Characterization of Waterjet Cutting Process on Different Machines on MIT Campus

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Abstract:
Three waterjet machines on MIT's campus were evaluated for dimensional accuracy through a range of cutting parameters. The quality parameter (set by the machine software) which dictates the traverse speed and the z-offset which affects kerf width were used in 2^2 full factorial experiments with center-points. Linear models were fit to the data and two out of the three regression models were found to have significant curvature. To a 95% confidence level, the statistically significant factors affecting cut dimension are quality and machine selection. Expected Quality Loss (EQL) and Grey Relational Analysis (GRA) were used to find the optimal machine and cutting parameter combination for maximizing the dimensional accuracy and minimizing the cutting time. The machine located in the MakerWorks provides the best dimensional accuracy at fastest cutting time. The optimal cutting settings are 0.060-inch z-offset and quality 5.

Index Terms: abrasive, aluminum, ANOVA, DOE, EQL, factorial design, GRA, regression, stand-off distance, waterjet.

I. INTRODUCTION

A waterjet is an industrial cutting method that can cut a variety of materials with a high-pressure jet of water or water with abrasive media. The pressurized water is mixed with sand, garnet, or other granular media and ejected from the nozzle. When the abrasive particles hit the cutting target, the target is eroded at a rate dependent on the material hardness. The time to pierce the target material depends on the thickness and hardness of the material. As the jet exits the nozzle, the jet diameter increases with distance from the nozzle exit point. Therefore, the farther the target material is from the nozzle, the more dispersed the abrasive particles are and the less impact energy per unit area it possesses. In thick material stock, there is a visible variation in surface finish along the depth of the cut because the particles eroding the deeper material have less impact energy.

Figure 1. Waterjet Cutting

Students have access to several waterjet machines on the MIT campus for a nominal fee based on cutting time. This experiment aims to characterize machine performance to balance cutting speed and dimensional accuracy. Most waterjet parameters are difficult to change or specific to the machine, such as nozzle diameter, abrasive grit size, pump flow rate, bed size, and cutting pressure. Dimensional accuracy is characterized between machines by varying the z-offset and nozzle traverse speed, as dictated by the software setting for quality.

A. Abbreviations and Acronyms

ANOVA — Analysis of Variance
D-Lab — Design Lab
DOE — Design of Experiments
HAZ — Heat Affected Zone
HS — Hobby Shop
LMP — Laboratory for Manufacturing and Productivity
MIT — Massachusetts Institute of Technology
MW — MakerWorks

II. BACKGROUND

Researchers have made numerous attempts at characterizing waterjet cutting as a process, however they have only included the impact of machine in the experiment on rare occasions. This study attempts to characterize the different process variables and then include machine as a factor to understand its impact on dimensional accuracy.

The waterjet is used to cut a variety of materials including concrete, metal, stone, wood, and plastic without raising the temperature of the surrounding material. Although waterjet machines are expensive to buy, maintain, and run, they are invaluable for temperature sensitive cuts because they do not produce heat affected zones (HAZ) that change local metallurgical properties. The machines are very accurate and possess the ability to cut complicated geometries.

The following list of factors can be varied and tested for influence on performance of a waterjet machine.

TABLE I
FACTORS INFLUENCING WATERJET CUTTING

Factors	Type
Traverse Speed	Equipment state
z-offset	Equipment state
Type of Material	Material property
Thickness	Material property
Garnet Size	Equipment state
Abrasive Flow Rate	Equipment state
Jet Pressure	Equipment state
Nozzle Diameter	Equipment state
Impingement Angle	Equipment state
Pass Increment	Equipment state

There were two underlying considerations in selection of two factors: (a) The experiment was targeted towards the average user who could easily change the factors in a laboratory setting (b) Level of simplicity and accuracy to which the factors can be varied and controlled.

Traverse speed and z-offset were the two factors selected based on the above considerations. Ozcelik, Y. et al. stress on traverse speed and z-offset to be the most critical parameters in a waterjet cutting system [1]. They mention that when the nozzle traverses along a path, the initial crater transforms into the kerf and depth of penetration decreases with the increase in travel speed. Filip, A. et al. state that the main parameters of influence were water pressure, traverse speed, abrasive flow rate and z-offset. They further established traverse speed and z-offset as the factors for their experiments based on empirical results of previous experimentation [2].

However, it was discovered that traverse speed was defined by the quality setting of the machine and could not be controlled independently. Hence, quality and z-offset were the two factors selected for the experiment.

III. Experiment

A. Factors

1) Quality

The quality of cut can be controlled using the OMAX Layout Software accessible on all machines. It is considered a credible indicator of the quality of the cut, from the surface finish to the dimensional accuracy. The software allows the user to choose between five different levels available, with number five having the highest quality.

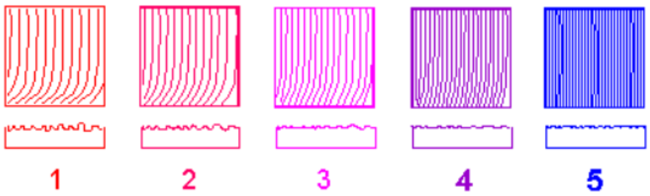

Figure 2. Different Quality Levels in Waterjet Cutting [3]

The different quality settings define the traverse speed required to pierce a certain thickness of the material. For instance, quality 1 is also known as the separation cut which defines the minimum traverse speed required to pierce the thickness of the target material, which explains the curved grain of the cut in Figure 2. Quality 3 sets the traverse speed such that it can pierce 3 times the thickness of the target material and quality 5 sets it to pierce 5 times the thickness. As the thickness to pierce increases, the cutting time would increase significantly. Hence, for the same material and machine properties, the quality selected is synonymous to the cutting speed with a higher quality indicating a slower cutting speed.

For assessing the full range of process and machine capability, quality 1 and quality 5 were chosen as the limits of the factorial design with quality 3 as the center-point. In doing so, the optimal settings for the best dimensional accuracy and least cutting time can be found. Quality 3 is usually recommended by the manufacturer.

2) z-offset

The z-offset or the standoff distance between the nozzle and the material is also another crucial factor chosen. As mentioned, the jet would lose its energy as it travels through the water layer and abrasively grinds the material. The z-offset would then theoretically affect the size of the taper and the dimensional accuracy of the cut.

Based on the recommended values, 0.06” and 0.16” were chosen as the limits for factorial design in this experiment. Intuitively, a shorter z-offset should provide the best performance. However, if the nozzle is too close to the material, it has a higher chance of getting plugged with backflow occurring in the abrasive line. As the three machines selected are not equipped with an automatic terrain follower, the z-offset needs to be set such that any collisions between the nozzle and the material is avoided. With these limitations, it would be interesting to observe the effect the z-offset has on the dimensional accuracy and if an optimal combination of factors exists.

3) Machine Selection

Three machines were identified for characterization. The Laboratory for Manufacturing Productivity has an OMAX 2652 Precision JetMachining Center (LMP). This machine is a cantilever type cutter that has a cutting bed of 4’4” x 2’2” and linear position resolution of ± 0.001”. It uses 85-mesh garnet.

Figure 3. Waterjet at the Laboratory for Manufacturing & Productivity, MIT

MakerWorks has an OMAX 2626 Precision JetMachining Center (MW). It is one of the first 2626s OMAX produced. It is a cantilever type machine with a cutting bed of 2’5” x 2’2” and a linear position resolution of ± 0.001”. It uses 85-mesh garnet.

Finally, the waterjet in the Hobby Shop, OMAX MicroMAX (HS) is built specifically for micromachining, with a bed size of 2’1” x 2’1”, a linear position resolution of ± 0.0001”, and 220-mesh garnet. It uses a gantry instead of a cantilever setup.

B. Output

1) Coupon Design

Four 2" x 2" coupons were designed using 0.25" thick Aluminum 6061 to measure the dimensional accuracy of the waterjet machines (Figure 4). The internal dimensions of the coupons were measured due to two major reasons:

(a) Prevents the coupons from falling into the water during the cutting process

(b) Eases the arduous process of tracking and storing the coupons.

Each 2" x 2" coupon represents a replicate of a treatment level. Four coupons (replicates) for single treatment level were cut on the same square stock of 7" x 7".

2) Measurement of Output

Internal dimensions of each coupon were measured in the X and Y directions respectively. The internal dimensions of the four replicates were measured in a clockwise direction as represented by 1 through 4 in Figure 4.

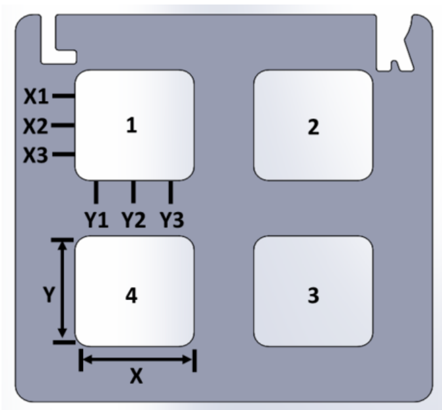

Figure 4. Coupon Design with the Measurement Positions marked

X and Y dimensions of each coupon were measured at three different designated locations to ensure uniformity of the measurements and to reduce measurement error. This system also makes the measurement traceable in the event of any aberration.

Standard measurement procedure was established to minimize the measurement variations due to different operators. The following measurement procedure was followed:

- All coupons were labelled to identify them based on different machines, treatment levels, and replicates
- Measurement sequences and locations in the X and Y directions were labelled as short horizontal and vertical lines on all the coupons as shown in Figure 4
- The small jaws of the digital calipers were aligned such that their tips touched the flat surface and are in-line with the respective location label, ensuring the caliper is straight
- Dimensions of replicate 1 were measured first from X1 to X3 and then, from Y1 to Y3; Other three replicates of the same treatment level were measured in a clockwise sequence from 2 to 4
- The same operator and measuring tool were used to ensure consistency in measurement

C. Procedure

1. Design: Full Factorial Design – 2 × 2 × 3 with 4 replicates and 1 center-point (for each individual machine) was selected [4]
2. Analysis (Individual Machine): The analysis is first carried out on each individual machine to find out which factors are the most significant in the waterjet cutting process. The center-point is then used to check the linearity of the model
3. Analysis (All Machines): The earlier analysis is then followed by addition of the machine variable to the design to evaluate its significance
4. Optimum Factor Setting: The optimum parametric setting for the best dimensional control at minimum cost is determined using the following methods:

a. Expected Quality Loss (EQL)

b. Grey Relational Analysis (GRA)

TABLE II: EXPERIMENT DESIGN

Factor A		Factor B	
Quality Uncode	Coded	z-offset Uncode	Code
1	-1	0.06”	-1
5	1	0.16”	1
3	0	0.11”	0

IV. RESULTS

Although the run order was different, the experimental data was recorded and analyzed in standard order. Averages of X and Y dimensions measured at three different locations of each coupons were calculated to know the mean internal dimensions of each coupon.

Combined average of X-bar and Y-bar values denoted by Z were used to perform the analysis (reducing the experimental outputs from two to just one). Taking combined average of X-bar and Y-bar was feasible as coupons were square in shape. The Figure 5 below shows a Z run chart for all the replicates of each treatment levels and center-points in standard order. For the LMP and MW machines, it is evident from Figure 5 that dimensional accuracy is higher whenever quality setting of 5 is used.

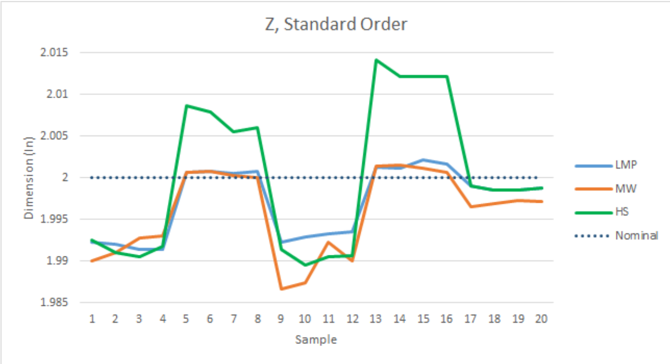

Figure 5. Run Chart of Z in Standard Order

Figure 6 shows the run chart of absolute error for all the replicates of each treatment levels and center-points in standard order. It's apparent that for the LMP and MW machines, absolute error is high for quality 1 setting and comparatively low for quality 5 setting.

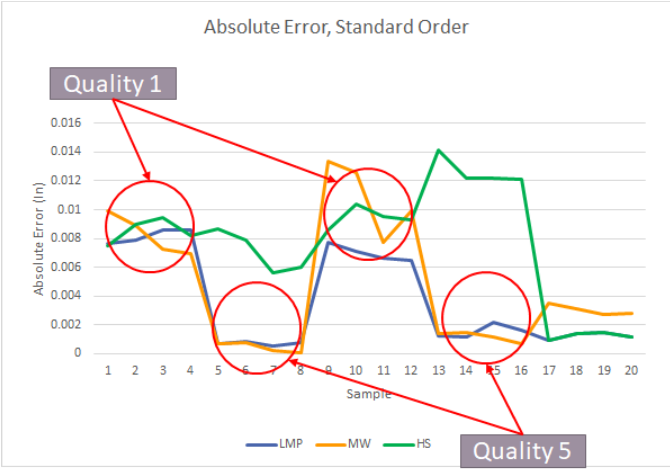

Figure 6. Run Chart of Absolute Error in Standard Order

V. ANALYSIS

For evaluating the significance of various factors in waterjet cutting, the data from the experiment was categorized and subsequently analyzed using different tests. This was followed by using the Quality Loss Function (QLF) and Grey Relational Analysis (GRA) to determine the optimum treatment. ANOVA tables for all the factorial design analyses are available in the Appendix.

A. Individual Machine

Literature suggests that the machine itself could be a significant factor affecting the results of the experiment, so inclusion of all machines in the analysis would render the result bias towards the effect of machine rather than the process itself. To avoid this, the factorial design was analyzed for all the machines individually to begin with.

1) Laboratory for Manufacturing & Productivity (LMP)

During the experiment, no major issues were experienced with this machine. On analyzing the results, it was concluded that quality was the most significant factor and there was no apparent effect of z-offset on dimensional accuracy.

Inclusion of center-point data in the analysis highlighted a significant quadratic error with a p-value of 2.56×10^{-7}. The significant curvature shows that a linear model is not sufficient to characterize the effects for this machine. Further work may include fitting a quadratic model using Central Composite Design (CCD).

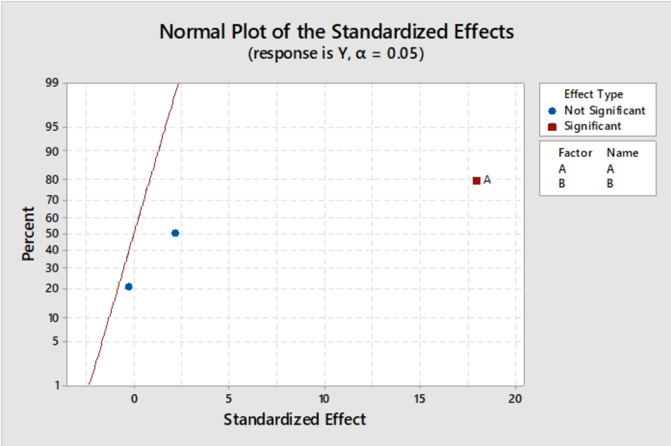

Figure 7. Normal Plot of the Standardized Effects for LMP

2) MakerWorks (MW)

The machine was very similar to the one used in LMP with the same cantilever style head traversing across the machine but, was considerably older. The analysis concluded very similar results as well i.e., there was no significant effect of z-offset on dimensional accuracy, but quality was very significant.

Inclusion of center-point data in the analysis resulted in no significant quadratic error. It was concluded that the linear regression model fits the data accurately.

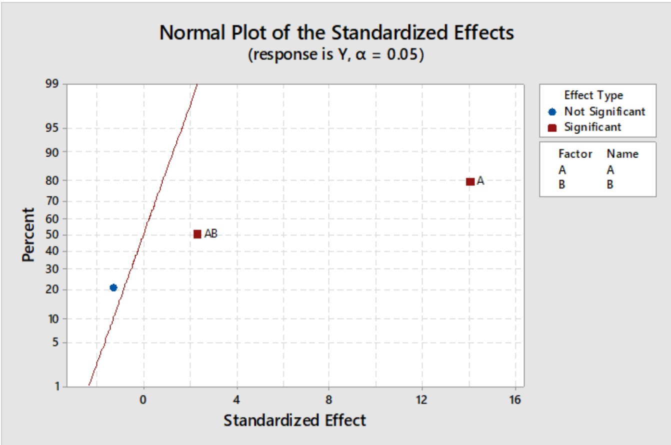

Figure 8. Normal Plot of the Standardized Effects for MW

3) Hobby Shop (HS)

The machine in HS was based on an entirely different mechanical system utilizing a gantry type mechanism to support the head movement instead of the cantilever on the other two. Moreover, some issues pertaining to garnet flow were encountered while conducting the experiment. It was also noted that there was a leak in the nozzle head (Figure 9) which could have an adverse impact on the machine performance.

Figure 9. Leak in the Nozzle in the machine at Hobby Shop, MIT

It is apparent on the run chart that the machine performed outside of the manufacturer's specifications ($\pm 0.001\ in$). However, it remains to be seen whether the leak would have a significant impact on the data analysis.

On analyzing the factorial design, it could be concluded that both the quality and z-offset are significant and so is their interaction due to inheritance. Inclusion of center-point data in the analysis highlighted a significant quadratic error with a p-value of 0.012. The significant curvature shows that a linear model is not sufficient to characterize the effects for this machine. Further work may include fitting a quadratic model using CCD.

Figure 10. Normal Plot of the Standardized Effects for HS

B. Across All Machines

Given the variability in results arising from different machines and the objective of characterization of machines on campus, Machine (C) was included as a factor in our factorial design. On analyzing this design, quality turned out to be the most significant factor with machine having the second most significant main effect. It was in line with the expectation given the difference in machine states and types.

The z-offset was found to be the least significant in affecting the final output. In the analysis of residuals, the data accurately follows the normal probability plot, indicating a proper normal distribution of variation in the output.

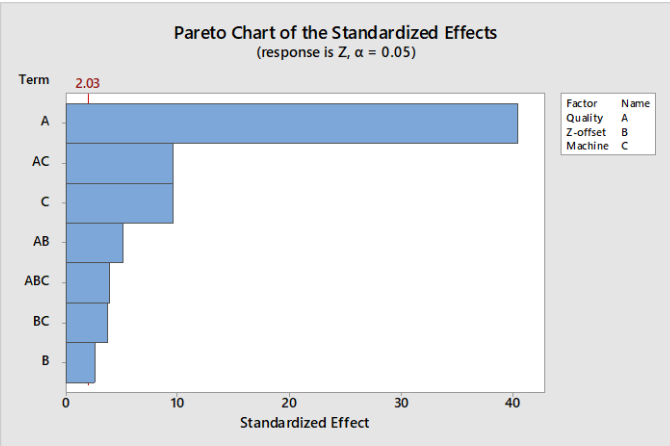

Figure 11. Pareto Chart for all Effects across all machines

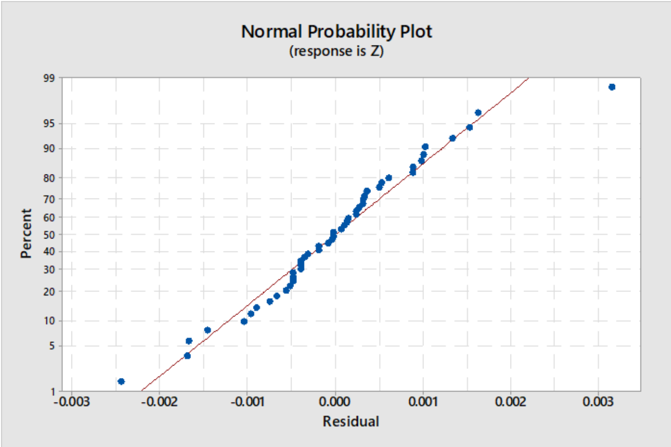

Figure 12. Normal Probability Plot for Residual Analysis

C. Expected Quality Loss (EQL)

After gaining an insight into the process and the effect of the different factors, it was important to choose the optimum factor setting for the cut. An attempt was made to minimize the absolute error from the nominal dimension and its standard deviation using the concept of quality loss. The technique essentially dictates that process quality doesn't plummet suddenly with a part being out of specifications, rather it progressively degrades due to the variation in process.

$$EQL = k\sigma_y^2 + k\left(\mu_y - y^*\right)^2 \qquad (1)$$

Where y is the output dimension and y* is the nominal dimension; σ and μ are the standard deviation and the mean of the sample set respectively; k is a scaling factor.

As shown in Eq (1), the expected quality loss takes into account the accuracy and precision of the part and translates it into a loss in quality. It was observed that the MW machine at Quality 5 and 0.06" offset was the optimum treatment with the lowest EQL. A scaling factor of $k = 10^5$ was used.

D. Grey Relational Analysis (GRA)

A popular technique in multiple attribute decision making, GRA is an alternative approach towards the selection of optimum factor setting. The procedure essentially normalizes the output based on the range of the dataset and the required target value to report Grey Relational Coefficients (GRC) for that setting and output.

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \qquad (2)$$

$$\xi_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(k) + \zeta\Delta_{max}} \qquad (3)$$

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \qquad (4)$$

Where $x_i(k)$ is the value after grey relational generation for the i^{th} treatment and the k^{th} output response; $y_i(k)$ is the value of the output response; the three responses considered are absolute error, standard deviation and cutting time. ξ is the GRC generated; $\Delta_{0i}(k) = \|x_0(k) - x_i(k)\|$; $\Delta_{min} = 0$; $\Delta_{max} = 1$; ζ is the distinguishing coefficient (0~1), a recommended value of 0.5 was chosen. γ is the GRG generated; n = number of output responses [5].

For this experiment, GRCs were found for the absolute error, its standard deviation and the cutting time of the machine to ultimately find a combined Grey Relational Grade (GRG) for each treatment. It was observed that MW at Quality 5 with 0.06" offset was the optimum treatment with the highest GRG coefficient.

TABLE III- EXPECTED QUALITY LOSS (EQL) & GREY RELATIONAL GRADE (GRG)

Quality	z-offset	Machine	EQL	GRG
1	0.06”	LMP	6.86	0.771
1	0.06”	MW	7.10	0.764
1	0.06”	HS	12.27	0.454
1	0.16”	LMP	5.10	0.784
1	0.16”	MW	15.44	0.629
1	0.16”	HS	16.19	0.433
5	0.06”	LMP	0.10	0.802
5	0.06”	MW	0.06	0.813
5	0.06”	HS	7.00	0.464
5	0.16”	LMP	0.31	0.768
5	0.16”	MW	0.30	0.760
5	0.16”	HS	19.95	0.384

VI. DISCUSSION

This experiment was designed to analyze the effect of three factors: quality, z-offset, and machine on dimensional accuracy. Individual machine analysis highlighted quality as the most significant factor influencing dimensional control of the machine, whereas z-offset is the least significant factor. This makes intuitive sense as the cutting speed increases at low quality setting resulting in inferior edge quality and dimensional control.

Based on the pooled analysis of all three machines, it can be concluded that quality significantly influences the dimensional accuracy followed by machine, whereas z-offset has negligible influence on the dimensional accuracy. This is reasonable given the dependence of dimensional accuracy on properties of machine, wear and tear of the machine, and cutting speed. A relatively new machine and machine with higher positional tolerance is expected to have better dimensional accuracy. However, it was surprising to find out that z-offset has negligible influence on the dimensional accuracy of the machine. This shows that there is no need to spend so much time accurately adjusting the z-offset.

Theoretically, Hobby Shop's MicroMAX waterjet should have the highest degree of control on dimensional accuracy for its higher positional resolution and rigid machine structure. However, the results suggested that the machine in LMP with quality 5 gave the best dimensional accuracy. This discrepancy in the results could be due to inordinate pressure drop caused by the nozzle leak.

VII. FUTURE WORK

If this project were to be continued, it’s recommended to conduct the experiment on Hobby Shop machine after nozzle replacement for more effective comparison of machine characteristics. Due to time constraints, the authors were limited to testing three machines. Characterizing other waterjet machines on campus, such as the one in the D-Lab or architecture lab will provide a more complete picture of waterjet capabilities at MIT.

Another scope of investigation would be to characterize the taper angle as a response to the experimental parameters. Measurements can be taken on the top and bottom of the coupon to characterize the taper angle. For designs requiring zero taper angle, cut parameters can be optimized to minimize the taper.

Another factor that would be interesting to characterize would be machine wear over time. This requires repeating the experiments at several points over a long period and to record the hours of operation and the time since last maintenance. The machines break down regularly; hence, characterizing the expected quality loss with respect to time since last maintenance can help develop a preventative maintenance model to prevent unexpected machine downtime.

Another interesting extension would be to characterize the minimum feature size resolvable on each machine as a result of the cutting parameters. The LMP and MW machine have linear positional resolution of 0.001” and the HS machine should have linear positional resolution of 0.0001”. This experiment would be carried out by cutting successively smaller features and characterizing the point at which a change in nominal dimension does not result in a change in cut dimension.

VIII. CONCLUSION

The OMAX 2626 located in MW is the best machine characterized to balance dimensional accuracy and cutting speed. The quality setting has the largest effect on cut dimension, followed by machine selection. The z-offset is much less significant, and for future experiments, only needs to be set near the manufacturer recommended 0.060 inch. The manufacturer optimized setting for quality 3 optimizes dimensional accuracy for the least cutting time. Although the Hobby Shop OMAX MicroMAX should have been the most accurate machine based on the manufacturer's specification, the broken nozzle hinders accurate dimensional control and therefore, the machine should be temporarily avoided.

APPENDIX

A. ANOVA TABLE FOR LMP

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.000308	0.000103	108.04	0.000
Linear	2	0.000308	0.000154	162.01	0.000
A	1	0.000304	0.000304	319.55	0.000
B	1	0.000004	0.000004	4.47	0.051
2-Way Interactions	1	0.000000	0.000000	0.10	0.753
A*B	1	0.000000	0.000000	0.10	0.753
Error	16	0.000015	0.000001		
Curvature	1	0.000013	0.000013	77.66	0.000
Pure Error	15	0.000002	0.000000		
Total	19	0.000324			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0009755	95.30%	94.41%	93.87%

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		1.99716	0.00022	9156.17	0.000	
A	0.008719	0.004359	0.000244	17.88	0.000	1.00
B	0.001031	0.000516	0.000244	2.11	0.051	1.00
A*B	-0.000156	-0.000078	0.000244	-0.32	0.753	1.00

Regression Equation in Uncoded Units

$$Y = 1.99716 + 0.004359\,A + 0.000516\,B - 0.000078\,A{*}B$$

B. ANOVA TABLE FOR MW

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.000447	0.000149	73.39	0.000
Linear	2	0.000435	0.000218	107.25	0.000
A	1	0.000431	0.000431	212.72	0.000
B	1	0.000004	0.000004	1.77	0.202
2-Way Interactions	1	0.000012	0.000012	5.69	0.030
A*B	1	0.000012	0.000012	5.69	0.030
Error	16	0.000032	0.000002		
Curvature	1	0.000006	0.000006	3.22	0.093
Pure Error	15	0.000027	0.000002		
Total	19	0.000479			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0014241	93.23%	91.96%	88.98%

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		1.99589	0.00032	6267.59	0.000	
A	0.010385	0.005193	0.000356	14.58	0.000	1.00
B	-0.000948	-0.000474	0.000356	-1.33	0.202	1.00
A*B	0.001698	0.000849	0.000356	2.38	0.030	1.00

Regression Equation in Uncoded Units

Y = 1.99589 + 0.005193 A - 0.000474 B + 0.000849 A*B

C. ANOVA TABLE FOR HS

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.001483	0.000494	352.88	0.000
Linear	2	0.001441	0.000720	514.05	0.000
A	1	0.001419	0.001419	1012.57	0.000
B	1	0.000022	0.000022	15.54	0.001
2-Way Interactions	1	0.000043	0.000043	30.54	0.000
A*B	1	0.000043	0.000043	30.54	0.000
Error	16	0.000022	0.000001		
Curvature	1	0.000008	0.000008	8.19	0.012
Pure Error	15	0.000015	0.000001		
Total	19	0.001506			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0011837	98.51%	98.23%	97.73%

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		2.00011	0.00026	7556.55	0.000	
A	0.018833	0.009417	0.000296	31.82	0.000	1.00
B	0.002333	0.001167	0.000296	3.94	0.001	1.00
A*B	0.003271	0.001635	0.000296	5.53	0.000	1.00

Regression Equation in Uncoded Units

Y = 2.00011 + 0.009417 A + 0.001167 B + 0.001635 A*B

D. ANOVA TABLE FOR ALL MACHINES

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	11	0.002440	0.000222	188.95	0.000
Linear	4	0.002129	0.000532	453.27	0.000
A	1	0.001919	0.001919	1634.59	0.000
B	1	0.000008	0.000008	6.63	0.014
C	2	0.000202	0.000101	85.93	0.000
2-Way Interactions	5	0.000288	0.000058	49.06	0.000
A*B	1	0.000031	0.000031	26.30	0.000
A*C	2	0.000235	0.000118	100.20	0.000
B*C	2	0.000022	0.000011	9.30	0.001
3-Way Interactions	2	0.000024	0.000012	10.03	0.000
A*B*C	2	0.000024	0.000012	10.03	0.000
Error	36	0.000042	0.000001		
Total	47	0.002482			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0010835	98.30%	97.78%	96.97%

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