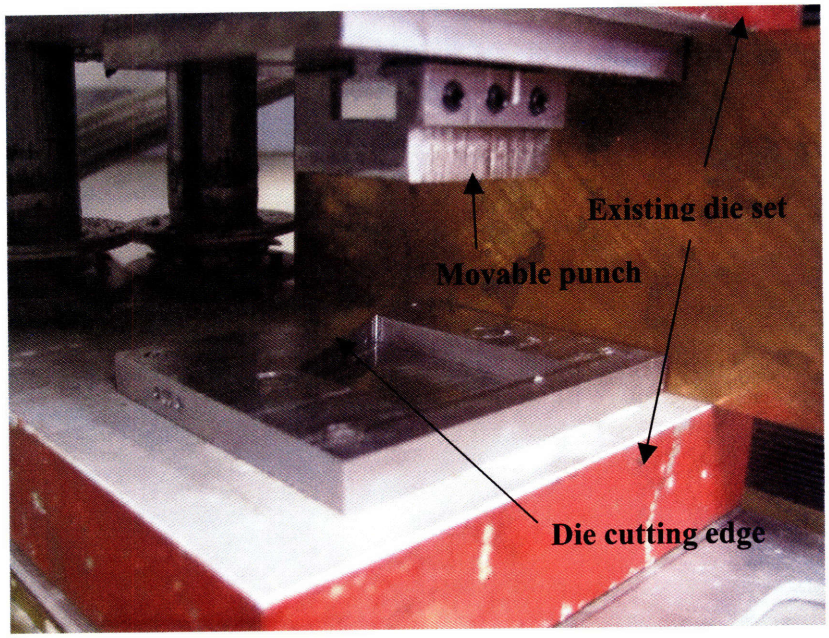


Figure 3-3: This shows a close-up image of the punch and die set used for the physical tests; note the movable punch on the top (and set screws to secure it in place). The cutting edge of the die is noted (it is the only one not perpendicular to the others). The cutting edge of the punch is the corresponding edge on the movable punch. The red die set includes two precision pins on both top and bottom so the special punch and die set could have precise alignment.

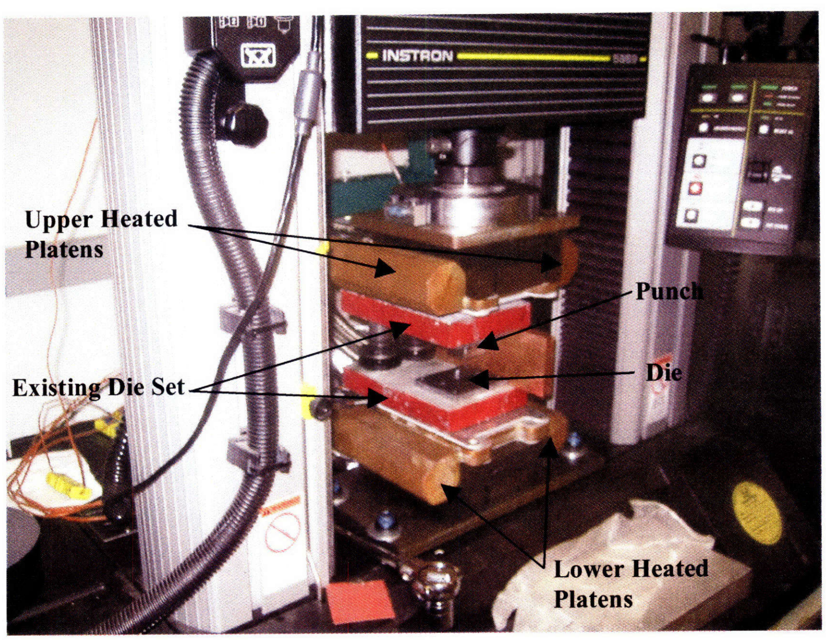


Figure 3-4: This image shows where the punch and die set was placed in the hot embossing machine in order to perform the necessary tests. The brown platens on top and bottom (in contact with the existing die set) were heated up in order for us to perform the above-room-temperature tests.

The shearing tests were done while varying three important parameters: temperature, shear speed and clearance. The tests were performed at room temperature (about 22°C), 80°C and 110°C (the punch and die set was kept within 3°C of these set points during testing). The second two temperatures were selected to span the glass transition temperature of typical PMMA, which is approximately 110°C. For the tests performed at 80°C, the top and bottom platens of the hot oil heating system were set to 90°C, while they were set to 130°C for the 110°C tests. Three shear speeds were used: 40, 80 and 160 millimeters per minute. Three different clearances were used for the punch and die setup. Using shim stock of .0005" thickness, we were able to produce clearances of 0.00025" (6.35 microns), 0.0005" (12.7 microns) and 0.001" (25.4 microns). For each unique combination of parameters, three tests were performed so that reasonable statistics could be developed; thus 81 tests were originally performed.

Later on, 18 tests were performed with a clearance of 0.002" (50.8 microns). The tests for this series were performed at the three previous shear speeds, but only at room temperature and 110°C. While these tests hadn't initially been planned, they were added to give a better idea of how the shearing changed (quantitatively and qualitatively) as the clearance increased significantly (relative to the previous tests).

For each test, force, displacement and time were logged. Force versus displacement and time profiles were then generated and stored. Peak forces during the shearing were determined and then catalogued for each test and used to assess the shearing process. Using a 10x-magnifying lens, the sheared pieces were also examined visually. To assess the quality, we looked at three important traits of the shear: the presence of burrs, the straightness of the shear, and evidence of any other anomalies (such as material lost during the shearing process, etc.). The samples were then all rated on a rough scale going from "Poor" to "Fair" to "Good." Parts labeled "Poor" typically had larger burrs and had sheared edges that were not very straight, while "Fair" parts had smaller burrs and straighter sheared edges. The parts marked as "Good" lacked noticeable burrs and typically had very straight sheared edges.

The results of the physical experiments can thus be divided up into two different sections: quantitative and qualitative. First, I'll discuss the quantitative results. Each physical test generated a force versus extension graph that shows how much force the hot-embossing machine exerted as it continued to extend. The shape of this graph was unique for experiments done at different temperatures, but fairly constant for all tests at a certain temperature. At room temperature (top in Figure 3-5), the force builds up quickly until the punch quickly shears through the PMMA. In the 80°C tests (middle image in Figure 3-5), however, we see the force reach a certain level and then stay nearly constant as the punch shears through the PMMA. The 110°C tests (bottom image in Figure 3-5) show a similar force plateau as the PMMA exhibits its viscous characteristics and is slowly sheared by the punch.

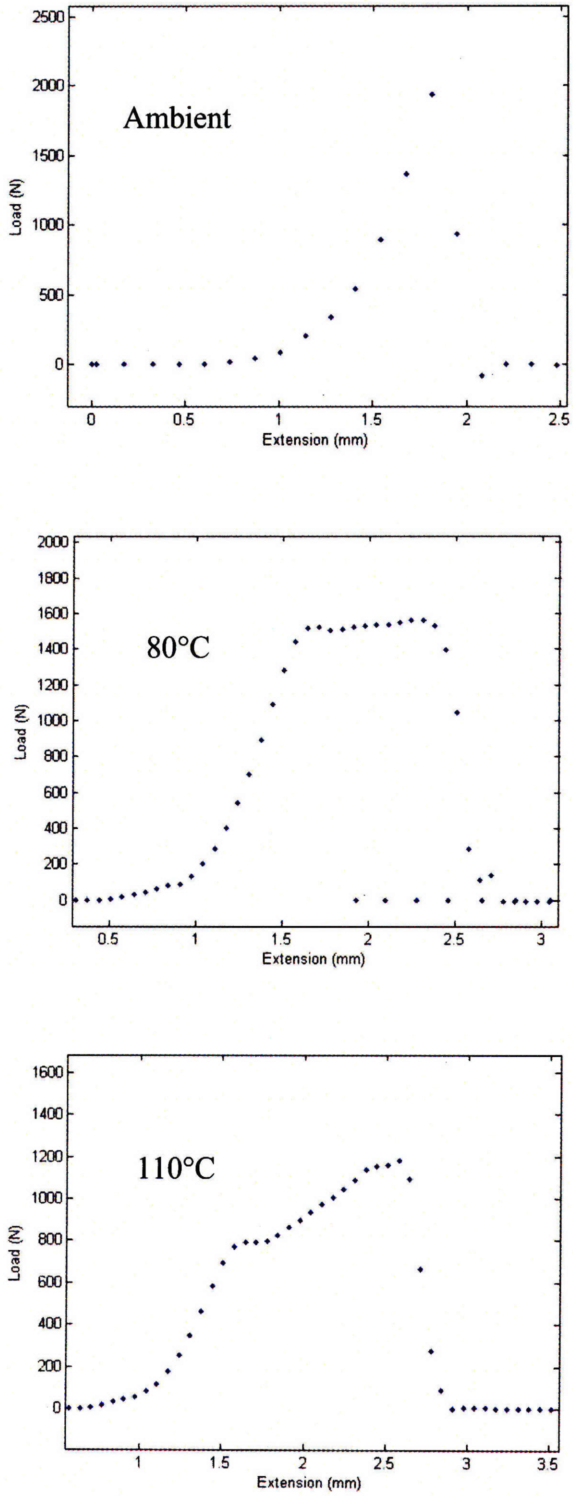


Figure 3-5: The top image shows the "Force versus Extension" graph for a typical room temperature shearing test. The middle image is of an 80°C test, and the bottom image is of a 110°C image.

The peak forces were then determined for each test. After measuring the length of the shear, a "force per unit length" value was calculated for each test. Figure 3-6 below shows the results from all of these tests in the "Force/shear length vs. Clearance" graph. The markers show the average value for all tests at that temperature and clearance; the error bars represent plus and minus one standard deviation. As we can see, there is a slight negative correlation between the "maximum force/length" and the clearance at each temperature. However, this is a weak correlation and the error bars overlap at least a little for each set of tests at a given temperature.

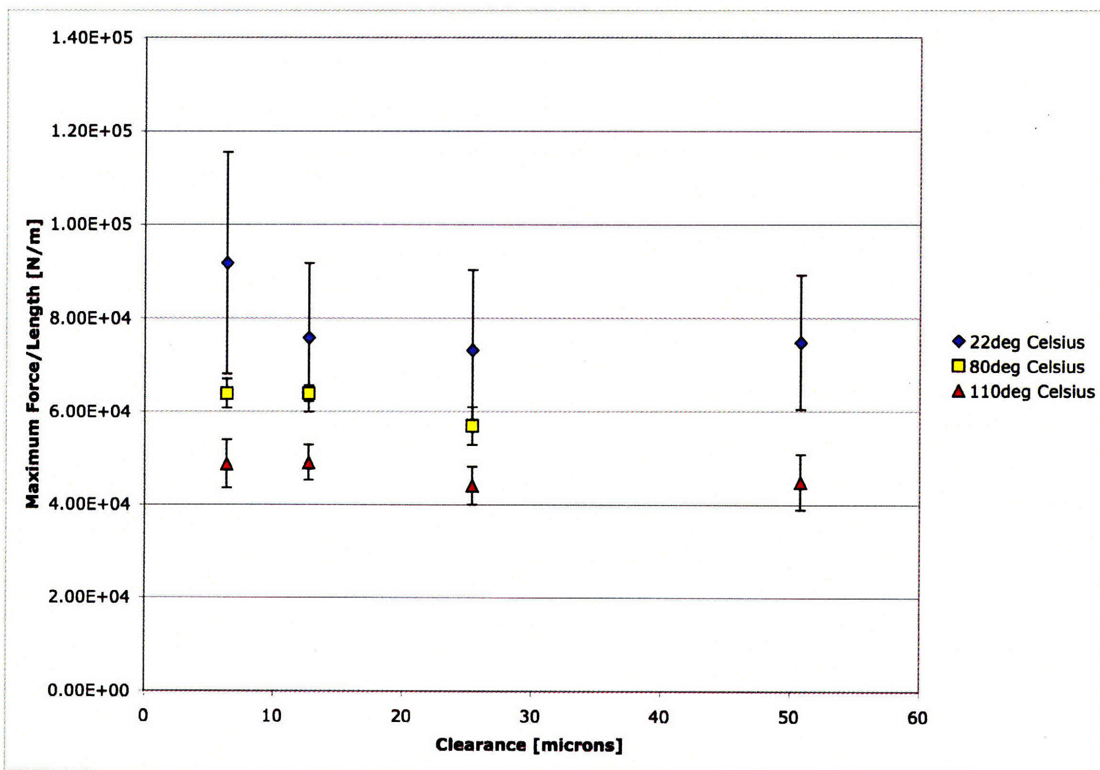


Figure 3-6: All the "Maximum Force/Length" values from the shearing experiments graphed against their respective clearances. The blue diamonds are the averages of tests done at room temperature (22°C), the yellow squares are the averages of tests done at 80°C and the red triangles are the averages of tests done at 110°C. The error bars represent plus and minus one standard deviation.

This correlation is still negative, but very weak, when further trellised by other values. For example, if we look only at the 110°C tests, and separate them by shear speed, we get the graphs shown below in Figure 3-7.

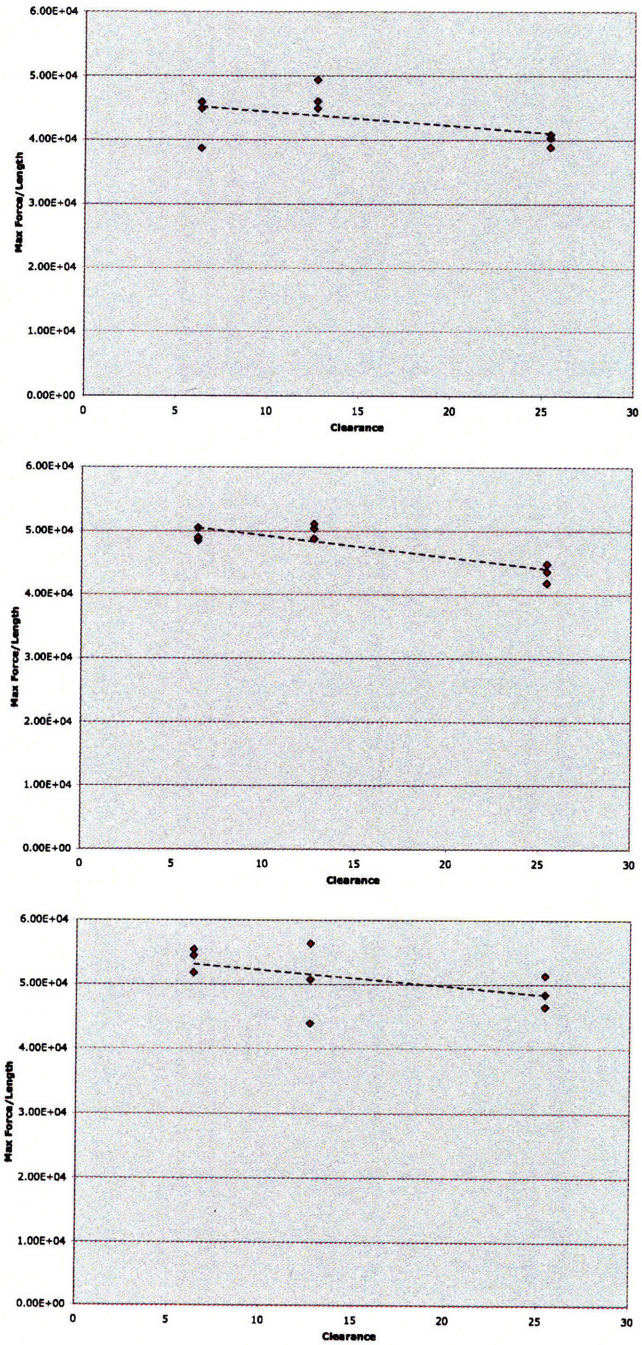


Figure 3-7: All three of these are Maximum Force/Length versus Clearance graphs for tests done at 110°C. The top graph has just the tests done at 160 mm/min shear speed, the middle graph shows the results from the tests done at 80 mm/min, and the bottom graph contains the results from the tests done at 40 mm/min.

As can be seen, there is the aforementioned negative correlation, but it is once again very weak and, because of the small sample size, is not a definitive indication of an actual negative trend. Using an Analysis of Variance test (ANOVA), none of the three 110°C subsets pictured in Figure 3-7 had a negative correlation that was significant at a .05 significance level; of the three corresponding subsets from the 80°C tests, only one showed a negative correlation significant at that level.

The qualitative assessment of the parts, as pointed out before, was done by grading each part as "Poor," "Fair," or "Good" (this was done after inspection with a 10x magnifying glass). Examples of parts with each of these three grades can be seen in Figure 3-8 below.

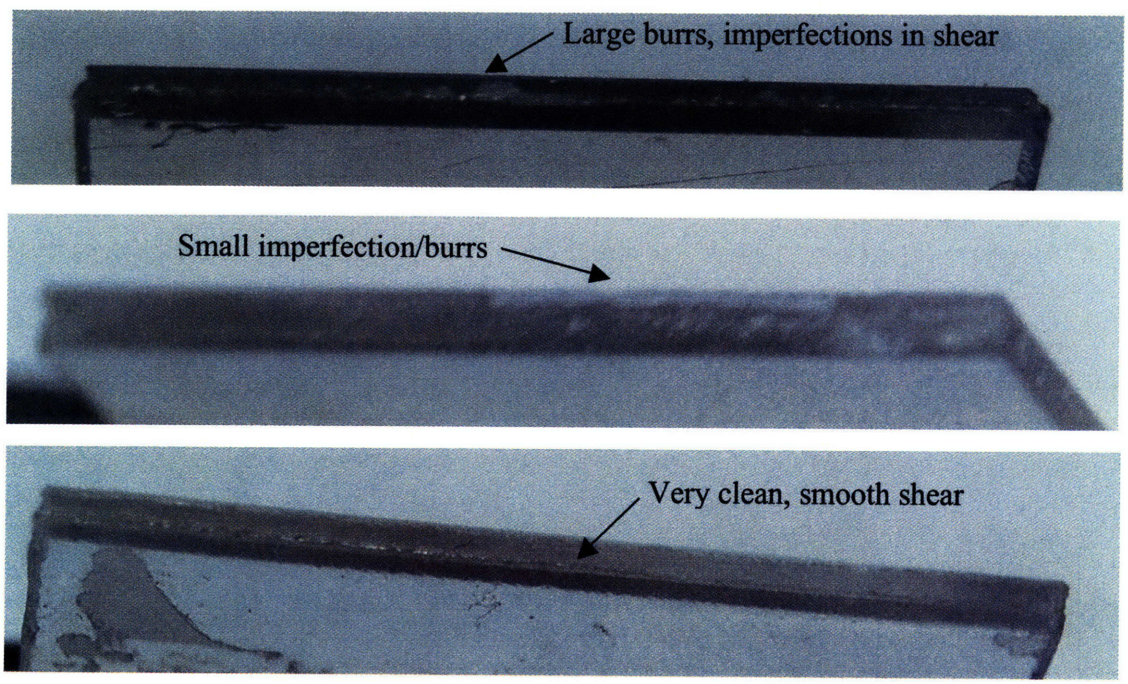


Figure 3-8: This image shows an example of each grade of shear. The top image is a shear that was graded "Poor," while the middle image shows a "Fair" shear and the bottom image shows a "Good" shear.

The results from the qualitative assessment of all the parts can be seen on the next page in Table 3-1. We can see clearly that the parts sheared at higher temperature consistently scored higher—something that we predicted would happen. However, there was minimal difference between the qualities of parts with different clearances within parts sheared at the same of temperature. In the 110°C tests, we do see more "Fair" parts in the set of 50.8 micron clearance tests, compared to the average "Good" parts that were produced at that temperature. It is not an overwhelming depreciation in quality, and, because of the sample size, not necessarily significant.

		Temperature		
		22deg C	**80deg C**	**110deg C**
Clearance	**6.35**	**Poor**	*Fair*	Good
		Poor	*Fair*	Good
		Poor	Good	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Good
		Poor	Good	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Good
		Poor	**Poor**	Good
	12.7	**Poor**	*Fair*	Good
		Good	*Fair*	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Fair
		Poor	*Fair*	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Good
	25.4	*Fair*	*Fair*	Fair
		Fair	*Fair*	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Good
		Poor	*Fair*	Fair
		Poor	**Poor**	Good
		Poor	*Fair*	Good
	50.8	**Poor**	--	Good
		Poor	--	Good
		Poor	--	Fair
		Poor	--	Good
		Poor	--	Good
		Poor	--	Fair
		Fair	--	Good
		Poor	--	Good
		Poor	--	*Fair*

Table 3-1: Each part was rated as "Poor," "Fair," or "Good" based upon the quality of the shear. Taken into consideration was the presence of burrs, the straightness of the shear and the cleanness of the shear. Bold font indicates the presence of large burrs, italics indicate small burrs and regular typeset indicates the lack of noticeable burrs.

Chapter 4

Conclusion

The ADINA simulations did not provide any definite conclusions, but they do begin to hint at a few possibilities. Most importantly, the shear-stress maps appear to indicate that the differences between punching at clearances in the sub 25-micron range do not have a significant effect. Greater than 25 microns, especially when we reach clearances of up to 100 microns, we begin to see more significant depreciation in the levels of shear stress below the punch edge—a possible indication that the quality of the shear at this level may be worse.

From the physical tests, we can draw a few conclusions. First, the temperature, as expected, is a huge indicator of the quality of the shear. When looking within the parts formed at a certain temperature, however, the variation may not have as much to do with clearance as predicted—at least at very low clearance levels. The tests done with 50.4-micron clearance gaps don't show conclusively that the quality of these parts is drastically worse, but a slightly greater drop in quality begins to appear. The fact remains, though, that these tests were, of course, straight-line shearing tests. While it gives us an idea of how the clearance might affect quality in through-hole punching, it cannot tell us for sure, and thus there is still uncertainty in our findings here.

For future work, it would be interesting to perform more of the physical experiments at 110°C to see if the slightly negative trend of Maximum Force/Length versus Clearance was actually significant. Development of a physical experiment more directly applicable to punching through-holes would also be ideal. While the shearing experiments provide a useful comparison, it would be ideal to develop a test where we could see actual through-holes punched with varying clearances. It would also be useful in the future to be able to verify the clearances in the tests are precisely what they are predicted to be. Finally, it would be useful to come up with a more quantitative way of measuring the quality of the parts produced from the test so that we could have a true assessment of the effect of different clearances.

Appendix A

PMMA Material Model

Developed by Matthew Dirckx

PMMA as a Viscoelastic Material (developed for use in ADINA)

(All Values in N-mm-s-C units)

Density: $1.18x10^{-9}$

Subdivisions of Strain Increments: 10

Mean Coeffeicient of Thermal Expansion: 13.2

Coef. Of Thermal Expansion (Temperature-Dependent)

Temperature	Coefficient
0	-0.000084
20	-0.000084
40	-0.000084
60	-0.000084
80	-0.000084
100	-0.000084
120	-0.00018
140	-0.00018
180	-0.00018
200	-0.00018

WLF (Williams-Landell-Ferry) Equation
Constant C1: 8.86 Constant C2: 101.6
Reference Temperature: 140

Shear Modulus
Long Term Modulus: 0.818

Modulus Value	**Decay Coefficient**
70.8	50.0
103.0	5.0
202.0	0.5
220.0	0.05
142.0	0.005
5.69	0.0005
1.5	5.000e-005
5.04	5.000e-006
1.35	5.000e-007
0.288	5.000e-008
0.35	5.000e-009

Bulk Modulus
Long Term Modulus: 2.87

Modulus Value	**Decay Coefficient**
249.0	50.0
363.0	5.0
710.0	0.5
772.0	0.05
497.0	0.005
200.0	0.0005
52.6	5.000e-005
17.7	5.000e-006
4.72	5.000e-007
1.01	5.000e-008
1.23	5.000e-009

Appendix B

ADINA Simulation Code

ADINA .in file generated for 500-micron-diameter punch with a 6.35-micron clearance

```
*
DATABASE NEW SAVE=NO PROMPT=NO
FEPROGRAM ADINA
CONTROL FILEVERSION=V84
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.00100000000000000 0
4 0.00000000000000 0.00000000000000 0.00100000000000000 0
5 0.00000000000000 0.000200000000000000 0.00100000000000000 0
6 0.00000000000000 0.00240000000000000 0.00000000000000 0
@
*
LINE STRAIGHT NAME=1 P1=1 P2=6
*
LINE STRAIGHT NAME=2 P1=6 P2=2
*
LINE STRAIGHT NAME=3 P1=2 P2=3
*
LINE STRAIGHT NAME=4 P1=3 P2=5
*
LINE STRAIGHT NAME=5 P1=5 P2=4
*
LINE STRAIGHT NAME=6 P1=4 P2=1
*
LINE STRAIGHT NAME=7 P1=5 P2=6
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.00100000000000000 0
4 0.00000000000000 0.00000000000000 0.00100000000000000 0
5 0.00000000000000 0.000200000000000000 0.00100000000000000 0
6 0.00000000000000 0.000240000000000000 0.00000000000000 0
@
```

```
*
FTABLE NAME=1 F0=0.818000000000000 OPTION=DIRECT WEIGHTIN=NO,
    W1=0.00000000000000 W2=0.00000000000000 TAU=0.00000000000000
@CLEAR
7.08000000000000E+07 50.0000000000000
1.03000000000000E+08 5.00000000000000
2.02000000000000E+08 0.500000000000000
2.20000000000000E+08 0.0500000000000000
1.42000000000000E+08 0.00500000000000000
5690000.00000000 0.000500000000000000
1500000.00000000 5.00000000000000E-05
5040000.00000000 5.00000000000000E-06
1340000.00000000 5.00000000000000E-07
288000.000000000 5.00000000000000E-08
350000.000000000 5.00000000000000E-09
@
*
FTABLE NAME=2 F0=2.87000000000000 OPTION=DIRECT WEIGHTIN=NO,
    W1=0.00000000000000 W2=0.00000000000000 TAU=0.00000000000000
@CLEAR
2.49000000000000E+08 50.0000000000000
3.63000000000000E+08 5.00000000000000
7.10000000000000E+08 0.500000000000000
7.72000000000000E+08 0.0500000000000000
4.97000000000000E+08 0.00500000000000000
2.00000000000000E+08 0.000500000000000000
5.26000000000000E+07 5.00000000000000E-05
1.77000000000000E+07 5.00000000000000E-06
4720000.00000000 5.00000000000000E-07
1010000.00000000 5.00000000000000E-08
1230000.00000000 5.00000000000000E-09
@
*
MATERIAL VISCOELASTIC NAME=1 NSUBD=10 TREF=140.000000000000,
    C1=8.86000000000000 C2=101.600000000000 ALPHA=13.2000000000000,
    G-FUNCTI=1 K-FUNCTI=2 DENSITY=1.18000000000000 MDESCRIP=,
'PMMA Visco N-m-s'
@CLEAR
0.00000000000000 -8.40000000000000E-05
20.0000000000000 -8.40000000000000E-05
40.0000000000000 -8.40000000000000E-05
60.0000000000000 -8.40000000000000E-05
80.0000000000000 -8.40000000000000E-05
100.000000000000 -8.40000000000000E-05
120.000000000000 -0.000180000000000000
140.000000000000 -0.000180000000000000
180.000000000000 -0.000180000000000000
200.000000000000 -0.000180000000000000
@
*
SURFACE PATCH NAME=1 EDGE1=1 EDGE2=7 EDGE3=5 EDGE4=6
*
SURFACE PATCH NAME=2 EDGE1=2 EDGE2=3 EDGE3=4 EDGE4=7
*
EGROUP TWODSOLID NAME=1 SUBTYPE=AXISYMMETRIC DISPLACE=DEFAULT,
    STRAINS=DEFAULT MATERIAL=1 INT=DEFAULT RESULTS=STRESSES,
    DEGEN=YES FORMULAT=0 STRESSRE=GLOBAL INITIALS=NONE FRACTUR=NO,
    CMASS=DEFAULT STRAIN-F=0 UL-FORMU=DEFAULT PNTGPS=0 NODGPS=0,
```

```
   LVUS1=0 LVUS2=0 SED=NO RUPTURE=ADINA INCOMPAT=DEFAULT,
   TIME-OFF=0.00000000000000 POROUS=NO WTMC=1.00000000000000,
   OPTION=NONE DESCRIPT='NONE' THICKNES=1.00000000000000,
   PRINT=DEFAULT SAVE=DEFAULT TBIRTH=0.00000000000000,
   TDEATH=0.00000000000000
*
SUBDIVIDE SURFACE NAME=1 MODE=DIVISIONS NDIV1=10 NDIV2=10,
   RATIO1=1.00000000000000 RATIO2=1.00000000000000,
   PROGRESS=GEOMETRIC EXTEND=NONE CBIAS1=NO CBIAS2=NO
@CLEAR
1
2
@
*
GSURFACE NODES=9 PATTERN=AUTOMATIC NCOINCID=BOUNDARIES NCEDGE=1234,
   NCVERTEX=1234 NCTOLERA=1.00000000000000E-05 SUBSTRUC=0 GROUP=1,
   PREFSHAP=AUTOMATIC MESHING=MAPPED SMOOTHIN=NO DEGENERA=NO,
   COLLAPSE=NO MIDNODES=CURVED METHOD=ADVFRONT FLIP=NO
@CLEAR
1
2
@
*
FIXBOUNDARY LINES FIXITY=ALL
@CLEAR
2 'ALL'
@
*
LOAD DISPLACEMENT NAME=1 DX=FREE DY=FREE DZ=-2.00000000000000E-05,
   AX=FREE AY=FREE AZ=FREE
*
APPLY-LOAD BODY=0
@CLEAR
1 'DISPLACEMENT' 1 'POINT' 5 0 1 0.00000000000000 0 -1 0 0 0 'NO',
   0.00000000000000 0.00000000000000 1 0
@
*
APPLY-LOAD BODY=0
@CLEAR
@
*
APPLY-LOAD BODY=0
@CLEAR
1 'DISPLACEMENT' 1 'LINE' 5 0 1 0.00000000000000 0 -1 0 0 0 'NO',
   0.00000000000000 0.00000000000000 1 0
@
*
MASTER ANALYSIS=STATIC MODEX=EXECUTE TSTART=0.00000000000000 IDOF=111,
   OVALIZAT=NONE FLUIDPOT=AUTOMATIC CYCLICPA=1 IPOSIT=STOP,
   REACTION=YES INITIALS=NO FSINTERA=NO IRINT=DEFAULT CMASS=NO,
   SHELLNDO=AUTOMATIC AUTOMATI=OFF SOLVER=SPARSE,
   CONTACT-=CONSTRAINT-FUNCTION TRELEASE=0.00000000000000,
   RESTART-=NO FRACTURE=NO LOAD-CAS=NO LOAD-PEN=NO MAXSOLME=0,
   MTOTM=2 RECL=3000 SINGULAR=YES STIFFNES=0.000100000000000000,
   MAP-OUTP=NONE MAP-FORM=NO NODAL-DE='' POROUS-C=NO ADAPTIVE=0,
   ZOOM-LAB=1 AXIS-CYC=0 PERIODIC=NO VECTOR-S=GEOMETRY EPSI-FIR=NO,
   STABILIZ=NO STABFACT=1.00000000000000E-12 RESULTS=PORTHOLE,
   FEFCORR=NO BOLTSTEP=1 EXTEND-S=YES CONVERT-=NO DEGEN=YES
```

```
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.00100000000000000 0
4 0.00000000000000 0.00000000000000 0.00100000000000000 0
5 0.00000000000000 0.000100000000000000 0.00100000000000000 0
6 0.00000000000000 0.000240000000000000 0.00000000000000 0
@
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.00100000000000000 0
4 0.00000000000000 0.00000000000000 0.00100000000000000 0
5 0.00000000000000 0.000100000000000000 0.00100000000000000 0
6 0.00000000000000 0.000100000000000000 0.00000000000000 0
@
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.00100000000000000 0
4 0.00000000000000 0.00000000000000 0.00100000000000000 0
5 0.00000000000000 0.000100000000000000 0.00100000000000000 0
6 0.00000000000000 0.000100000000000000 0.00000000000000 0
@
*
APPLY-LOAD BODY=0
@CLEAR
1  'DISPLACEMENT' 1  'LINE' 5 0 1 0.00000000000000 0 0 0 0 0  'NO',
    0.00000000000000 0.00000000000000 1 0
@
*
ELDELETE SURFACE GROUP=1 SUBSTRUC=0 NODE-DEL=YES
@CLEAR
1
2
@
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.000500000000000000 0.00000000000000 0
3 0.00000000000000 0.000500000000000000 0.00100000000000000 0
4 0.00000000000000 0.00000000000000 0.00100000000000000 0
5 0.00000000000000 0.000100000000000000 0.00100000000000000 0
6 0.00000000000000 0.000100000000000000 0.00000000000000 0
@
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.000500000000000000 0.00000000000000 0
3 0.00000000000000 0.000500000000000000 0.00100000000000000 0
```

```
4 0.00000000000000 0.00000000000000 0.00100000000000000 0
5 0.00000000000000 0.000100000000000000 0.00100000000000000 0
6 0.00000000000000 0.000100000000000000 0.00000000000000 0
@
*
GSURFACE NODES=9 PATTERN=AUTOMATIC NCOINCID=BOUNDARIES NCEDGE=1234,
   NCVERTEX=1234 NCTOLERA=1.00000000000000E-05 SUBSTRUC=0 GROUP=1,
   PREFSHAP=AUTOMATIC MESHING=MAPPED SMOOTHIN=NO DEGENERA=NO,
   COLLAPSE=NO MIDNODES=CURVED METHOD=ADVFRONT FLIP=NO
@CLEAR
1
2
@
****
*** ADINA OPTIMIZE=SOLVER FILE=,
*** 'C:\Documents and Settings\Staff\Desktop\Stu-thesis\Final\Thic
*** kness_1mm\Punch Diam .1 mm\Clearance_0microns.dat' FIXBOUND=YES,
***     MIDNODE=NO OVERWRIT=YES
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.000500000000000000 0.00000000000000 0
3 0.00000000000000 0.000500000000000000 0.00100000000000000 0
4 0.00000000000000 0.00000000000000 0.00100000000000000 0
5 0.00000000000000 0.000100000000000000 0.00100000000000000 0
6 0.00000000000000 0.000103175000000000 0.00000000000000 0
@
*
ELDELETE SURFACE GROUP=1 SUBSTRUC=0 NODE-DEL=YES
@CLEAR
1
2
@
*
GSURFACE NODES=9 PATTERN=AUTOMATIC NCOINCID=BOUNDARIES NCEDGE=1234,
   NCVERTEX=1234 NCTOLERA=1.00000000000000E-05 SUBSTRUC=0 GROUP=1,
   PREFSHAP=AUTOMATIC MESHING=MAPPED SMOOTHIN=NO DEGENERA=NO,
   COLLAPSE=NO MIDNODES=CURVED METHOD=ADVFRONT FLIP=NO
@CLEAR
1
2
@
*
APPLY-LOAD BODY=0
@CLEAR
1  'DISPLACEMENT' 1  'LINE' 5 0 1 0.00000000000000 0 0 0 0 0  'NO',
   0.00000000000000 0.00000000000000 1 0
@
*
LOAD DISPLACEMENT NAME=1 DX=FREE DY=FREE DZ=-0.000100000000000000,
   AX=FREE AY=FREE AZ=FREE
*
APPLY-LOAD BODY=0
@CLEAR
1  'DISPLACEMENT' 1  'LINE' 5 0 1 0.00000000000000 0 0 0 0 0  'NO',
   0.00000000000000 0.00000000000000 1 0
@
```

```
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.000525000000000000 0
4 0.00000000000000 0.00000000000000 0.00100000000000000 0
5 0.00000000000000 0.000100000000000000 0.00100000000000000 0
6 0.00000000000000 0.000103175000000000 0.00000000000000 0
@
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.000525000000000000 0
4 0.00000000000000 0.00000000000000 0.000525000000000000 0
5 0.00000000000000 0.000100000000000000 0.000525000000000000 0
6 0.00000000000000 0.000103175000000000 0.00000000000000 0
@
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.000525000000000000 0
4 0.00000000000000 0.00000000000000 0.000525000000000000 0
5 0.00000000000000 0.000250000000000000 0.000525000000000000 0
6 0.00000000000000 0.000253175000000000 0.00000000000000 0
@
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.000525000000000000 0
4 0.00000000000000 0.00000000000000 0.000525000000000000 0
5 0.00000000000000 0.000250000000000000 0.000525000000000000 0
6 0.00000000000000 0.000253175000000000 0.00000000000000 0
@
*
ELDELETE SURFACE GROUP=1 SUBSTRUC=0 NODE-DEL=YES
@CLEAR
1
2
@
*
GSURFACE NODES=9 PATTERN=AUTOMATIC NCOINCID=BOUNDARIES NCEDGE=1234,
   NCVERTEX=1234 NCTOLERA=1.00000000000000E-05 SUBSTRUC=0 GROUP=1,
   PREFSHAP=AUTOMATIC MESHING=MAPPED SMOOTHIN=NO DEGENERA=NO,
   COLLAPSE=NO MIDNODES=CURVED METHOD=ADVFRONT FLIP=NO
@CLEAR
1
2
@
*
GSURFACE NODES=9 PATTERN=AUTOMATIC NCOINCID=BOUNDARIES NCEDGE=1234,
   NCVERTEX=1234 NCTOLERA=1.00000000000000E-05 SUBSTRUC=0 GROUP=1,
```

```
   PREFSHAP=AUTOMATIC MESHING=MAPPED SMOOTHIN=NO DEGENERA=NO,
   COLLAPSE=NO MIDNODES=CURVED METHOD=ADVFRONT FLIP=NO
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.000525000000000000 0
4 0.00000000000000 0.00000000000000 0.000525000000000000 0
5 0.00000000000000 0.000250000000000000 0.000525000000000000 0
6 0.00000000000000 0.000250000000000000 0.00000000000000 0
@
*
ELDELETE SURFACE GROUP=1 SUBSTRUC=0 NODE-DEL=YES
@CLEAR
1
2
@
*
GSURFACE NODES=9 PATTERN=AUTOMATIC NCOINCID=BOUNDARIES NCEDGE=1234,
   NCVERTEX=1234 NCTOLERA=1.00000000000000E-05 SUBSTRUC=0 GROUP=1,
   PREFSHAP=AUTOMATIC MESHING=MAPPED SMOOTHIN=NO DEGENERA=NO,
   COLLAPSE=NO MIDNODES=CURVED METHOD=ADVFRONT FLIP=NO
@CLEAR
1
2
@
*
COORDINATES POINT SYSTEM=0
@CLEAR
1 0.00000000000000 0.00000000000000 0.00000000000000 0
2 0.00000000000000 0.00100000000000000 0.00000000000000 0
3 0.00000000000000 0.00100000000000000 0.000525000000000000 0
4 0.00000000000000 0.00000000000000 0.000525000000000000 0
5 0.00000000000000 0.000250000000000000 0.000525000000000000 0
6 0.00000000000000 0.000256350000000000 0.00000000000000 0
@
*
ELDELETE SURFACE GROUP=1 SUBSTRUC=0 NODE-DEL=YES
@CLEAR
1
2
@
*
GSURFACE NODES=9 PATTERN=AUTOMATIC NCOINCID=BOUNDARIES NCEDGE=1234,
   NCVERTEX=1234 NCTOLERA=1.00000000000000E-05 SUBSTRUC=0 GROUP=1,
   PREFSHAP=AUTOMATIC MESHING=MAPPED SMOOTHIN=NO DEGENERA=NO,
   COLLAPSE=NO MIDNODES=CURVED METHOD=ADVFRONT FLIP=NO
@CLEAR
1
2
@
```

Bibliography

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