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Grinding Mechanisms and Effect of Coolant Application in Thin Precision Slicing of Electronic Materials

A Major Qualifying Project Proposal
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WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science

by

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Robert Leblanc-Shoemaker

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Gina Melendez

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Approved:

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Professor Yiming Rong

Abstract

Various types of grinding and abrasives are used when working with electronic materials. Based on the necessary parameters, multiple nozzle designs were created to incorporate Saint Gobain's patented nozzle profile on the high precision slicing machine used there. The standard nozzle and the new designs were analyzed after slicing glass wafers to allow for the analysis of the following to determine the best design: Chip removal rate/Kerf width; Wear on the grinding wheel; Power; Chip size; and Bottom/top edge comparison.

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1. Introduction

The grinding of electronic materials is a high precision process that must take into account as many variables as possible. This particular project will focus on the variables associated with the application of coolant to the grinding process. The project will test the effects that coolant and the different methods of application have on process efficiency, chippage, temperature, and the wear on the grinding wheel. The results of the tests will be used to design an optimum coolant system that can be applied to the grinding machines at Saint Gobain.

The project will proceed by first designing the best possible single nozzle system for grinding processes. This will include designing and testing the effects of the nozzle shape, the pipe system, the system pressure, and filtering devices that reduce the turbulence in the coolant flow. Once the optimum design for a single nozzle system has been finalized the next step is test multiple nozzle systems and to determine if they have a significant impact on the grinding process. After this a final system will be designed based on all of the results gathered. The final system will be one that improves both the efficiency of grinding electronic materials and the final product quality and will be presented to Saint Gobain for application on their grinding machines.

2. Literature Review

2.1. Abrasives

Abrasives are used in processes in which the accuracy requirements are too high; or in many cases the work piece is too hard or too brittle to be worked on by just the standard machining processes, like milling or drilling.[1] Abrasives in general are small pieces of materials which no define shape and are nonmetallic, similar to sand. They are used to remove material in the form of chips. Abrasives are commonly used in the finishing process to buff or polish materials to remove any imperfection on the work piece surface.

There are many characteristics considered when choosing an abrasive. The hardness of the abrasive will determine the type of material it can be used for. The abrasive's friability, its ability to break, is also evaluated; this characteristic is used to determine how sharp the abrasive will be overtime. The size of the abrasive is also used to describe how much materials the abrasive will remove. The finer the grain, the higher the grit number is, and the smaller the amount of material it can remove.

Some of the abrasive used in manufacturing are aluminum oxide, silicon carbide, cubic boron nitride and diamond.[2] For our project we will be focusing on diamond abrasives.

2.2. Bonded Abrasive Grinding Wheels

Grinding wheels, or stones, can form naturally or can be formed synthetically. Natural grinding stone can be found under water. These natural grinding stones would form underwater where grain and quartz sand were present. With the natural disposition of the water, quartz grains would bond together. Since the grains were various sizes, from very fine to coarse, the resulting stones would be of various strengths.[3] Given the impurities found in natural grinding stones, synthetic grinding wheels are most commonly used. For our project, will be working with

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[1] Kalpakjian, Serope and Steven R. Schmid; Manufacturing Engineering and Technology, 4th Edition; Prentice-Hall Inc.. 2001; pg 704
[2] Kalpakjian, Serope and Steven R. Schmid; Manufacturing Engineering and Technology, 4th Edition; Prentice-Hall Inc.. 2001; pg 706
[3] Members of the Executive and Technical staffs of the Norton Company; Grinding,Wheels, Machines, Methods; The Plimpton Press. 1922; pg 12-13

synthetically bonded diamond abrasive grinding wheels. Figure 1 below is a "schematic illustration of a physical model of a grinding wheel, showing its structure and wear and fracture patterns" of a simple grinding wheel.[4]

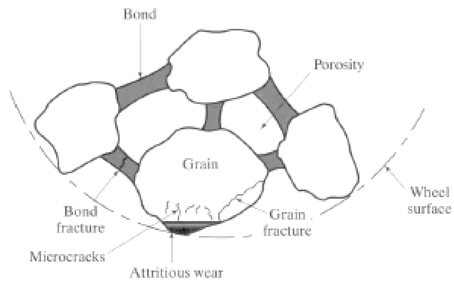

Figure 1- Grinding Wheel Schematic

Grinding wheels are made by combining an abrasive with a bonding agent. In addition to the grain size, grinding wheels are classified by bond types and grades. Some bonding types include vitrified, resinoid, rubber and metal. Vitrified bonds are composed of feldspar and clays. Resinoid bonds are composed of thermosetting resins. Rubber bonds are composed of crude rubber and sulfur. Metal bonds are composed of powdered metals. Once these binding agents are combined with the abrasives in molds, they are compressed and heated together with varying amount of pressure and heat, depending on type of bonding agent to create the grinding wheel. [5]

The grade of the wheels is determined by the type and amount of bonding agent in the wheel. The grade is used to describe the strength of the bonds. The harder the wheel, the stronger the bonds are, and the greater the amount of agent in the mixture. The resulting pores of the grinding wheels allow for material be removed from grinding area while keeping the materials from over heating, altering the final result of the cut. If the chips are not removed properly, they will be ground back into the material altering the final desired result.

2.3. Grinding

There are multiple methods used for cutting materials. For our project, we will be focusing on the grinding process for cutting/slicing materials. In general grinding is referred to a as a chip removal process, since abrasives create chips when used on materials; we will be grinding c-

[4] Kalpakjian, Serope and Steven R. Schmid; Manufacturing Engineering and Technology, 4th Edition; Prentice-Hall Inc.. 2001; pg 708
[5] Kalpakjian, Serope and Steven R. Schmid; Manufacturing Engineering and Technology, 4th Edition; Prentice-Hall Inc.. 2001; pg 708-711

plane sapphire. During the grinding process, the grinding wheels experiences many type of wear similar to the wear a drill bit or tool tip experiences over time in a vertical mill. These changes in the grinding wheel alter the desired cut of the work piece.

Attritious grain wear is when the grinding wheel develops a dull point, referred to as a wear flat[6], where it was originally a sharp abrasive. This is due to the chemical make up of the materials used in the grinding wheel and the material of the work piece. If two materials are likely to react chemically, then they should not be used together. During the grinding process, pieces of the materials fall off the grinding wheel and are removed as the chips from the work piece are removed; this is referred to as grain fracture. Depending on the strength of the bond, the dull grains will easily fall off the grinding wheel; this in referred to as bond fracture. The stronger the bond, the harder it is for the grain to come off, on the other hand, if the bond is too weak, the grains will easily fall off whether it is dull or not.

Grain and bond fracture are natural for a grinding wheel to experience. This is the natural method by which a grinding wheel sharpens itself. Dull grinding wheels ruin the work piece and are very inefficient. As the wheel becomes duller, the temperature at the point of contact between the grinding wheel and work piece increases. The increase in temperature can cause sparks, tempering, burning and heat checking. Sparks are heated chips that come off the materials. If chips are not removed properly, they will stick on the surface of the work piece. In addition, the temperature can cause the work piece to soften. As the work piece softens, it deforms during the grinding process. Burning also alters the work piece as a result of a chemical reaction on the surface, for example oxidation. Heat checking is when the work piece cracks as a result of the high temperature conditions in which it is being grinded.[7] The temperature is controlled by the coolant system used during the grinding process.

2.4. Coolant Systems

[6] Kalpakjian, Serope and Steven R. Schmid; Manufacturing Engineering and Technology, 4th Edition; Prentice-Hall Inc.. 2001; pg 717
[7] Kalpakjian, Serope and Steven R. Schmid; Manufacturing Engineering and Technology, 4th Edition; Prentice-Hall Inc.. 2001; pg 716

Because our project focuses on the application of coolant to grinding processes a review of why coolant is used as well as what variables in a coolant system affect its application. In cutting and grinding processes fluids are used both as coolants and lubricants, often at the same time. The effects that fluid use yields include: improved tool life and surface finish, reduced forces and energy consumption, reduction of thermal distortion, washing away chips, and protection from environmental corrosion.[8] At the high cutting speeds which we will be focusing on cooling the tool and work piece is the most important factor so our experiments and research will be focused on coolant application.

The most important piece in a coolant system is the nozzle that directs the coolant into the work zone. The condition of the coolant flow into the work zone effects how well the coolant performs. If the nozzle causes turbulence in the coolant flow then a portion of the coolant will not enter the work zone, thus increasing the amount of coolant required. Conversely if the flow is uniform with very little turbulence then the maximum benefit of coolant application can be achieved with the least amount of coolant used. Previous research, including an MQP, has already determined the most effective nozzle, illustrated in Figure 2. This improved nozzle allows more effective coolant application which increases the benefit of coolant application.

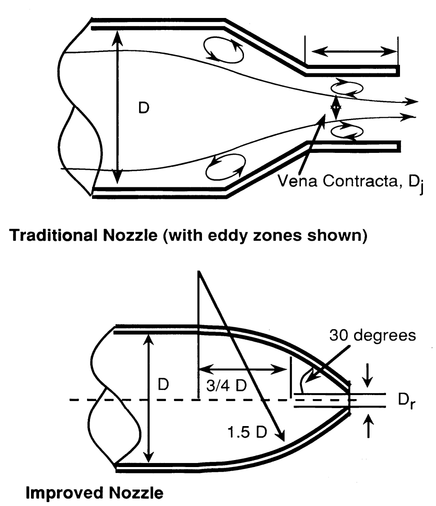

Figure 2- Traditional and Improved Nozzle Design

[8] Kalpakjian, Serope and Steven R. Schmid; Manufacturing Engineering and Technology, 4th Edition; Prentice-Hall Inc.. 2001; pg 585-586

While the nozzle has the most immediate impact on the coolant flow and thus its effectiveness, the flow of the coolant through the pipe system factors in as well. Because turbulence hinders coolant application, reducing it within the pipe system before it reaches the nozzle is ideal. One method of achieving this is to install a flow conditioner inside the pipe system. A flow conditioner is a small filter like with "tunnels" through it in one direction. It reduces turbulence by allowing only those particles that are traveling in line with its "tunnels" to pass through. A flow conditioner and its effects are illustrated below in Figure 3.

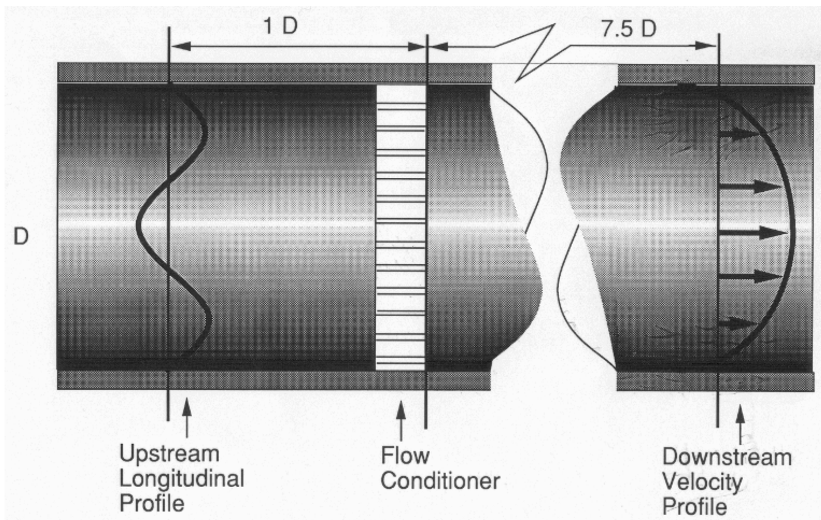

Figure 3- Flow conditioner

The turbulence in a pipe system can also be optimized by proper design. A typical fluid mechanics textbook will describe the difference between a turbulent and smooth, or laminar, flow by use of the Reynolds number, Re, of that flow. The Reynolds number is defined as the ratio between the density and the dynamic viscosity multiplied by the average velocity in the pipe and the diameter of the pipe ($Re = (\rho * V * D)/\mu$).[9] In order for the pipe system to have a laminar flow the Reynolds number must not exceed 2100. For our purposes the velocity will have to be very high in order to match the speed of the cutting wheel which could mean that a fully laminar flow might not be possible. However, the diameter of the piping in the machine we will be using is very small, which may counteract the high velocity.

[9] Munson, Bruce R. et al; Fundamentals of Fluid Mechanics, 5th Edition; John Wiley & Sons, Inc., 2006; pg 404

Yet another factor affecting the flow in the pipes are the bends in the pipe. The effect that a bend has on the velocity profile of a flow is illustrated below in Figure 4.

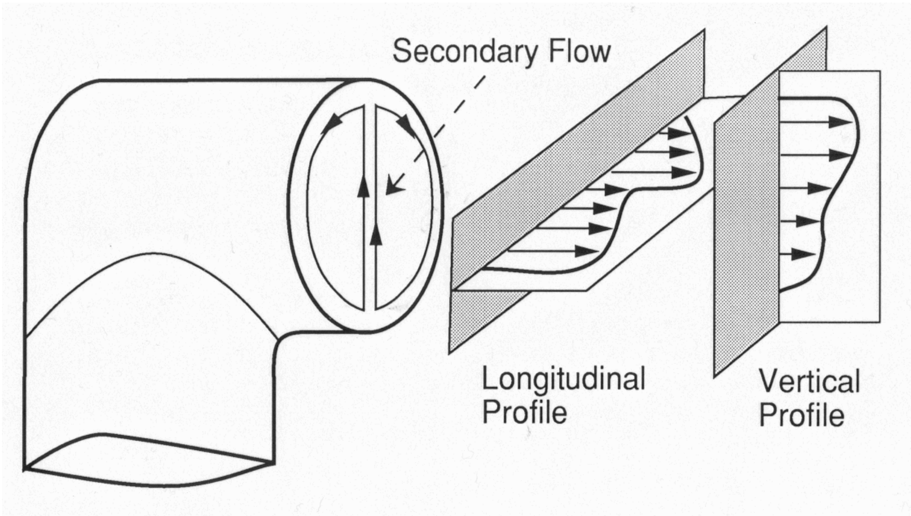

Figure 4- Bend effects

The bend causes undesirable changes in the velocity profile that affect the performance of the coolant system. The effects of the change are demonstrated in Figures 5 and 6 comparing a nozzle with bends and a nozzle without bends.

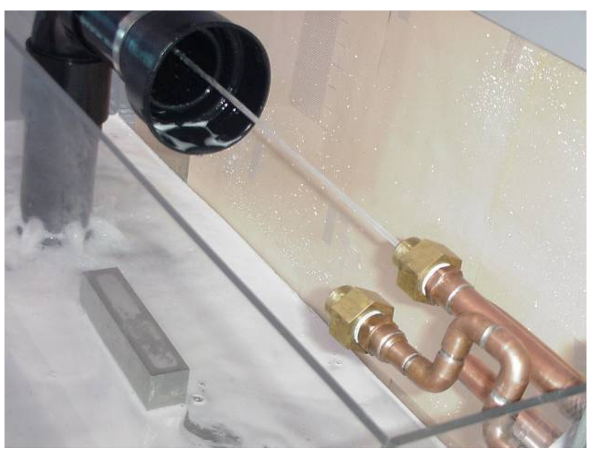

Figure 5- Nozzle without bend

Figure 6- Nozzle with bend

There are many factors that must be considered in order to design an optimized coolant system. Many of these factors have been tested independently, however, there has been little work done on optimizing the full system, which is what this project will do.

2.5. Loadpoint MicroAce Series 3

Loadpoint MicroAce Series 3 is used for precision slicing of electronic materials at Saint Gobain. The machine is capable of slicing materials in the x, y, and z-axis with high accuracy due to the LDS4 Air Bering spindle (Figure 8) and Theta axis Air Bearing unit with low spindle vibration, this also decreases the amount of chips produced during the grinding process.[10]

Figure 7- LDS4 Air Bearing Spindle

High precision is also due to the combination of servo motors used; a stepless DC motor for the x-axis, a DC servomotor for the y-axis and an acoustic datum sensor for the z-axis. The work piece used can be in the shape of a square, rectangle or circle. The MicroAce Series 3 is a very

[10] Microace Series 3 Brochure http://www.loadpoint.co.uk/documents/MicroAce_Brochure.pdf

easy machine to use. The instructions are very easy to follow and the error messages are easy to understand.

2.6. Evaluation of Current Nozzle

Due to the fact that we have not had time in the lab, our observations and background research are based on just watching the nozzle spray the coolant while the grinding wheel is not actually cutting the material. The nozzle/jet that is currently being used on the Microace does not deliver the coolant in a very efficient manner, in our opinion, considering that there is coolant that sprays out of the end outlet, on both sides, sprays off to the outside of the part and does not look as if it would aid in the removal of the chipagge. The nozzle does not incorporate the ideal nozzle specifications stated earlier. As you can see in the following picture of the nozzle, from the physical characteristics it would seem that the water interacts with a sharp edge which in turn creates turbulence within the fluid being delivered to the grinding application. However, given our limited access we are unsure of what the inside passages for the coolant actually looks like. The second picture is a close up of the jet. As you can see the outlet of the jet is so spaced out from the center of the blade that when the coolant is being sprayed, is doesn't contribute much while it's grinding. This nozzle is referred to as the "standard jet" by LoadPoint, the manufacturer of the Microace.

Figure 8- Standard Jet

Figure 9- Standard Jet mounted on MicroAce

2.7. Current Coolant Flow Analysis

One of the most important areas to consider is the flow of the coolant once it is on the grinding blade. The idea situation would be that the coolant flows up smoothly at the end of the blade that is not doing the cutting. Figures 12 and 13 show the current flow of the coolant on the grinding wheel while in use.

Figure 10- Coolant flow 1

Figure 11- Coolant flow 2

The flow is very turbulent and has many gaps. Our goal with our redesign is to focus the flow on the grinding wheel to ensure chips are removed and the temperature of the part and grinding wheel are as low as possible.

2.8. Glass Wafers

Originally we were going to be using C-plane sapphire but that was too expensive for our project. The next type of material we were going to use was Bororfloat wafers, but given our limited time to work on the project, our representative at Saint Gobain decided we would be able to work with Soda lime glass wafers and would obtain similar results and it was readily available.

Glass in general is very hard and very fragile. The melting point for Soda lime glass is about 1000°C, which must be considered during grinding to ensure that the temperature at and around the grinding wheel's contact with the wafer do not reach or exceed the melting point temperature to ensure that the quality of the final part is not deformed. It comes in many different chemical compositions and is used for many applications, such as electrical transmission and fiber optics, just to name a few. Soda lime glass is the glass that is used more for commercial purposes, such as drinking glasses. [11] "The composition of soda-lime glass is normally 60-75% silica, 12-18% soda, and 5-12% lime." (Lenntech Glass) Below is a table with the technical properties provided from the company the wafers were purchased from, Silicon Quest International, Inc.

Thickness: 125mm ±0.2mm
Double-Side polished
TTV: <40µm
Surface Roughness (Å°): <20
Surface Quality (MIL-0-13830): 60/40
Flatness (µm / 25.4mm): <4
Parallelism (µm / 25.4mm): <5
Machine Chamfered edges
Maximum edge chip (1mm): 0.1

[11] What is glass and how is it produced? Lenntech Glass http://www.lenntech.com/Glass.htm

Table 1- Soda lime wafer technical specifications

2.9. Coolant Nozzle Design and Effectiveness Evaluation MQP

Last years MQP investigated the optimum configuration of Saint Gobain's improved nozzle design with a specific focus on the ratio of the inlet diameter to the outlet diameter. They recommended that nozzles have an outlet to inlet diameter ratio of less than 0.30 to produce the most cohesive flow with the highest velocity. This however means that there is a drop in the volumetric flow rate. As a result the group recommends that multiple nozzle designs should be used to maintain a high flow rate. They also recommend that length of pipe be added to the front of the nozzle that will increase jet cohesion. We will take these findings into consideration when designing our own nozzle to manufacture and test.

3. Methodology

Based on Saint Gobain's previous research and analysis of effective nozzle designs, the ideal nozzle geometry has already been determined. We will calculate the necessary fluid dynamic calculations to determine the specs for our final design. Given the limited time we have with Saint Gobain and the machine's availability we will conduct both our testing for the current nozzle and our proposed nozzle. We have decided to use Gambit, a drawing program, and FLUENT, a fluids analysis program, to determine which of our design provides us with the necessary velocity and flow profile we need for our system. The final design will be machined at WPI and will be implemented onto the MicroAce for analysis.

Using the current nozzle design and associated systems we will test how the coolant affects the temperature of the work piece, the chip removal rate, and wear on the grinding wheel. This will be the baseline against which all other tests are compared. The next step will be to test how the our new nozzle incorporating the ideal nozzle profile affects all of the previously mentioned categories as compared to the original nozzle design.

Our experiments will be conducted using a diamond wheel slicing machine at Saint Gobain. We will be using glass wafers as our experimental material. As we perform our experiments the machines at Saint Gobain are equipped with a number of sensors that can detect and display all the relevant data that we require (i.e. temperature, wheel load, etc.). All of this data will compared against current industry standards to measure any improvement.

4. Nozzle Design

4.1. Preliminary Calculations

We know that the maximum flow rate of the machine is 3 L/min. We also know that the inside diameter of the pipe is .0025 m. Using this information we can calculate the velocity of the water inside the pipe which equals 10.19 m/s. Taking this information as well as other known properties of water (density = 1000 kg/m^3 and dynamic viscosity @ 21C = 9816 N*s/m^2) we then can calculate the Reynolds number to determine if the flow is turbulent or laminar. In this case the Reynolds number equals 26,000, which means the flow will be turbulent.

We can now begin making calculations for our nozzle design. Ideally we want the exit velocity to match the speed of the wheel. The wheel spins at 10,000 rpm and is
.1822 m in circumference, thus its tangential speed is 30.4 m/s. The ideal nozzle design does not include any specifics for the outlet diameter (D_r) however using drill bits used to manufacture these ideal nozzles we measure the D_r to be .00163 m. Using this information we calculated the theoretical exit velocity to be 24.0 m/s. This number is likely to change under real world conditions. This change will guide our decision on whether or not a pump will be needed to increase the velocity of the water.

4.2. Summary of Calculations

Max flow rate= 3 L/min * 1min/60 sec = .05L/s * 10^{-3} m^3/L = 5*10^{-5} m^3/s

Inside diameter = .0025 m

Max velocity in pipe = (5*10^{-5} m^3/s)/(π*(.0025/2)^2) = 10.19 m/s

Density = 1000 kg/m^3

Dynamic viscosity @ 21C = .9816 N*s/m^2

Reynolds number = (1000 kg/m^3 * 10.19 m/s * .0025 m)/(.9816 N*s/m^2) = 26,000 (turbulent flow)

Wheel speed: 10,000 rpm

Wheel diameter = 2.283 in * .0254 m/in = .05799 m

Wheel circumference = .05799 m * π = .1822 m/rotation

Tangential wheel speed = 10,000 rpm * .1822 m/rotation * 1 min/60 sec = 30.4 m/s

$A_1 = 4.90*10^{-6}\ m^2$

$V_1 = 10.19$ m/s

$A_2 = 2.08*10^{-6}\ m^2$

$V_2 = (A_1*V_1)/A_2 = 24.0$ m/s

4.3. Proposed jet designs

To evaluate our proposed designs for the improved nozzle, we decided to analyze the flow using FLUENT and Gambit; FLUENT is commonly used to model flow and Gambit is used to create the geometry for FLUENT. This analysis was the most quantitative method to evaluate our designs to determine the best design for our application. There were road blocks when we originally started working with FLUENT and Gambit since neither of us had ever working with the programs; we set-up a training session to familiarize ourselves with the programs to evaluate our designs.

We developed two different designs that incorporated Saint Gobain's patented nozzle profile. Although both designs may look the same on the outside, it is the internal geometry that is different. The first design profile is shown in the figure following. This design has the flow entering the nozzle at the back of the nozzle, rather than coming from the top. The design incorporates a straight route of flow for the coolant to reduce the creation of turbulent flow within the nozzle. The second design profile is shown in the figure following. This design has the flow entering the nozzle from the top and has the coolant coming into a reservoir in the vertical direction before entering the horizontal passage with the patented nozzle profile. This design incorporates a reservoir to add in additional pressure to increase the speed of the flow once the coolant exits the nozzle.

The speed of the coolants once it exists has to overcome the air barrier created by the grinding wheel that is slicing to allow the coolant to add in the grinding process. As previously mentioned in our calculations section, the ideal exit velocity of the coolant has to be at least 30.4 m/s to overcome the wheel's tangential speed. The flow of the coolant delivered to the nozzle is controlled by an outside source which limits the flow to a max of 3L/s. The outcome of this nozzle design will also determine whether the addition of a pump is needed to ensure the necessary exit velocity is obtained.

4.3.1. Design One Analysis

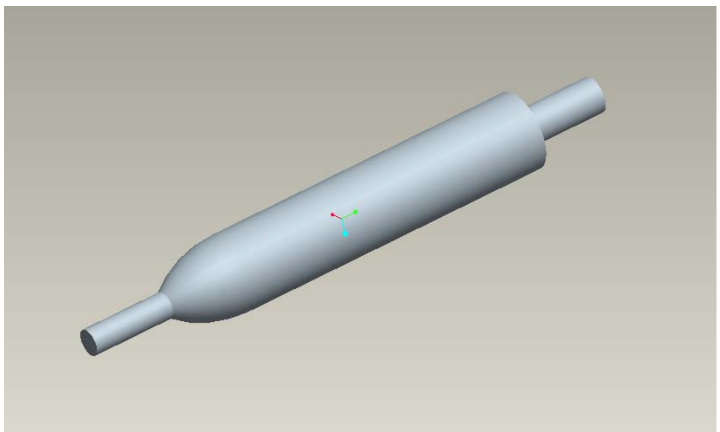

Figure 12- Internal Design 1

As previously mentioned, this design incorporates a straight horizontal flow of the coolant from the point of entrance to the point of exit. The design was analyzed with different coolant inlet velocities, starting from 0.5 liters per second up to the max of 3 liters per second; these values were converted to the proper meters per second values for the proper analysis results. Screen shots of the FLUENT analysis are included in the Appendix. Below is Table 2 that displays the inlet velocity and the exit velocity of the coolant with this design.

Coolant Setting (Liters/second)	Inlet Velocity (Meters/second)	Exit Velocity (Meters/second)
0.50	1.70	5.17
1.00	3.40	10.3
1.50	5.96	18.1
2.00	6.79	20.7
2.50	8.49	25.9
3.00	10.2	31.0

Table 3- Results from FLUENT

Although this design meets matches the necessary exit velocity needed to overcome the wheel's tangential velocity, we feel that we need to have a design that has a significant value above the needed speed so that we can account for any variability that might exist.

4.3.2. Design Two Analysis

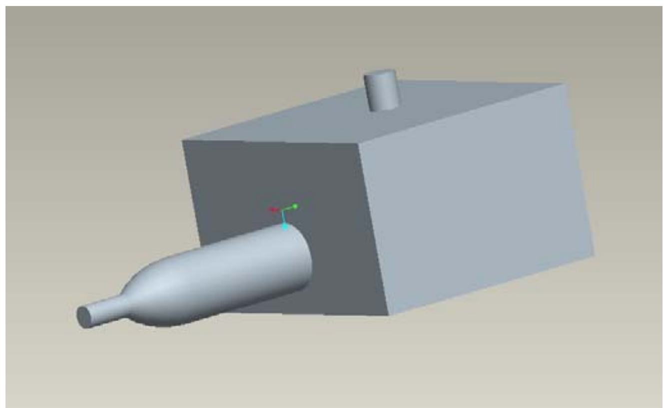

Figure 13- Internal Design Geometry 2

This design includes a reservoir for the coolant to fill prior to exiting the nozzle. The point of this reservoir is to increase the pressure of the coolant, which in turn would increase its exit velocity. However, FLUENT Analysis for this model is very complicated. As a result, we machined both nozzle types to determine which design would be the best for this grinding application.

5. Testing Methodology

In order to test the effectiveness of the new nozzle design we will look at several factors of the cutting process. We will determine how much material the slicing wheel is removing by measuring and comparing the Kerf width (width of cut) and also measuring the chippage on the wafers. In order to determine the wheel wear, we will evaluate the power usage of the grinding wheel during the testing. The grinding wheel used for the testing shall remain the same. The grinding wheel used will be a diamond blade with a diameter of 58.11mm and a width of .3031mm.

We will start by testing with the current nozzle in order to set a baseline for comparison with the new nozzles. The same testing parameters will be used with the new nozzles to determine which nozzle provided the best results, which in our case would be a decrease in kerf widths and a decrease in the size of chippage on the edges of the cut.

The glass wafers will be attached to tacky film and mounted on the precision slicing machine. Two wafers were made for the preliminary testing. The testing will include three feed rates of 5mm/s, 10mm/s, and 20mm/s. The first wafer will consist of 5 lines at 5mm/s and 27 lines at 10mm/s. The second wafer will consist of 10 lines cut at a feed rate of 20mm/s. The coolant flow to the nozzles will be tested at 1L/min, 2L/min, and 3L/min.

Once the wafers are cut, the kerf width and chippage will be measured with a microscope. The average and maximum chippage measurements will be taken at a point in the beginning of the slice, two random points along the same line, and at the end of the line. The power usage will be obtained from the sensors incorporated in the precision slicing machine. The same procedure will be performed on the wafers that are cut with the new nozzles in place.

Data from the 3 tests will be compared to determine if the new designs actually increase the efficiency of the grinding process and maintain the desired final product quality.

6. Testing Results

6.1. Benchmarking Results

The testing was performed as specified, however, due to the additional machines in the grinding center at Saint Gobain, the flow rate to the nozzle was tested at only 1L/min since all the machines are connected to the same source.

6.1.1. Feed rate of 5mm/s

The data obtained from the cuts at 5mm/s are located in the Table 4.

Line on Wafer 1		Chippage								Kerf Width			
		Beginning		1		2		End					
		Avg	Max	Avg	Max	Avg	Max	Avg	Max	B	1	2	E
1	Top	0.023	0.051	0.023	0.047	0.024	0.059	0.024	0.051	0.312	0.306	0.310	0.313
	Bottom	0.018	0.062	0.022	0.051	0.021	0.065	0.020	0.051				
3	Top	0.038	0.074	0.028	0.031	0.026	0.046	0.032	0.680	0.295	0.300	0.307	0.317
	Bottom	0.055	0.090	0.047	0.084	0.042	0.105	0.044	0.076				

Table 3- Results from feed rate 5mm/s

The average size of the chippage has little variation along the cut. However, the values obtained on line 3 on the bottom are much higher than those on the top of that same line. This can be caused by chippage from previous points on the cut that were not removed from the cutting area by the coolant jet.

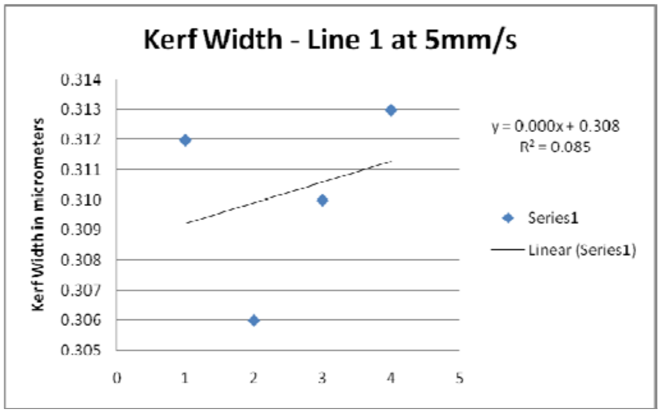

Figure 14- Kerf Width Variation on Line 1 at 5mm/s

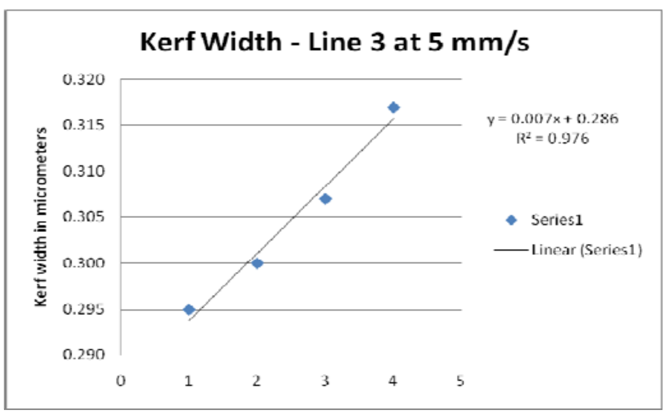

Figure 15- Kerf Width Variation on Line 3 at 5mm/s

Noting the points in line 1 versus the points in line 3, it is clear to see that the variation in kerf width is greater in the first cut than in the second pass. This variation is due to the wear on the grinding wheel. Since this was the first cut for the grinding wheel on the glass wafers, the wheel was not uniform. After the first couple of passes, the grinding wheel sharpened itself as it was performing the cut. Although there was variation in the kerf width, it increased in a somewhat uniform manner. The overall variation is due to chippage in the path of the cut and the heat buildup during the process which causes the grinding wheel to slightly expand. Figure 16 has the power usage for all the lines cut at 5mm/s.

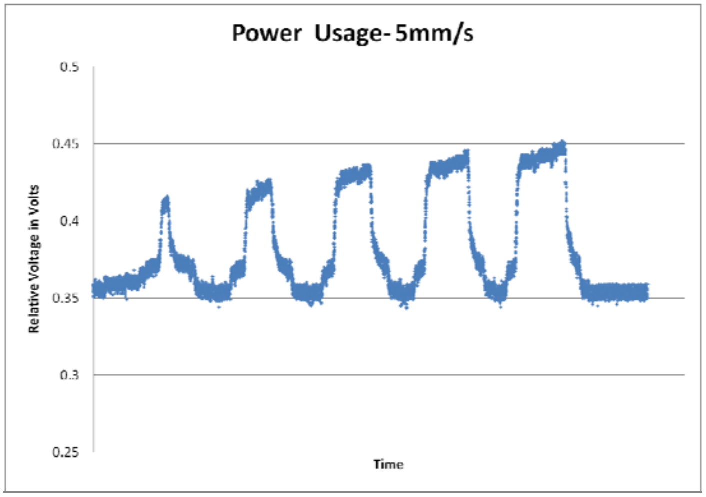

Figure 16- Power Usage at 5mm/s

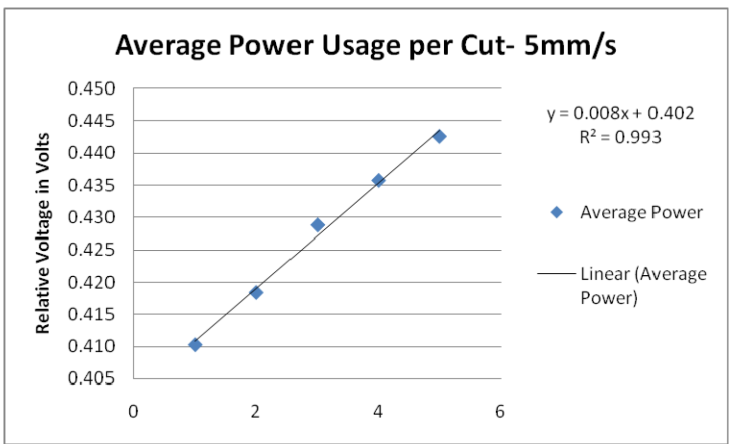

Figure 17- Average Power Usage at 5mm/s

The power is increasing at a constant rate since the grinding wheel is slowly wearing away.

6.1.2. Feed rate of 10mm/s

The data obtained from the cuts at10mm/s are located in the Table 4.

Line on Wafer 1		Chippage								Kerf Width			
		Beginning		1		2		End					
		Avg	Max	Avg	Max	Avg	Max	Avg	Max	B	1	2	E
5	Top	0.034	0.065	0.037	0.080	0.028	0.059	0.033	0.066	0.301	0.298	0.312	0.323
	Bottom	0.023	0.059	0.033	0.071	0.029	0.055	0.026	0.055				
7	Top	0.026	0.061	0.020	0.038	0.025	0.050	0.020	0.370	0.301	0.306	0.310	0.322
	Bottom	0.037	0.070	0.026	0.049	0.029	0.053	0.034	0.067				
9	Top	0.034	0.078	0.016	0.031	0.020	0.037	0.014	0.056	0.300	0.312	0.317	0.317
	Bottom	0.031	0.076	0.035	0.065	0.030	0.056	0.038	0.061				
11	Top	0.033	0.052	0.026	0.056	0.022	0.053	0.028	0.074	0.302	0.310	0.309	0.323
	Bottom	0.031	0.076	0.043	0.076	0.024	0.056	0.029	0.063				
13	Top	0.024	0.055	0.016	0.061	0.020	0.045	0.020	0.075	0.310	0.319	0.320	0.313
	Bottom	0.026	0.064	0.028	0.074	0.028	0.075	0.034	0.077				
15	Top	0.020	0.040	0.017	0.056	0.017	0.051	0.018	0.045	0.310	0.314	0.316	0.319
	Bottom	0.038	0.093	0.029	0.056	0.030	0.062	0.027	0.059				

Table 4- Results from feed rate 10mm/s

The chippage for the cuts at 10mm/s have a lot of variation through all the cuts. Comparing all the values obtained, it is looks like that at the end of cut 13 the variation starts to level off and the cut at line 15 is most consistent.

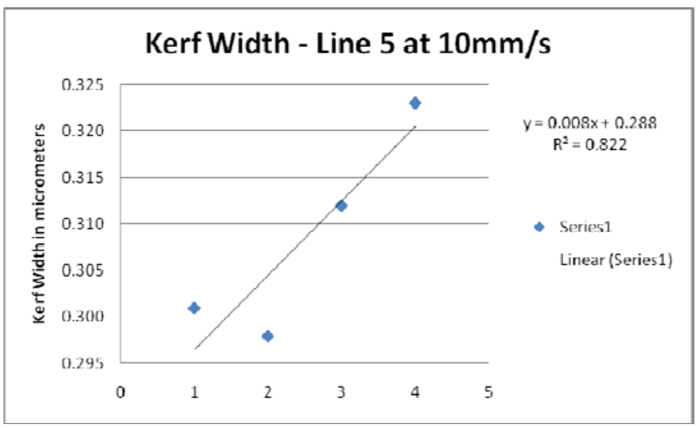

Figure 18- Kerf Width Variation on Line 5 at 10mm/s

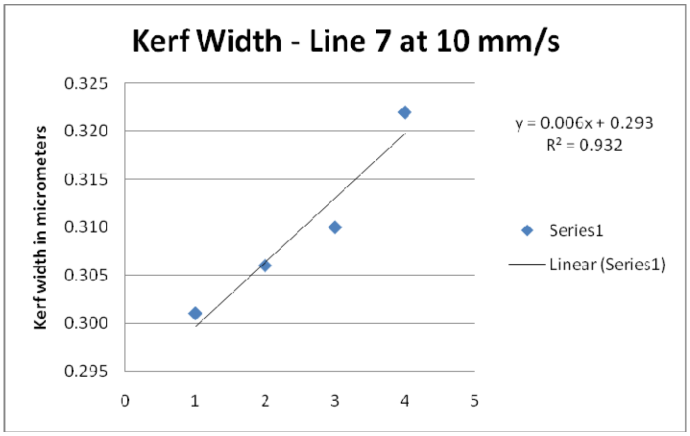

Figure 19- Kerf Width Variation on Line 7 at 10mm/s

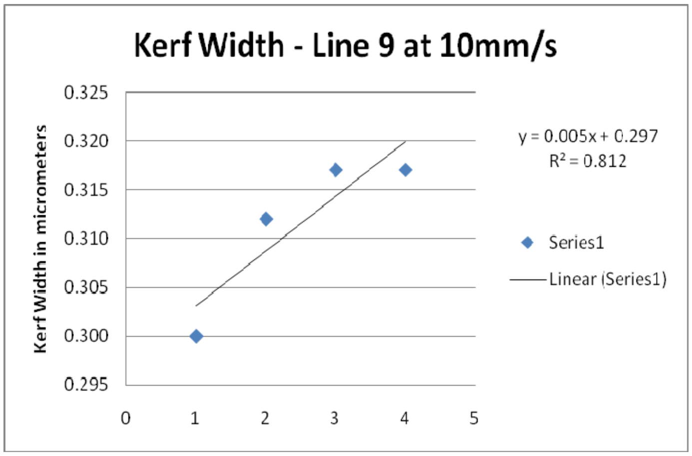

Figure 20- Kerf Width Variation on Line 9 at 10mm/s

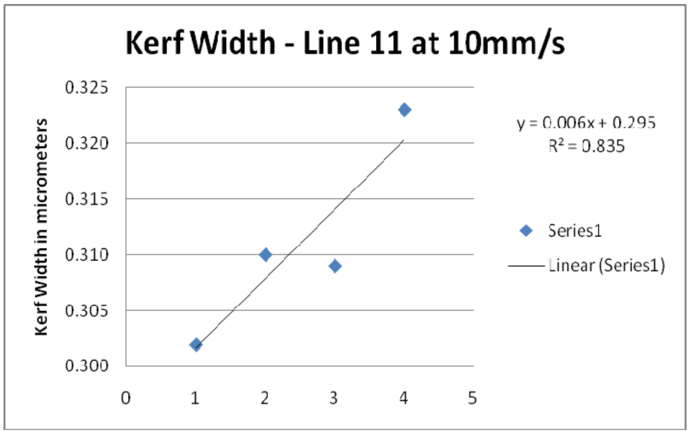

Figure 21- Kerf Width Variation on Line 11 at 10mm/s

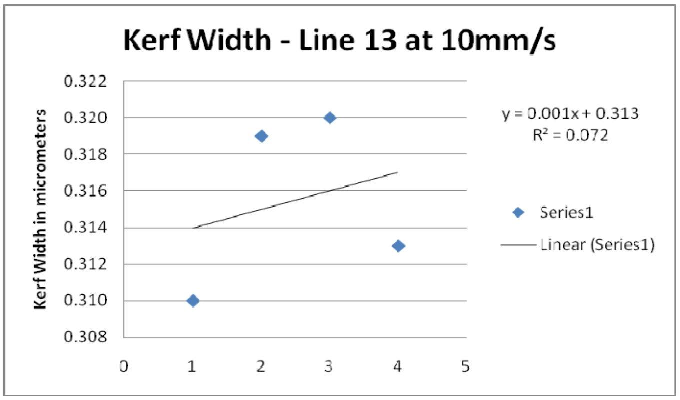

Figure 22- Kerf Width Variation on Line 13 at 10mm/s

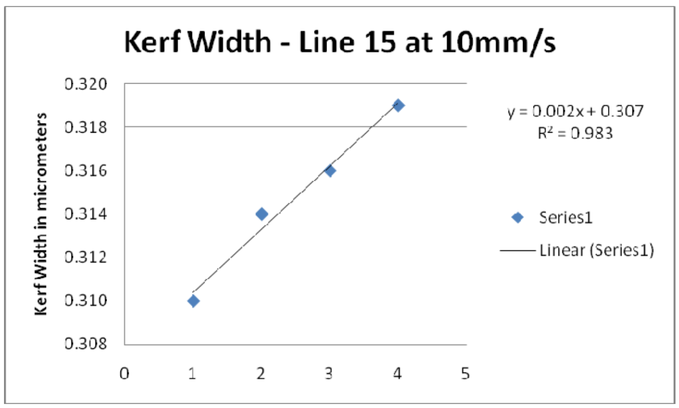

Figure 23- Kerf Width Variation on Line 15 at 10mm/s

Comparing all the kerf width trend lines, the wear on the grinding wheel's affect on the cut is noticed much better when looking at the trend lines than just the data obtained from the chippage. In the middle of line 13, the grinding wheel wear must have reached the point where it reached a point of dullness where new diamonds were exposed and reached a steady state for grinding at this feed rate. This is evident in the power usage for this feed rate, which is shown in Figure 24.

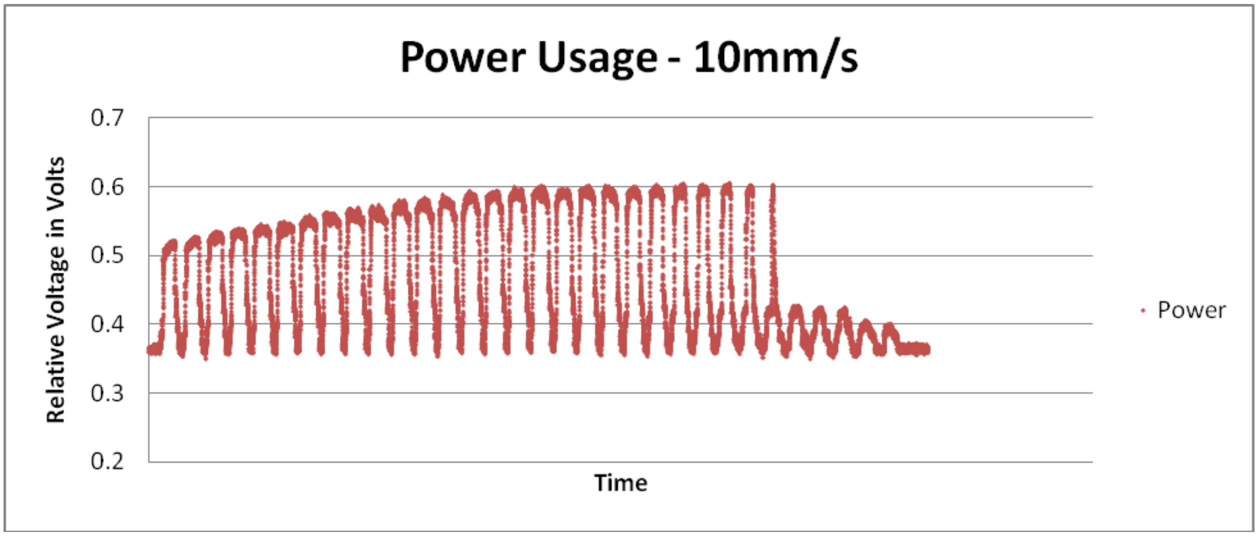

Figure 24- Power Usage at 10mm/s

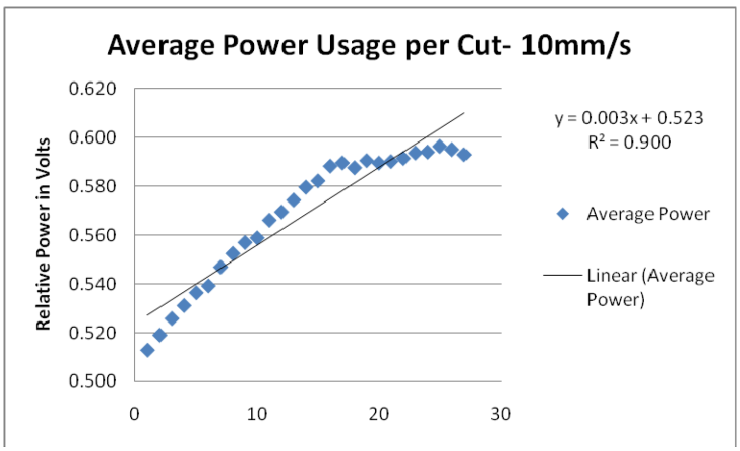

Figure 25- Average Power Usage at 10mm/s

Looking at the average power usage from the spindle while cutting at 10mm/s, it can be seen that the power usage increases and hits a steady state around cut 15. These results are due to the grinding wheel wearing itself to a point of dullness that will remain constant for the rest of the grinding process. At this point, the grains in the grinding wheel are uniform and any grains that were worn would have fallen off by this point.

6.1.3. Feed rate of 20mm/s

The data obtained from the cuts at 20mm/s are located in the Table 6.

Line on Wafer 2		Chippage								Kerf Width			
		Beginning		1		2		End					
		Avg	Max	Avg	Max	Avg	Max	Avg	Max	B	1	2	E
1	Top	0.021	0.048	0.017	0.041	0.019	0.053	0.024	0.076	0.291	0.331	0.333	0.355
	Bottom	0.022	0.039	0.026	0.070	0.031	0.057	0.028	0.055				
3	Top	0.031	0.067	0.025	0.048	0.036	0.107	0.023	0.043	0.373	0.367	0.343	0.338
	Bottom	0.029	0.065	0.024	0.043	0.019	0.450	0.032	0.057				
5	Top	0.021	0.063	0.096	0.145	0.038	0.074	0.106	0.233	0.266	0.346	0.310	0.308
	Bottom	0.022	0..069	0.100	0.127	0.124	0.226	0.012	0.034				

Table 6- Results from feed rate 20mm/s

There is slight variation in the average chippage for cuts 1 and 3 on wafer 2. The maximum values of chippage are much higher than those from feed rates of 5mm/s and 10mm/s previously mentioned. The chippage ranges greatly on cut 5, this is a few cut before the spindle just stopped working. Many stress fractures occurred during the final lines due to the expansion of the grinding wheel.

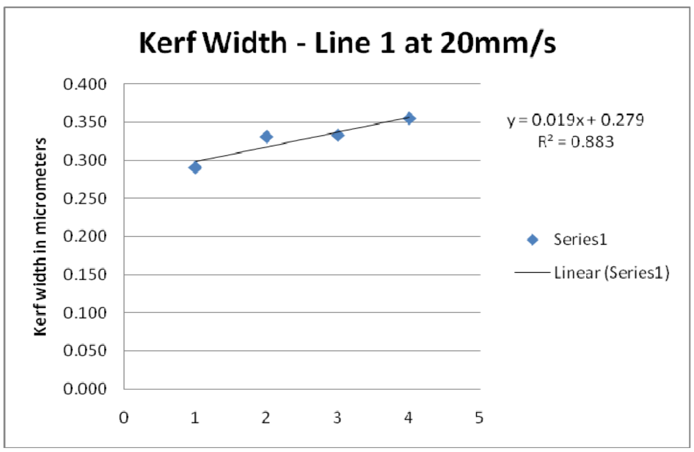

Figure 26- Kerf Width Variation on Line 1 at 20mm/s

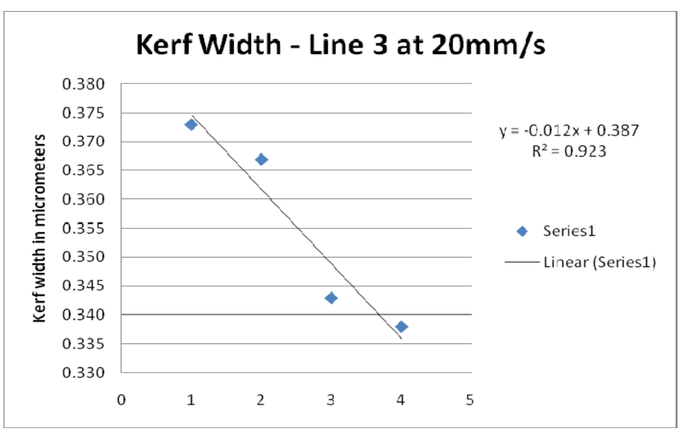

Figure 27- Kerf Width Variation on Line 3 at 20mm/s

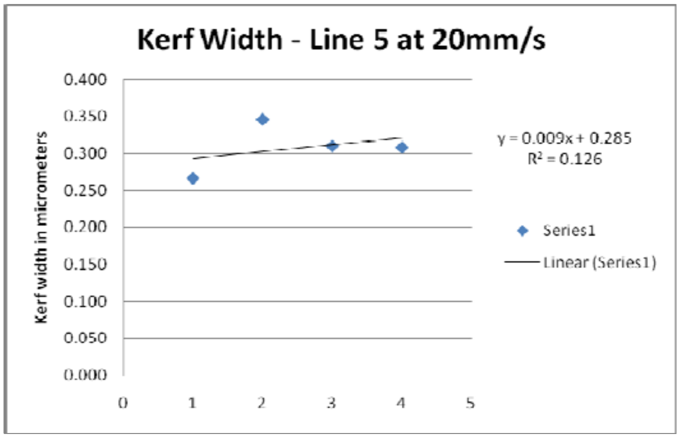

Figure 28- Kerf Width Variation on Line 5 at 20mm/s

The following Figures 29 through 32 are images from a cut on wafer 2 that completely broke off at the end. Figures 31 and 32 show the damage done to the wafer during the grinding. These fractures and eventual break off at the end of the line are due to the grinding wheel heating up during the grinding at 20mm/s. This is due to general heat buildup from the process, but also from the coolant jet delivery not contributing to the reduction in temperature of the wafer during the process.

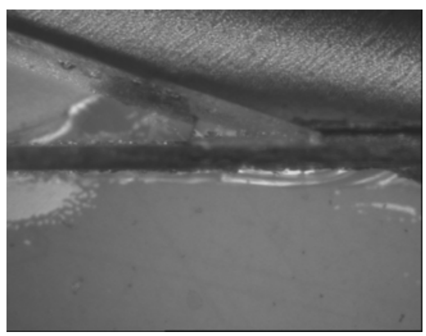

Figure 29- Beginning Cut

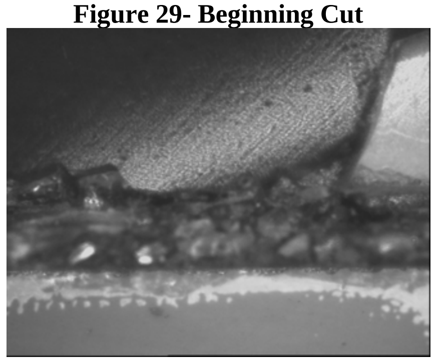

Figure 30- Breakage at end of cut

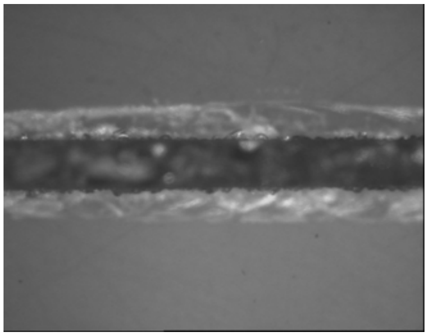

Figure 31- Chippage along cut

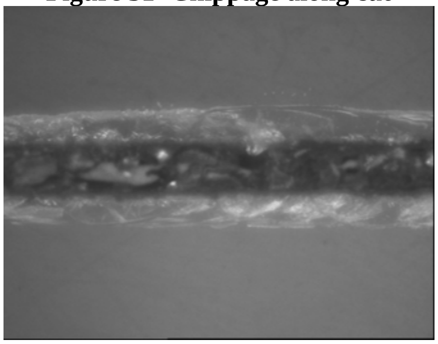

Figure 32- Subsurface damage to wafer 2

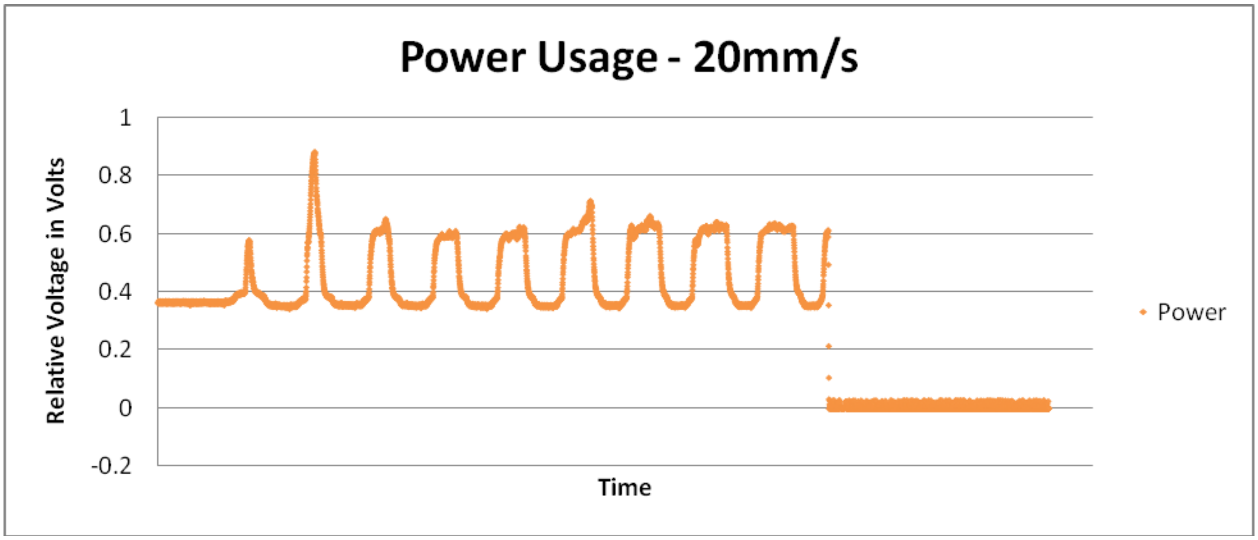

Figure 33- Power Usage at 20mm/s

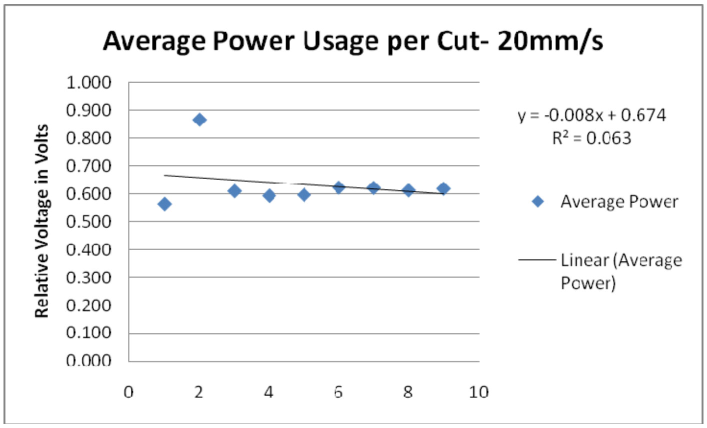

Figure 34- Average Power Usage at 20m/s

The second cut on the wafer required more power than the power used for the previous two feed rates. The power usage continues at a steady decline before the spindle on the machine just turns off. This end results is due to the heat buildup and expansion of the grinding wheel that damaged the wafer and caused the spindle to fail, which can be noted in the power usage in Figure 33.

6.2. Results from New Design Testing

6.2.1. Design 1 Results

6.2.2. Design 2 Results

6.3. Comparison of Results from Benchmarking and New Designs

7. Conclusion

Given the results from our benchmarking and general observation of the flow of coolant on the grinding wheel, our new nozzles needed to address the issues of variation in kerf width and chippage by means of concentrating the stream of coolant on the area of the cut.

Future Recommendations

8. References

Kalpakjian, Serope and Steven R. Schmid; Manufacturing Engineering and Technology, 4th Edition; Prentice-Hall Inc.. 2001; pg 704

Members of the Executive and Technical staffs of the Norton Company; Grinding,Wheels, Machines, Methods; The Plimpton Press. 1922; pg 12-13

Munson, Bruce R. et al; Fundamentals of Fluid Mechanics, 5th Edition; John Wiley & Sons, Inc., 2006; pg 404

9. Additional Resources

http://www.photonicsonline.com/Content/ProductShowcase/product.asp?DocID=%7B8D1A6F29-6C70-11D4-8C57-009027DE0829%7D

http://www.photonics.com/content/spectra/2006/September/LED/84257.aspx

http://www.marketech-sapphire.com/index.html

http://www.loadpoint.co.uk/documents/MicroAce_Brochure.pdf