Process Simulation of Mono-Layer Super Abrasive Grinding Wheels

By Yann Schoenhagen & Jonathan Vasquez

A Major Qualifying Project

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Yann Schoenhagen   Jonathan Vasquez

In Collaboration with BJTU University & Saint Gobain

BJTU Students: Qi Li, Shou Li, Gaoxiang Wang

Co-Advisors: Professor Li (BJTU), Professor Lu (Tsinghua)

Industrial Advisor: Dr. Feng Liu (Saint Gobain)

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_____
Advisor: Professor Rong
Mechanical Engineering Department

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Abstract

Grinding is a machining process where complexity of the process lies in the microscopic interaction within the wheel-work piece contact zone. Understanding the microscopic interaction can lead to many advancements in the area of grinding. These advancements can be very beneficial for companies designing and developing grinding wheels and grinding tools for the field. Saint-Gobain had given the opportunity to study the grinding process, specifically the interactions and performance of super abrasive wheels. Experiments were created around changing the input factors (grain geometry, cutting depth, and wear) to gain results in the outputs (force and side flow) to be able to define a quantitative relationship. Using design of experiments to reduce the number of experiments needed, 50 experiments were able to define the range needed, from which quantitative equations were derived for the Force in the X & Y direction as well as Side Flow Height and Width. Using this data, it will be possible to update current grinding parameter to simulate an entire grinding wheel interacting with a work piece material.

1.   Introduction

In today's world, the manufacturing industry has been producing an all-time high. Whether it be the billions of vehicles on the road today or everyday house hold items such as toothbrushes or plastic bottles, most of the goods we use in the world today are produced using some type of manufacturing process to transform raw material into a finished product. Manufacturing is generally defined as the use of machines, tools and labor to produce goods for use or sale. There are many different machining manufacturing processes such as milling, turning, and drilling just to name a few, but this project will focus on a more specialized technique, grinding.

Saint-Gobain is constantly improving their technology to lead to higher productivity while lowering costs of grinding and finishing. Because grinding is such a complex process, there is still a lot to be accomplished by way of research and development efforts. As a result, Saint-Gobain has given us the opportunity to study the grinding process and more specifically, the performance of super abrasive wheels.

The objective of this research project was to improve the ability to synthesize the grinding process of single layer super abrasive wheels at the microscopic level. This was done throughout an 8-week process, while collaborating with industrial engineering students from Beijing Jiaotong University as well as engineers from Saint-Gobain Researcher Center.

Different simulations and experiments were used to gain a better understanding of the grinding process. This including using an assortment of grinding wheels, and changing factors such as process parameters and work piece material. With data, it is possible to develop a quantifiable relationship between the input and output parameters that could be used to better the manufacturing field.

The software which was utilized was AdvantEdge Micro-Cutting Simulation, developed by Thirdwave Corp, along with a grinding simulation package developed

by THU-WPI. With the software, we hoped to determine whether the grinding model could effectively and appropriately forecast the grinding process and wheel performance. If achieved, the understanding will lead to better knowledge and more effective use in grinding applications with mono-layer super abrasive wheels.

# 2.	Background

## 2.1	Background

Grinding is a machining process where complexity of the process lies in the microscopic interaction within the wheel-workpiece contact zone. Grinding typically uses a wheel embedded with thousands of abrasive particles, each of these abrasive particles are defined as cutting edge interacting with work materials at high velocities. While typical manufacturing processes will have one or two points of contact from the tool to the work piece, a grinding wheel has thousands. Different grinding processes are used for a large variety of manufacturing applications and settings. This sets grinding apart from other manufacturing process and makes it very interesting for analytical purposes. At the microscopic level, important topics include cutting, plowing, sliding, chip/workpiece friction, chip/bond friction, and bond/workpiece friction.

Within grinding, there are many different applications, techniques, and wheels used. Companies use this to their advantage, using a range of grinding wheel to manufacture a large variety of products. An example of such a company is Saint-Gobain, who works with many different grinding wheels, including a very special type called super-abrasive grinding wheel.

Saint-Gobain is a leader in producing industrial and manufacturing materials. The Saint-Gobain Abrasives division is the largest global abrasive supplier with their products currently being sold worldwide. These abrasives can be used for a variety of applications including grinding, trimming, and polishing. A special product produced by the abrasives division is the super abrasive grinding wheels.

Super-abrasive grinding wheels are defined as having characteristically long life and high grinding productivity, which is due to the materials used to construct the wheel. Super-abrasive wheels are typically made of either diamond or cubic boron nitride abrasives, which are respectively the first and second hardest material

known. When referring to grinding wheels and their productivity, the term G-ratio is used. G-ratio is defined as the cubic volume of stock removed divided by the cubic volume of wear. In conventional grinding, the ratio ranges from 20:1 to 80:1, while with super abrasive wheels, the ratio can be hundreds of times higher.

Due to the ability of super abrasive wheels to produce a substantially greater amount then a typical grinding wheel, super abrasive wheels have garnered an increasing amount of attention. Benefits of using a super abrasive include being able to function at higher speeds, better G-ratios, and cost-effective machining. With lean processes and machining catching on throughout the world, companies are always looking for increased efficiency. In this case the increased efficiency can be realized by cutting more with less material.

Grinding is a major industry in the manufacturing world, used for a wide varying amount of processes and applications. In precise machining alone, grinding accounts for over 70% of the processes used. Understanding the wheel material, grains used and also work-piece material is essential and very beneficial to a manufacturer or user. The next step in fully understanding the grinding process would be to be able to fully predict the outcome of a project. This includes the resulting grain wear, power, and force. Even though there have been advances in technology there is much work to be done in the area of result prediction.

Although a grinding process can be regarded as a multiple edge cutting process, it differs from the cutting process in two key areas: chip-bond/workpiece interaction and the bond-work interaction. These can be absent in other cutting processes such as turning or milling. Modeling of any grinding processes can be broken down into 2 levels, the modeling of multiple edges micro-cutting, or grain-workpiece interactions and the modeling of other frictional interactions that are introduced after the micro-cutting process.

Research and development projects are created due to industry demand and the lack of knowledge and research in the matter. In our case of super abrasive grinding wheels, the gap between industry need and academic research exists. More specifically, there are three major gaps listed below:

- A description of the grinding physics for better grinding process predictability
- A prediction of time dependent microscopic behavior of grinding processes.
- More accurate grinding models

There are many benefits and advantages in bettering the grinding process predictability. Having an improved understanding of the process can greatly enhance the way in which the manufacturing world uses grinding wheels. Better grinding process predictability can lead to grinding optimization, where less material will be wasted and efficiency increased.

2.2   *Grinding Wheel*

An electro plated single layer Cubic Boron Nitride [CBN] grinding wheel is composed of several components. Typically, there is a stainless steel core that small CBN grains are bonded onto via an electroplating process. This process entails a thin layer of hard nickel to adhere the CBN grains to the stainless steel core. Prior to the electroplating process, the CBN grains are glued onto the wheel as method a to secure them so the hard nickel would fill in around the CBN grains and bond them in place permanently. This method does not allow the grains to be bonded onto the wheel in a specific orientation. thus the shape of the grain must be analyzed so that all of the geometries can be considered.
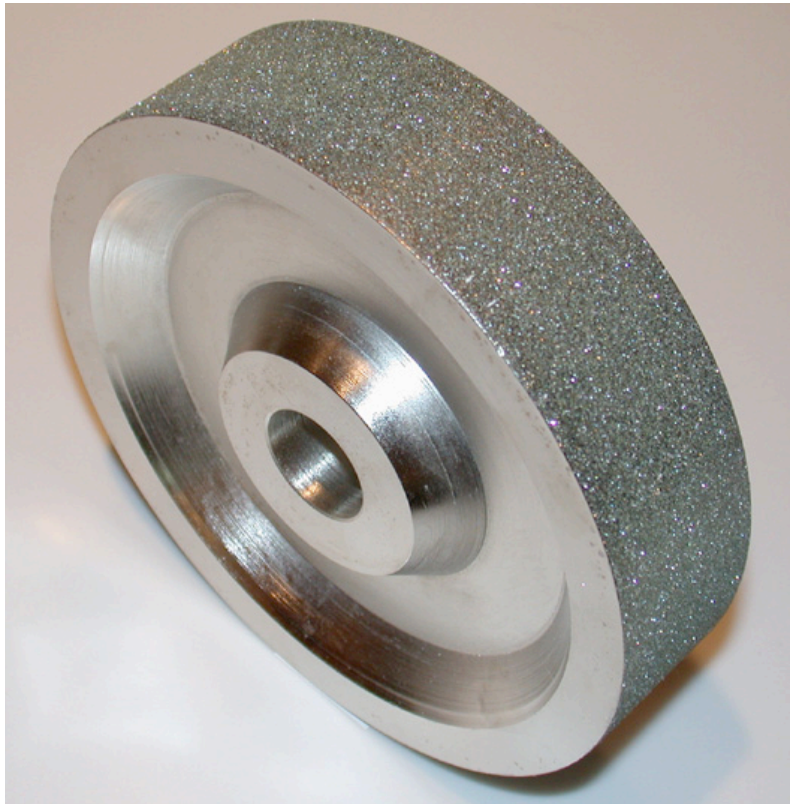
Figure 1 - Cubic Boron Nitride Mono-Layer Grinding Wheel

2.3   Prior Methods

There has been previous research done in this area including the work of Professor Xuekun Li, who studied the cutting of a single grain under different conditions to characterize and quantify the grain-work piece interface. Through this study, it was established that force, chip generation, and material plastic flow could be determined through the simulation results while also providing output values including the tangential force and surface texture. While the study was successful in foreseeing and predicting results of a grinding experiment, it is possible that the accuracy can be raised to provide better predictions. This work was used as a foundation for this research project as it is important to analyze the prior methods, including the inputs, the outputs, as well as limitations.

Figure 2 - Professor Li's Micro Cutting Study Framework

The figure above shows the different input and output parameters used for the single grain cutting study. As shown, the dominate factors included cutting speed ,

depth of cut, grain geometry, material, workpiece material status, lubrication and coolant conditions. Expected output includes the cutting force, the side flow width and he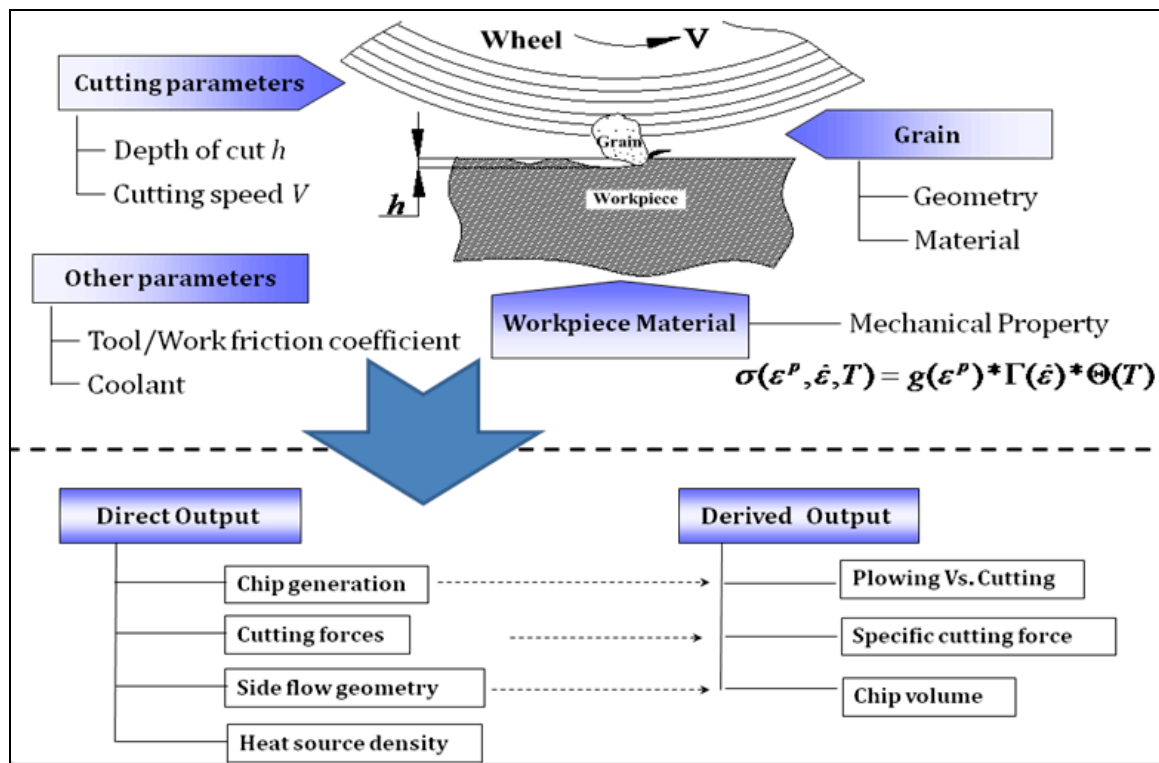ight, and chip volume generated. The simulations were carried out to reveal how following parameters affect the material removal in terms of the direct output and the derived output.

2.3.1 Input

The controllable input parameter were as foloows:

- Cutting Depth
- Wheel Speed
- Tool/work friction Coefficient
- Work piece Material (Mechanical Property)
- Grain (Geometry and Material)

Cutting depth corresponds to the depth at which the tool tip is into the work material, compared from its surface. Wheel speed is the rate, in this case measured in m/min, at which the grinding wheel disk rotates. The tool/workpiece friction coefficient defines the ratio of the force of friction between the two bodies and the force pressing them together. Workpiece material is the mechanical property of material. The grain parameter defines the geometry and material of the grain.

2.3.2 Output

- Direct Output
  - Chip Generation
  - Cutting Forces
  - Side Flow Geometry
  - Heat Sources Density
- Derived Output

  - Ability to distinguish between different modes of cutting, as shown in Figure 2, specifically Plowing, Cutting, and Sliding.

- Plowing is when dull grains push into the workpiece without cutting it. Plowing leaves grooves and deforms the work surface, in addition it results in higher energy consumption.
- Cutting is the main action occurring when sharp grains dig into the workpiece and removes chips.
- Sliding is associated with rubbing dulled flattened areas on the abrasive grain tips (wear flats) against the workpiece surface and is an energy intensive process
  - Specific Cutting Force and Chip Volume
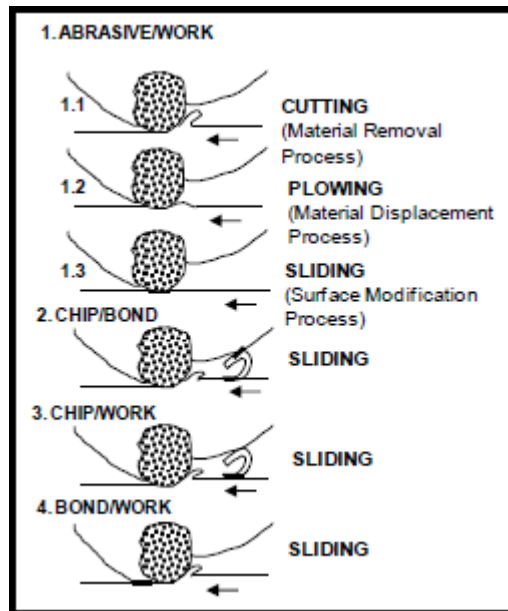
Figure 3 - Different Modes of Cutting

2.3.3 Results

The study successfully achieved its goal to characterize and quantify the grain-work piece interface. It was determined that the entire grinding process model can be effective in predicting the technical output measures of the process and explaining the mechanism in grinding process. The grinding wheel model itself could be used to optimize and design the wheel composition as well as its fabrication parameters, which could minimize the "trial and error" in current wheel design procedure and be able to proactive design wheels tailored to specific applications.

Based on the research study it can be deduced that future work needs to be undertaken for enhancements. The simulations and predictions didn't take into account the time dependent factors that occur with grinding, including grain wear and dressing of the grinding wheels. Grain wear refers to the loss of material on the grain over time. Grain wear occurs at a much smaller rate with super abrasive grinding wheels then most other common grinding wheels, yet grain wear still plays a big factor in the performance of a wheel. Even though grinding wheels are self-sharpening to a small degree, for optimal use they may be dressed, which refers to removing the current layer of abrasive materials. This means that a fresh and sharp surface is exposed to the work surface. These two factors must be considered in order to further increase the accuracy of the simulations.

Virtual representation of the grain also requires further study to enhance it's accuracy. Professor Li's study didn't use the actual microscopic geometry of the grain but simple shapes were used which only took into the consideration the grain protrusion. Factors such as density of grain on a grinding wheel and actual shape need to be considered to be able to analyze the 3 cutting modes, plowing, sliding, and cutting, more accurately.

2.4 Problem Statement

This research project may be dissected into two separate perspectives, from a company's aspect and from the technology view. The technological problem is that the traditional technique, used by Professor Li, currently does not synthesize the grinding process of super abrasive wheels. And from a company's perspective, specifically Saint Gobain, the traditional technique cannot predict the result of a grinding process to a high level of accuracy and for Saint Gobain to use the amount of resources needed to synthesize the process would not be cost-effective. These problems lead us to create our overall goal.

2.5 Overall Goal

The focus of this research is to analyze the grinding process as an integration of all microscopic interactions and improve the methodology for the physics based modeling used in the traditional method. The overall goal for this project is to determine a cost-effective method to predict the result of CBN monolayer wheel grinding process with a high level accuracy for SGRS.

2.6 Objective

The main objective in this project is to verify the traditional model created by Professor Li of the CBN monolayer wheel grinding based on the microscopic interaction characterization. Through this work this research aims to to identify the correlation of the output measures with input parameters for process prediction and optimization, with the input parameters and the output measures being the following:

- **Input Variables**: Depth of Grinding, Work-Piece Material Type, Tool Orientation

- **Output Measures**: Surface Topography, Force (Power), G-Ratio

2.7 Tasks

The following list is used to outline the important tasks of this project which were followed to arrive at the results portion of this report.

- Background study
    - Understand Grinding Process
    - Superabrasive wheels Vs. Conventional Wheels
    - Input/Output Parameters
    - Review of Previous Studies and Literature
- Grinding wheel model verification (THU & BJTU)
    - Visual Comparison
    - Grain Count Comparison
- Single grain micro-cutting study (with AdvantEdge)
    - Change Input Parameters for CBN grain
    - Grain in Different Orientations
    - Depth of Cut (Plowing Vs. Sliding Vs. Cutting)
- Grinding Process Simulation (with THU Software)
    - Time Dependent Performance Variables
        - G Ratio
        - Power Used
        - Surface Topography
- Experiment Verification (@ SGRS)
    - Verify that the Time Dependent Performance Variables from the Grinding Process Simulation is Accurate with an Actual Experiment at SGRS

2.8   Tools

The main software in this project was used for simulating the single grain micro cutting study using a program called AdvantEdge.   AdvantEdge FEM is a CAE software solution for the optimization of metal cutting. AdvantEdge is used to improve tool design, increase material removal rates, extend tool life, and improve part quality among other uses. It's a vital program for manufacturing because of its ability to decrease the need for trial and error testing, which leads ultimately to the product getting to market faster. Other tools used include Tsinghua University Laboratory as well as the software created by the THU and WPI Team. Saint Gobain Research Facility will also be used to verify the experiment.

2.9   Expected Results

From this project, the group expects the following results:
- Better Understanding of the Grinding process
- To have enhanced the CBN Monolayer Grinding Model that Predicts the Grinding Process to a Higher Level of Accuracy
- Result of Experiment Matches Forecasted Simulation Results from the Software

3.   Research

3.1   *Carbon Boron Nitride [CBN]*

The material of the grain on the super-abrasive wheel is Cubic Boron Nitride, also known as CBN. Cubic boron nitride is the second hardest material known to man preceded by diamond. One of the main differences between diamond and CBN is that diamond is found naturally while CBN is a manufactured material. CBN is an ideal candidate for use in grinding due to its material properties as it can withstand harsh conditions that are involved in the grinding process. These properties include high thermal conductivity, excellent wear resistance, and great chemical inertness. The figure below shows a picture of the amber colored CBN material.

Figure 4 - CBN Grains

3.2   *Creating Virtual Grain*

To create virtual grain replica of the cubic boron nitride grain, actual grain samples had to be analyzed. With a small tray of CBN grains, observations were made under a high powered microscope to analyze the actual microscopic geometry. What could be seen was a variety of different shapes of the CBN grains, something which was expected. However there was a recurring shape that seemed to be cut perfectly, and that was that of a sixteen-sided figure, known as a hexa-decagon, as seen below in **Figure 3**. While these shapes were found in abundance throughout the CBN sample being observed, it was noted that not all of the grains followed this exact shape, but for analytical purposes, these grains were the most appropriate.

Figure 5 - CBN Grain Under High-Powered Microscope

Using the scale ratio, the size of the grain was determined to be three hundred microns from end to end. Then using the size, shape and a visual comparison, a SolidWorks model of the grain was created, which could then be transferred for use in the simulation software AdvantEdge. The following series of figures depict different stages of the CBN virtual grain model. **Figure 4** depicts the visual

comparison of an actual CBN grain and the created virtual grain in SolidWorks is shown in the following figure. The SolidWorks model is shown in isometric view below in **Figures 5 and 6**.
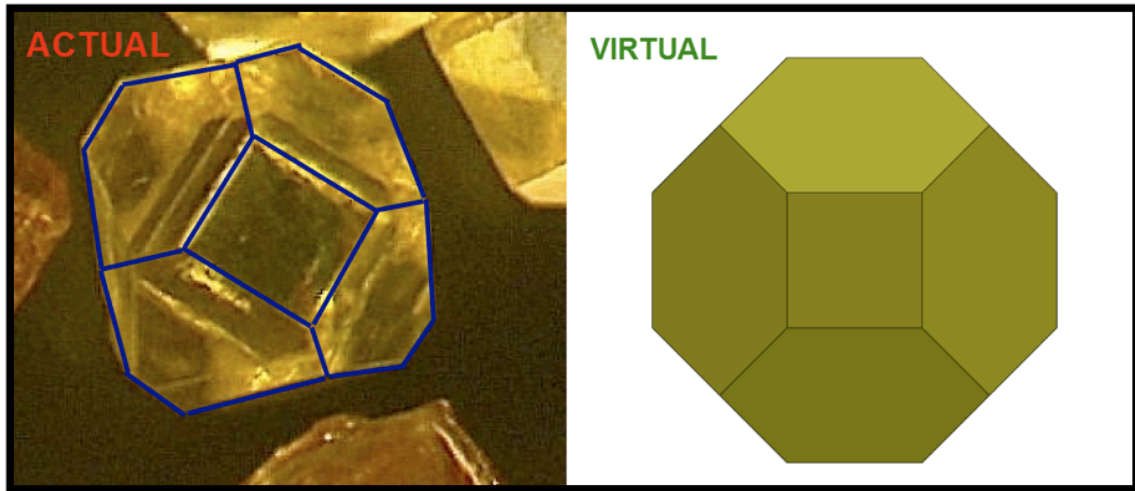
Figure 6 - Actual CBN Grain and Virtual Grain

Figure 7 - SolidWorks Grain Model

16-Sided Polygon SolidWorks Model
with Filets (Hexa-decagon)
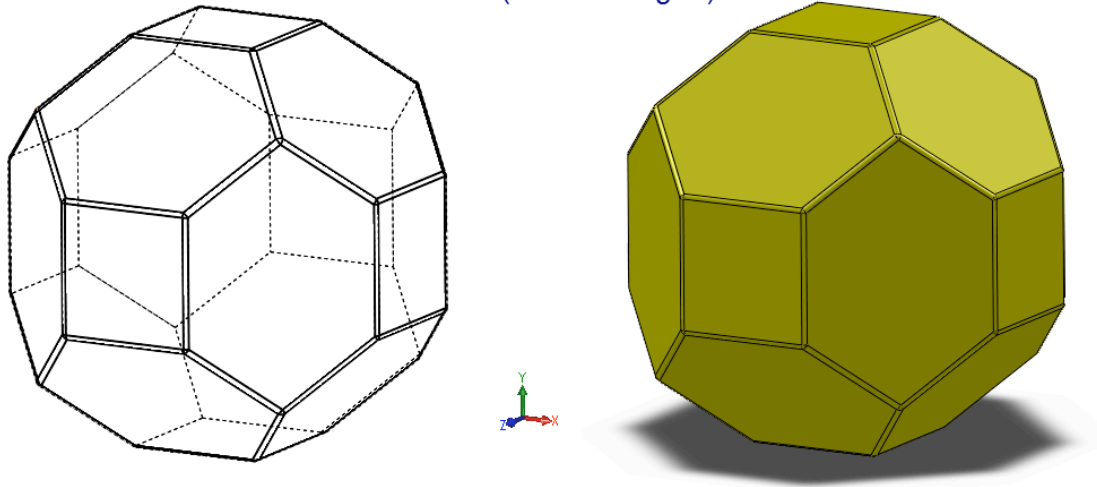
Figure 8 - SolidWorks Grain Model

The visible change between **Figure 5 and 6** shows a CBN grain without fillets in **Figure 5** and a grain with filets in **Figure 6**. These filets were added to better replicated the microscopic geometry of CBN grains, where the edges typically aren't as sharp and perfect. Since the sharpness of the edges effects the performance of a grain as a cutting tool, these filets allow for more round edges which better simulate how a grain would perform.

The procedure for creating the grain in SolidWorks is as follows;

1. A basic block of a length, width, and height of three hundred microns was created.
2. Then three equal polygon-shaped extruded cuts on the top, right, and front faces were made to get the nearly finished shape of the CBN grain.
3. Lastly, fillets along the edges of the virtual grain to emulate the rounded edges were generated.

3.3   Grain Density

After creating a replica grain of Cubic Boron Nitride, the next step was to analyze the grinding wheel that was to be modeled. This was done to deduce the density of grains on an area of the wheel, which would allow for a reproduction wheel model to be created later using the exact density of the replica grains. **Figure 8** shows the picture of the grain wheel on the left, and a closer view of the wheel.
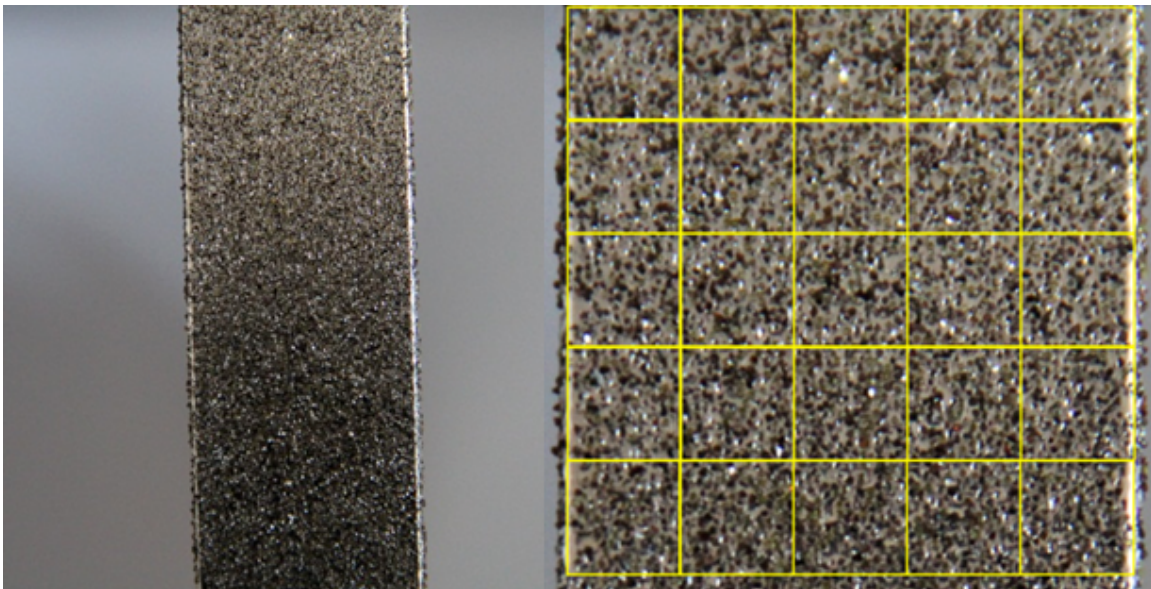
Figure 9 - Grain Density on Grinding Wheel

A grid was laid out to divide the wheel surface into 20 sections, where it was possible to count the amount of grains in each area. The average grain per area was obtained for the 4x5 grid, with the data shown in **Table 1** below. The calculated average per square millimeter was 5.306 grains/mm^2

Table 1 - Grain per Area

130	110	143	138	157
117	105	128	145	155
156	131	118	141	152
103	146	129	125	124

3.4   Framework

In order to fully understand all the different input and output parameters, an updated framework was created, following the original framework created by Professor Li. The updated framework is shown below in **Figure 9**. It shows the input parameters that can be adjusted in the simulations, as well as the outputs that can be identified as a result of the simulations.
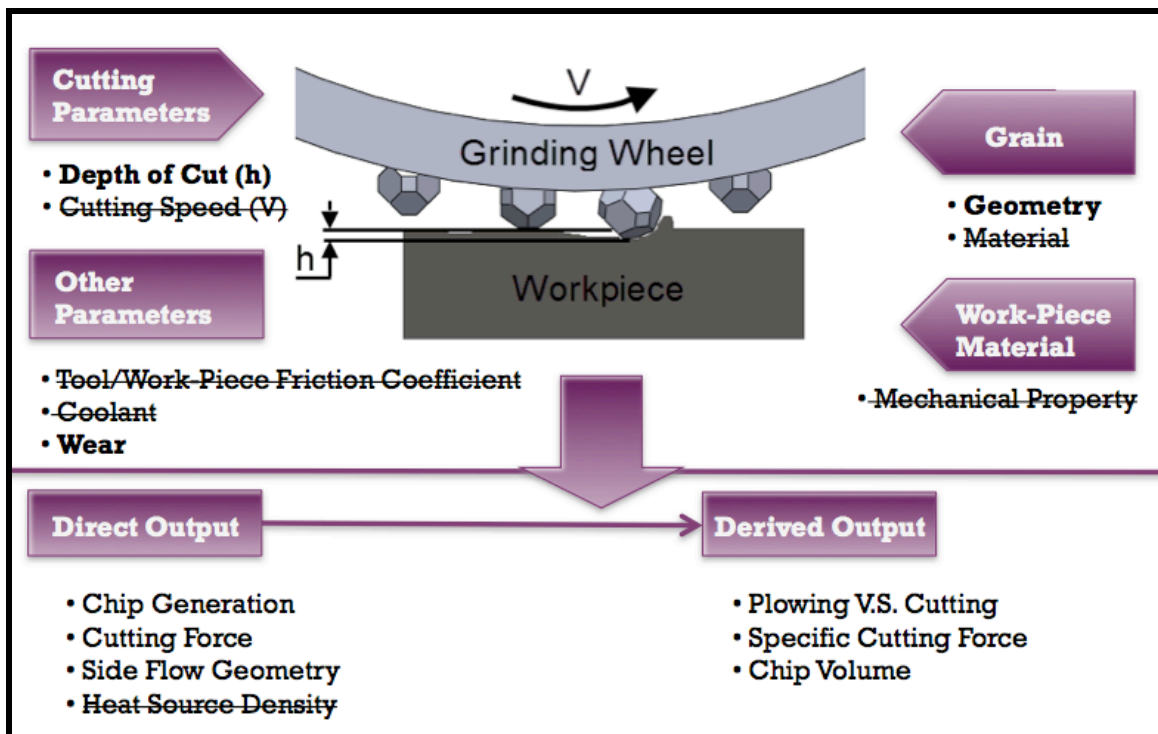
Figure 10 - Updated Framework

The original framework was created with the intention for use in all grinding wheels. But since this research focused on super abrasive grinding wheels as well as modifying the original intention, some parameters were changed. Input parameters have pre-defined constants which were used, therefore these constants were not changed at any point throughout the simulations. The variables and constants are defined the following **Table 2** and **Table 3**.

Table 2 - List of Variables and Constants

Variable	Constant
Depth of Cut (h)	Cutting Speed
Grain Geometry	Work-Piece Material
Grain Wear	Tool/Workpiece Friction
	Coolant

Table 3 - Project Constants and Respective Values

Constant	Value
Cutting Speed	40 meters / sec or 2400 meters/min
Work-Piece Material	D2 - Steel
Tool/Workpiece Friction	.11-.13
Coolant	n/a

This leads into the cutting conditions used in the simulations. Next, the variable cutting conditions, depth of cut, grain geometry, and grain wear, were analyzed and defined.

3.4.1   Depth of Cut

Depth of cut is defined as the thickness of material removed by one pass of the cutting tool, translating the amount of D2-Steel cut from each pass of the CBN grain. As shown in **Figure 10** below, we were able to change the depth of cut to remove more or less of the workpiece.
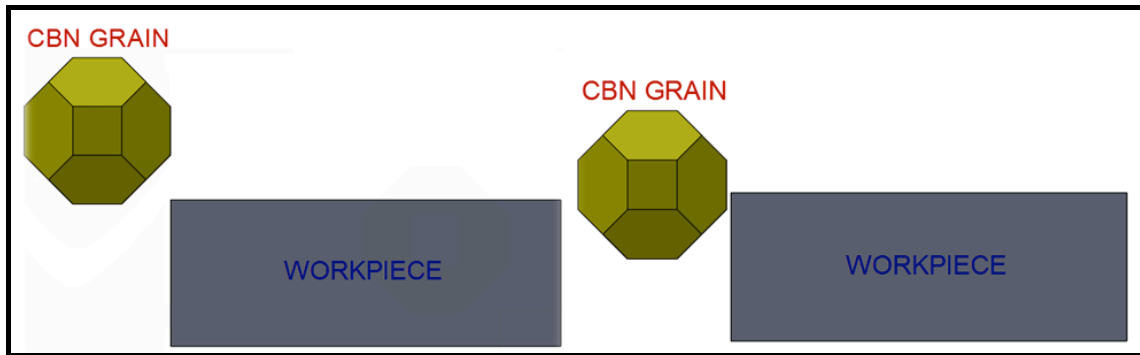
Figure 11 - Depth of Cut Representation

3.4.2   Grain Geometry

Grain geometry refers to the orientation of the CBN grain in respect to a neutral position against the workpiece. As described in **Table 4** and shown in **Figure 11**, three axes of rotation were defined to be able to fully describe a CBN grain's orientation.

Table 4 - Grain Geometry

Axis	Definition
Angle of Lead	Rotation about the X-Axis (Red)
Angle of Orientation	Rotation about the Y-Axis (Green)
Angle of Inclination	Rotation about the Z-Axis (Blue)
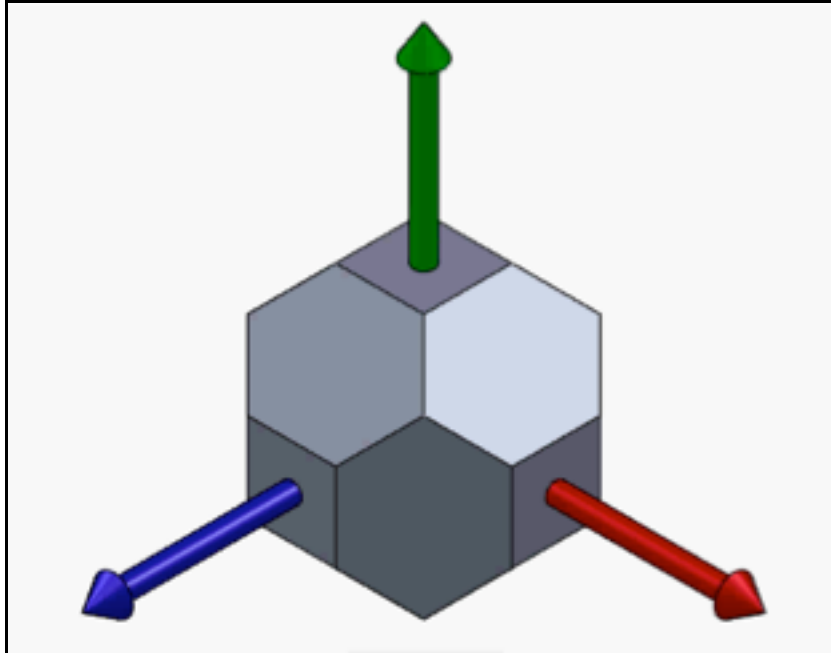
Figure 12 - Representation of Grain Geometry

3.4.3 Grain Wear

Wear is defined as the gradual deterioration of an asset which results naturally from use and/or age. In the case of this project, the grain will wear over time as it keeps creating contact with the workpiece material. **Figure 12** below represents a grain with no wear on the left side, along with the grain with wear on the right side.
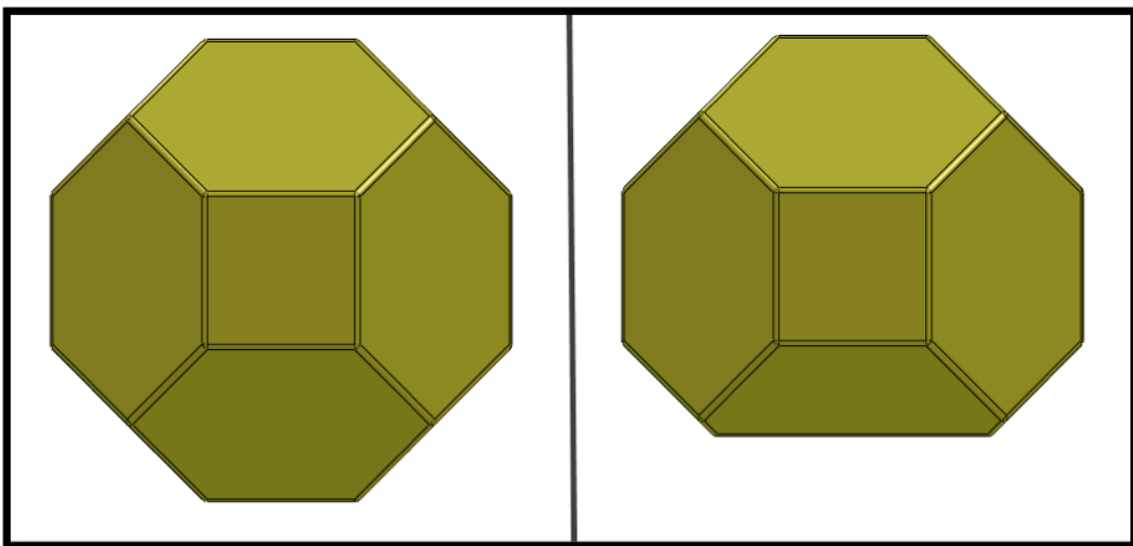
Figure 13 - Representation of Grain Wear

3.5   Project Assumptions

The following were the project assumptions used throughout the project simulations:

- All grains were consistent with the Grain Model
- The grinding system is considered to be rigid and the dynamic responses in grinding processes are not considered. The vibration of the grinding wheel and system is negligible.
- The change to the grinding wheel surface results from wear, loading and pull-out. In our model, we only concern the wear and neglect the loading and pull-out phenomenon.
- The work piece material metallurgy structure does not change during the grinding process.

3.6   Design of Experiments

A quantitative relationship had to be defined between the variable input parameters (grain geometry, depth of cut, and grain wear) and the outputs and the output we measured (force and side flow geometry). In order to define all of the simulations needed to determine the quantitative relationship, a technique called Response Surface Methodology or RSM was used.

Response Surface Methodology is a collection of mathematical and statistical techniques useful for the modeling and analysis of problems in which a response of interest is influenced by several variables. Using the RSM method, a quantitative relationship was defined between the input parameters and the output in an equation form as well as in graphical form, an example is shown in **Figure 13.**

Figure 14 - Response Surface Methodology Graphical Form
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Design of experiments (DOE) is defined as the design of any information-gathering exercises where variation is present, whether under the full control of the experimenter or not. The experimenter is often interested in the effect of some

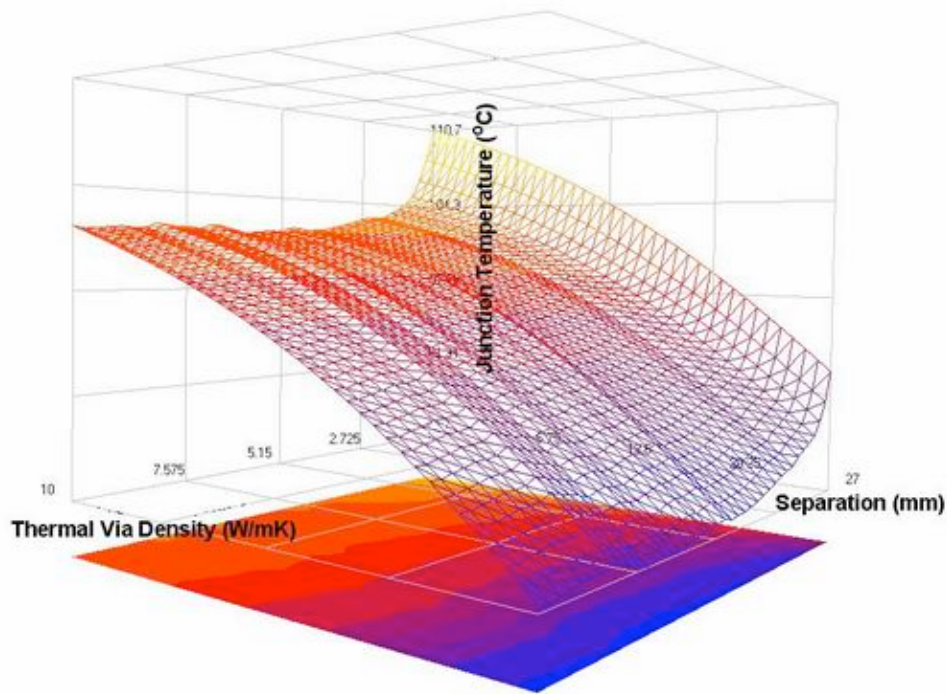process or intervention (the "treatment") on some objects (the "experimental units").

Using a traditional method known as the full factorial design, experimental units take on all possible combinations of these levels across all such factors. The factors and their levels are defined in **Table 5 below:**

Table 5- Factors and Levels

Factor	Level Range
Orientation Angle	$[0, \pi/2] \rightarrow \{1°, 45°, 89°\}$
Inclination Angle	$[0, \pi/2] \rightarrow \{1°, 45°, 89°\}$
Lead Angle	$[0, \pi/2] \rightarrow \{1°, 45°, 89°\}$
Wear	$[1, 8] \rightarrow \{1, 2, 4, 8\}$
Depth of Cut	$[1, 32] \rightarrow \{1, 2, 4, 8, 16, 32\}$

With the full factorial design and the factors stated above, this would give us a total of 648 (3*3*3*4*6 = 648) experiments needed to be done to test all of the different combinations to get the full spectrum. Due to the time and computational constraints, the process was simplified to lower the amount of testing but still achieve the full spectrum. This could be done by removing factors, removing levels, or overlooking some combinations. Using a different technique, called the Orthogonal Design, it was possible to be able to reduce the amount of testing needed to be done.

The Orthogonal Design is a design where the total variation in the response can be reduced into components due to each factor and interaction. This makes it possible to rank the importance of factors with respect to their contribution to total performance variance. This allows us to reduce the numbers of testing from 648 experiments to only 49, with **Table 6** showing the different experiments.

Table 6 - Orthogonal Design Testing

Si
fo

	OA	LA	I A	W	D
	1	1	45	4	13
	1	45	1	4	13
	1	45	89	4	13
	1	89	45	4	13
	45	1	45	4	1
	45	1	45	4	25
	45	45	1	0	13
	45	45	1	8	13
	45	45	45	0	1
	45	45	45	0	25
	45	45	45	4	13
	45	45	45	4	13
	45	45	45	4	13
	45	45	45	8	1
	45	45	45	8	25
	45	45	89	0	13
	45	45	89	8	13
	45	89	45	4	1
	45	89	45	4	25
	89	1	45	4	13
	89	45	1	4	13
	89	45	89	4	13
	89	89	45	4	13
	1	45	45	0	13
	1	45	45	4	1
	1	45	45	4	25
	1	45	45	8	13
	45	1	1	4	13
	45	1	45	0	13
	45	1	45	8	13
	45	1	89	4	13
	45	45	1	4	1
	45	45	1	4	25
	45	45	45	4	13
	45	45	45	4	13
	45	45	45	4	13
	45	45	89	4	1
	45	45	89	4	25
	45	89	1	4	13
	45	89	45	0	13
	45	89	45	8	13
	45	89	89	4	13
	89	45	45	0	13
	89	45	45	4	1
	89	45	45	4	25
	89	45	45	8	13

3.7 Single Grain Micro Cutting Study

Having defined the 49 experiments needed to develop a quantitative relationship between the input parameters and the outputs, the group was able to start the simulation process using AdvantEdge FEM, a finite element analysis software widely used in machining simulations. A screenshot of the AdvantEdge FEM software is shown below in **Figure 14.**
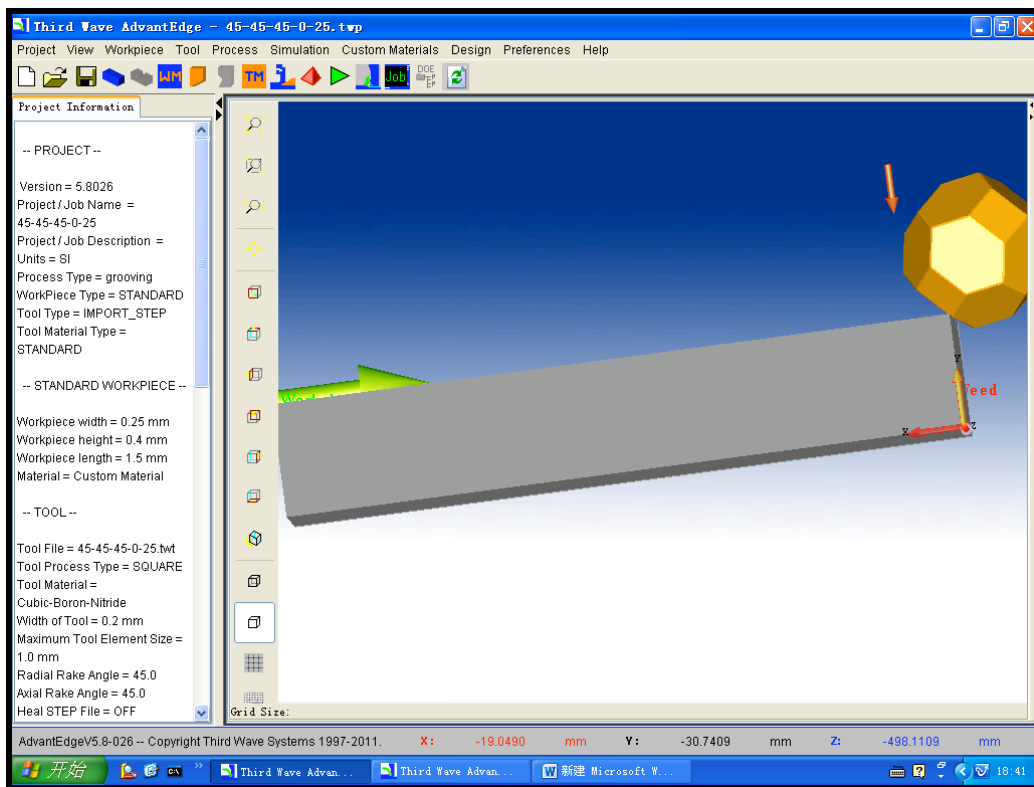
Figure 15 - AdvantEdge FEM Screen Shot

Certain parameters required definition when using the program other than the input factors. Several trials of experiments were attempted to gauge the ability of the software to increase the accuracy of the results. After analyzing all of the results, the final AdvantEdge parameters that were chosen are shown in **Table X** were used throughout the experiments.

Table 7 - AdvantEdge Parameters

Parameter	Value
Workpiece Dimensions	0.2 mm * 0.4 mm *1 mm
Workpiece Material	D2 – Steel [Imported]
Tool Material	Cubic Boron Nitride [CBN]
Cutting Speed	2400 meters/min
Initial Temperature	20
Friction Coefficient	0.4
Coolant Heat Transfer Coefficient	10,000 W/m^2*k
Coolant Temperature	20

After inputting the parameters as well as the input parameters for an experiment, the experiment could be run. Resulting from an experiment, a visual simulation of the grain cutting workpiece could be viewed, from which it was possible to analyze the sideflow and chip generated, as well as heat density and values. A screenshot of the visual simulation is shown below in **Figure X**.
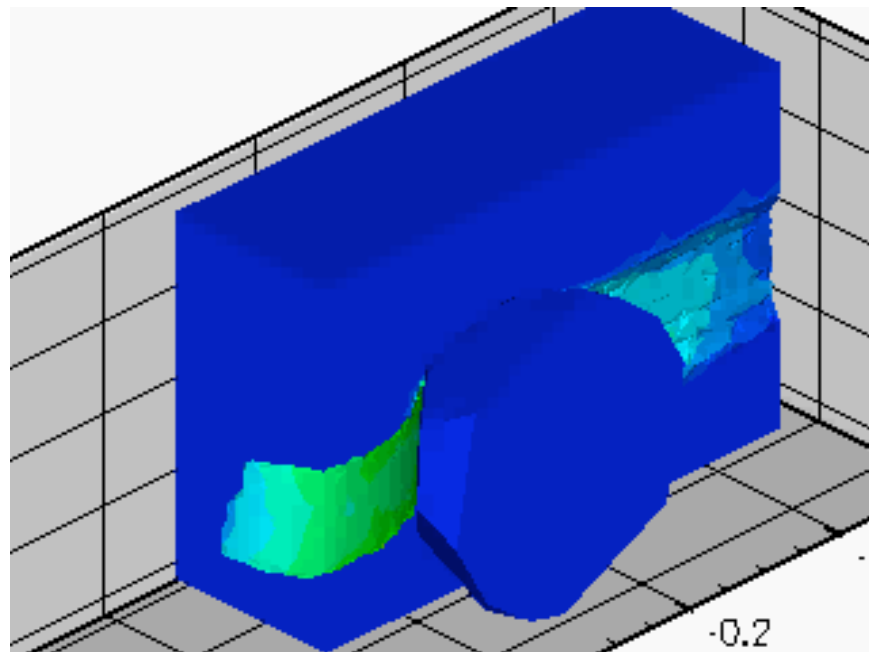
Figure 16 - Single Grain Cutting Workpiece

From the results, force diagrams are also produced displaying the values of force in the x, y, and z directions in respect to time. These force diagrams are shown in **Figure X**, showing the original non-filtered force diagram alongside the filtered version. Filtering the force diagrams removed a lot of the "noise" in the data collection and gave a much smoother diagram. This information was critical in developing a quantitative relationship.
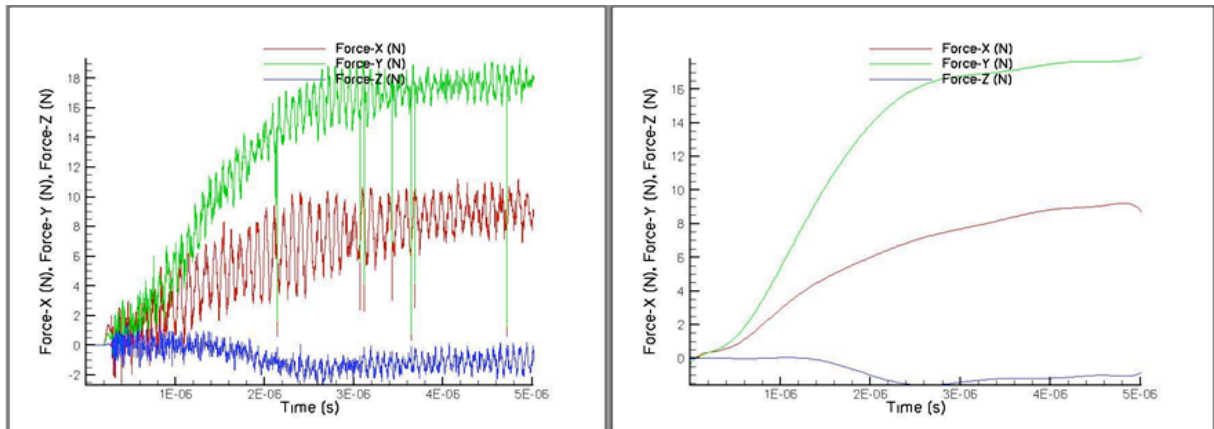
Figure 17 - Force Diagrams - Non-Filtered vs. Filtered

When the simulation on AdvantEdge finished, from the visual simulation run, it is possible to extract a single slice from the workpiece, as shown below in **Figure X**. This slice allows for examination of the side flow geometry, which is done using a program developed by THU/WPI students.
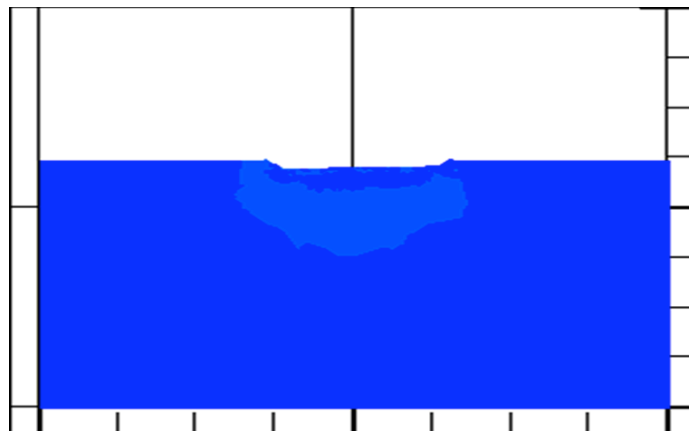
Figure 18 - Slice of Workpiece Material
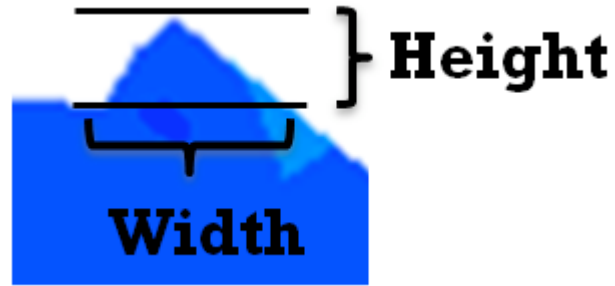
Figure 19 - Side Flow Analysis of Workpiece

3.8   Saint Gobain Experiment

3.8.1 Background

In order to validate the accuracy of the grinding simulations of a monolayer super abrasive grinding wheel, a real-life experiment must be carried out, with both resulting data sets from the simulations and the experiment should be compared for accuracy. The following sections were sent to Saint Gobain Research center, outlining a method in which it may be carried out.

3.8.2 Materials
- Three Grinding Wheels
  - CBN [Cubic Boron Nitride]
- Grinder
  - To be determined, provided by Saint Gobain
- Material Block Samples
  - **(X by X by X)*** mm
  - Ten(tentative) D2-Steel for one wheel test (2 wheels in total)
  - Ten 4340 Steel for one wheel
- Specified Coolant [to be determined]
- Grinding Analysis Machine & Software [Provided by Saint Gobain]
- Grinding Simulation Data

3.8.3 Method
1. Insert the CBN Grinding wheel in the Grinding Analysis Machine.
2. Fix 1 sample block to the Grinding Analysis Machine worktable.
   - Either D2-Steel or 4340 Steel.
3. Run the CBN Wheel while recording data.
   - Cut Depth of **(X)*** - *Varies*
   - Cutting Speed of **(X)*** - *Suggested Rate of 2400 m/min*
   - Feedrate of **(X)***
   - [30***** full cycles for D2-Steel and 40***** cycles for 4340 Steel]

4. For the last 30 or 40 cycles, measure the power cure on each sample for further analysis.

5. Once 30 or 40 cycles are complete, stop machine and analyze Wheel Sections for wear.

6. Replace sample block with a new D2-Steel or 4340 sample block.

7. Repeat and run through all 10 Samples of the block, until the wheel is completely worn.

8. Analyze data from the Grinding Analysis Machine and compare with grinding simulation data.

9. Analyze sample blocks for cut features and surface topography.

Material	Wheel speed	Depth of grinding	Table speed	Coolant
D2	40m/s	50μm / 20μm	4000mm/min	
4340	40m/s	50 μm	4000mm/min	

3.8.4 Anticipated Results
- Power**
- Surface Topography (Ra)**
- Wheel Wear**
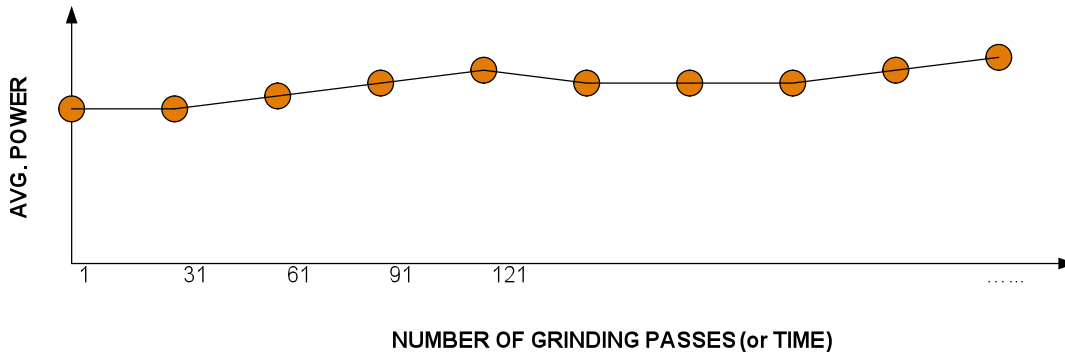
Sample result

* - Denotes value to be further discussed and specified

** - Base on a time dependent analysis

4. Results

Around 50 experiments were run following the rubric stated in section 3.6 and 3.7. With the grain geometry, depth of cut, and wear set, the corresponding forces in the X and Y direction were calculated as well as the side flow. The Box-Behnken layout of the project is shown below in Figure 20, showing all the experiments and their configurations.

模式	OA	LA	IA	W	D	Y	Xforce	Yforce	side folw
--000	1	1	45	4	13	Done	12	25	V
-0-00	1	45	1	4	13	Done	8	15.5	V
-0+00	1	45	89	4	13	Done	7	21	V
-+000	1	89	45	4	13	Done	9	15	V
)-00-	45	1	45	4	1	A			
)-00+	45	1	45	4	25	Done	15	27	V
)0--0	45	45	1	0	13	Done	16	44	V
)0-+0	45	45	1	8	13	Done	10	27	V
)00--	45	45	45	0	1	A			
)00-+	45	45	45	0	25	Done	8	12.5	V
)0000	45	45	45	4	13	Done	0.8	2.3	V
)0000	45	45	45	4	13	Done	0.8	2.3	V
)0000	45	45	45	4	13	Done	0.8	2.3	V
)00+-	45	45	45	8	1	A			
)00++	45	45	45	8	25	B			
)0+-0	45	45	89	0	13	Done	13	32	V
)0++0	45	45	89	8	13	Done	9	17	V
)+00-	45	89	45	4	1	A			
)+00+	45	89	45	4	25	Done	20	50	?
⊢000	89	1	45	4	13	A			
⊦0-00	89	45	1	4	13	Done	7	17	V
⊦0+00	89	45	89	4	13	Done	7.5	13	V
⊦+000	89	89	45	4	13	Done	4.5	10	V
-00-0	1	45	45	0	13	Done	6.5	15	V
-000-	1	45	45	4	1	A			
-000+	1	45	45	4	25	C	15	20	V
-00+0	1	45	45	8	13	Done	8	15	V
)--00	45	1	1	4	13	Done	6	15	V
)-0-0	45	1	45	0	13	Done	5.5	13	V
)-0+0	45	1	45	8	13	Done	9	22	V
)-+00	45	1	89	4	13	Done	4.5	10.5	V
)0-0-	45	45	1	4	1	A			
)0-0+	45	45	1	4	25	C	11	25	V
)0000	45	45	45	4	13	Done	0.8	2.3	V
)0000	45	45	45	4	13	Done	0.8	2.3	V
)0000	45	45	45	4	13	Done	0.8	2.3	V
)0+0-	45	45	89	4	1	A			
)0+0+	45	45	89	4	25	Done	15	30	V
)+-00	45	89	1	4	13	Done	3.5	9.5	V
)+0-0	45	89	45	0	13	Done	12	33	无
)+0+0	45	89	45	8	13	Done	11	27	V
)++00	45	89	89	4	13	Done	7.5	18.5	V
⊦00-0	89	45	45	0	13	Done	2.6	3.4	V
⊦000-	89	45	45	4	1	A			
⊦000+	89	45	45	4	25	Done	13	27	V
⊦00+0	89	45	45	8	13	Done	8	17.5	V

Figure 20 - Box-Behnken Layout

After all experiments were run, the data was compiled and information was taken on the different force values and side flow geometry. With these spreadsheets on the outputs, statistical software for expert data analysis called JMP Statistical Software was used.
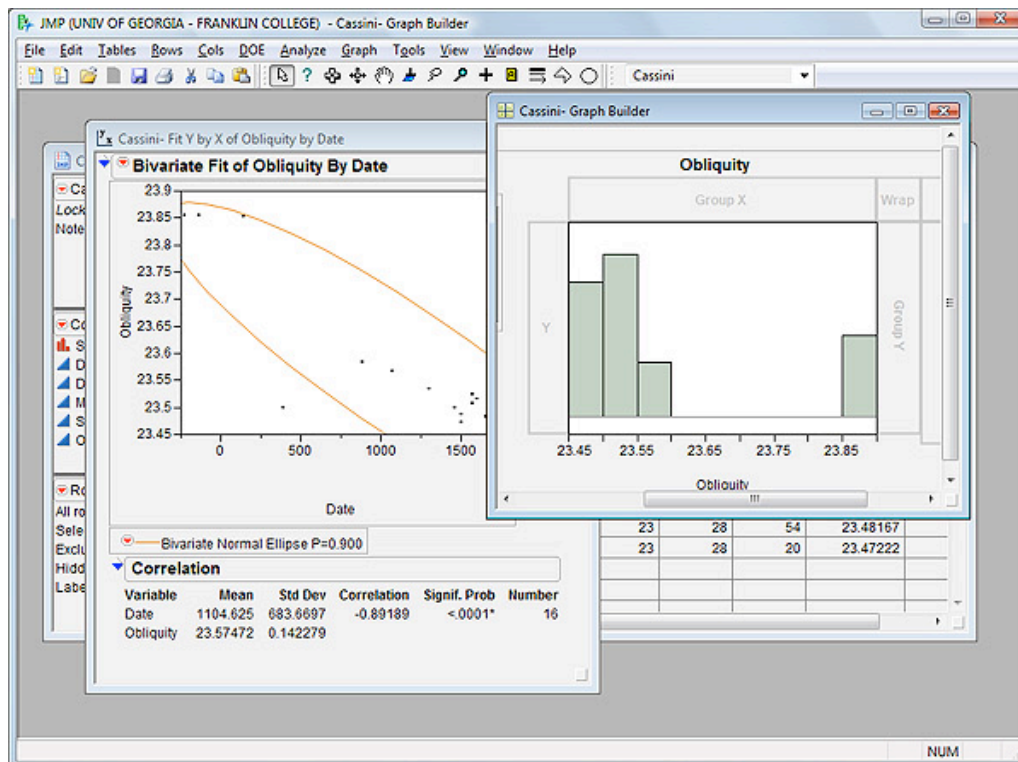
Figure 21 - Screenshot of JMP Software

From this software, it was possible to analyze the different effects that the factors had on the outputs. To increase the accuracy of the relationship between factors and outputs, it was in the best interest to remove the factors which were not statistically reasonable or effective. Those factors with a probability less than 0.01, meant that the effect of experimental factors are more significant than the effect of experimental error, thus the result is statistically reasonable. Shown in the figure below are the significant factors taken.

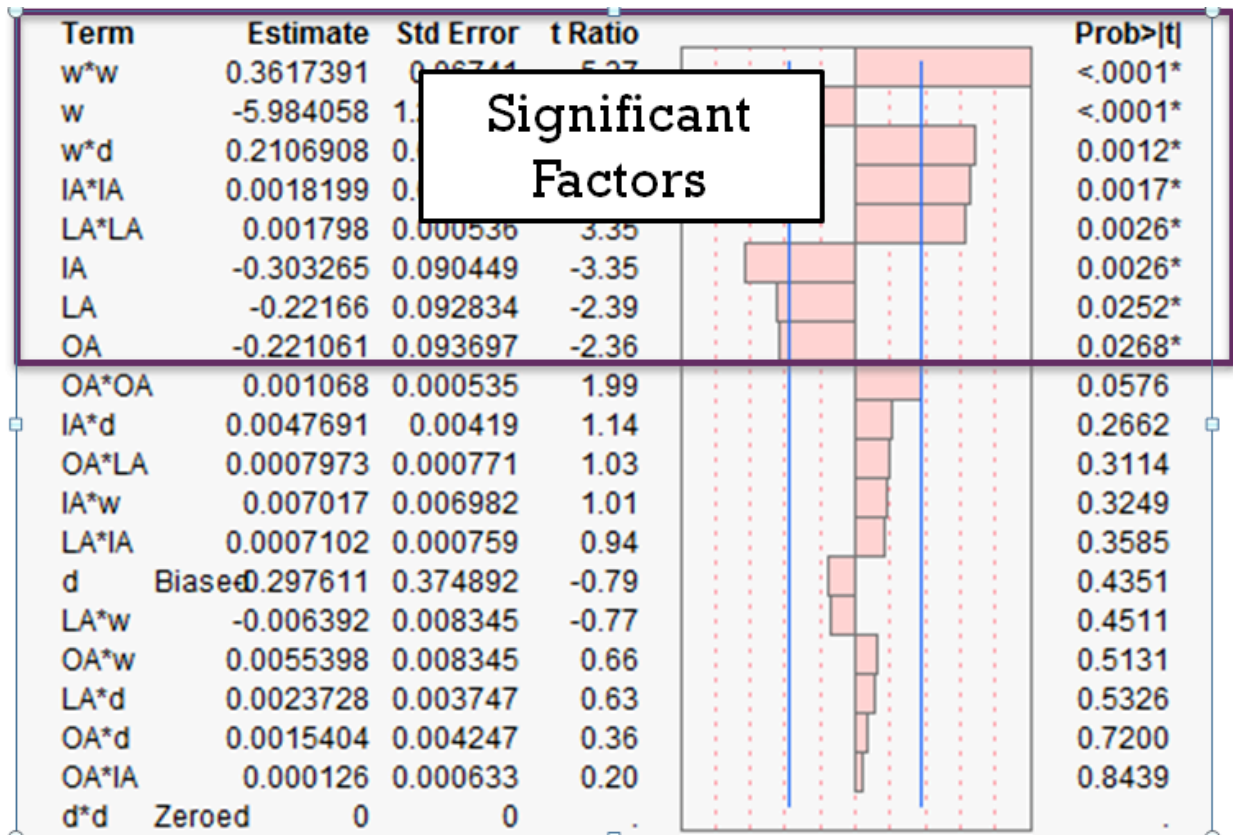| Term	Estimate	Std Error	t Ratio		Prob>|t|
w*w	0.3617391	0.06744	5.37		<.0001*
w	-5.984058	1.			<.0001*
w*d	0.2106908	0.			0.0012*
IA*IA	0.0018199	0.			0.0017*
LA*LA	0.001798	0.000536	3.35		0.0026*
IA	-0.303265	0.090449	-3.35		0.0026*
LA	-0.22166	0.092834	-2.39		0.0252*
OA	-0.221061	0.093697	-2.36		0.0268*
OA*OA	0.001068	0.000535	1.99		0.0576
IA*d	0.0047691	0.00419	1.14		0.2662
OA*LA	0.0007973	0.000771	1.03		0.3114
IA*w	0.007017	0.006982	1.01		0.3249
LA*IA	0.0007102	0.000759	0.94		0.3585
d	Biased	0.297611	0.374892	-0.79	0.4351
LA*w	-0.006392	0.008345	-0.77		0.4511
OA*w	0.0055398	0.008345	0.66		0.5131
LA*d	0.0023728	0.003747	0.63		0.5326
OA*d	0.0015404	0.004247	0.36		0.7200
OA*IA	0.000126	0.000633	0.20		0.8439
d*d	Zeroed	0	0		

Note overlay on figure: "Significant Factors"

Figure 22 - Table of Factors

Data found is shown in the Appendices attachment of this report, reflecting the results found for the X and Y forces, as well as sideflow results. From which led to the development of the equation that represents the relationship of all of the input parameters with a given output. The equation takes into consideration all of the factors used, as defined below:

OA – Orientation Angle

IA – Inclination Angle

LA – Lead Angle

W – Wear

D – Depth of Cut

The following are resulting equations, derived from JMP software:

Force in X Direction

26.3+ **W*W***(0.36) – **W***(5.97) + **W*D***(0.211) + **IA*IA***(0.002) + **LA*LA***(0.0018) – **IA***(0.302)

Force in Y Direction

80.7 + **W*W***(0.917) – **W***(16.1) + **W*D***(0.593) + **IA*IA***(0.005) + **LA*LA***(0.004) – **IA***(0.680)

Side Flow Height

2.27 + **W*D***(0.0635) + **OA*D***(-0.00682) + **OA*W***(0.00761) – **W***(1.13)

Side Flow Width

- 6.49 + **OA*OA***(0.02) + **IA*D***(0.01) + **W*D***(0.091) + **LA*LA***(0.0016)

These equations represent the respective output factors with the effects of the most dominant inputs in a mono layer super abrasive grinding wheel simulation. Comparing this data with actual experiments from Saint Gobain, it will be possible to show the accuracy and precision of the modeled experiments and equations, which will lead to improvements and advancement of grinding processes.

5. Conclusions and Recommendations

Modeling of the physics in grinding process is not a perfected science, which creates gaps due to the complexities in the process. Understanding and modeling the characterization of the microscopic interaction in grinding can be a powerful tool to enhance grinding mechanism understanding, process optimization, and proactive design.

In conclusion, the project was successful in the enhancement of the Cubic Boron Nitride model grains. With Professor Li's study as a framework, time dependent properties were successfully added and taken into account in the series of simulations. With the data collected from the 50+ experiments, the group believes the results are statistically reasonable to able get the functional relationship between the inputs parameters and outputs. This proves that a quantitative relationship is viable to be developed from a single grain micro cutting study.

Furthermore the significant factors and their impacts can be better understood. For the force in the X & Y direction, the significant factors and their interactions are W, IA, LA, LA*LA, IA*IA, W*W and W*D. The significant factors and their interactions for side flow height are W*D, OA*D, OA*W, W. The significant factors and their interactions for side flow width are OA*OA, IA*D, W*D, LA*LA.

This understanding of the microscopic interaction is a very important step but in achieving the final goal, but not the end product. What is needed is a full grinding wheel study using the data derived from this project to simulate a full grinding wheel cutting into a work material. Comparing this with data from Saint Gobain Verification Experiment would validate the work done and show where the work has room for improvements and adjustments.

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