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Magnetic Holding of Synthetic Quartz For Precision Grinding

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for Precision Grinding

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

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The objective of this research work is to investigate the practicality of magnetic workholding of non-magnetic synthetic quartz during high-speed grinding. This research work is sponsored by Quartzdyne and will be used as the starting point to applying single-piece rounding of its quartz. Hypotheses were created that would permit the authors to conclude that magnets are in fact worthwhile workholders for non-magnetic materials. Designs of Experiments were used to reject or fail to reject the null hypotheses.

Experiments were carried out using a custom HAAS lathe, modified into a grinding center with an NSK live spindle, and neodymium-iron-boron magnets used to obtain both the holding and shear forces. Lastly, purchased polyolefin foam bumpers were used to increase the shear force, values were obtained with the Starrett force measurement machine. Input variables for the Design of Experiments (DOE) comprised of the holding force, feed-rate, part rotation, and in-feed size of cuts. Sample rotation relative to the magnets was the singular output variable.

Experimental results were fitted with the correct distribution and modeled. Once a statistically significant model was attained input settings that minimized quartz sample rotation were determined and used to create an optimized program. Two sets of experiments were needed before the data could be properly fitted with a model. Thirteen out of fifteen samples remained stationary during the optimized program, which was adequate in failing to reject the second null hypothesis; *a static sample at 350 RPM will remain static when undergoing high-speed rounding of its outside perimeter*. Comparison of cycle times was crucial in reaching this conclusion; in fact, the cycle time of 7 minutes and 58 seconds for the optimized program was substantially less than Quartzdyne's estimated batch flow per piece cycle time of around 15 minutes. Obtaining a model was not possible or needed for the first hypothesis due to all experiments having zero rotation, therefore the authors also failed to reject the first null hypothesis; *a static sample sandwiched between two permanent magnets with adequate holding force will remain stationary during rotation (min 250 RPM)*

Larger in-feed size cuts are possible when the quartz is square in shape –interrupted cuts. As it becomes cylindrical, cuts were reduced to experimental levels. Also, due to the amount of material being removed, the resin bonded wheel required dressing, without it rotation is expected. Variation was noticed while quantifying the shear force; it is attributed to the polyolefin foam bumper with its inconsistent coefficient of friction. A more uniform material, which can provide repeatable shear force values, would lessen the variation. All optimized program samples turned out perfectly round- even the two that had slight rotation.

Keywords: Saudin Basic, workholding, quartz, grinding, magnetic, magnets, non-magnetic

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1 INTRODUCTION

This chapter introduces the thesis background, purpose, motivation and objectives or goals for the study. It also presents the thesis problem statement along with the hypotheses. Later the methodology for rejecting and or failing to reject the hypotheses is summarized along with sections that outline the definitions, significance and delimitations of the research study.

1.1 Background, Purpose and Motivation

Magnetic workholding devices clamp ferrous metals and aside from light grinding duties most engineers see no substantial benefit in using them (Anon, 1985). The difficulty is in implementing magnetic workholding devices on non-magnetic materials and depending on the circumstances it is not clear if this approach is feasible. Magnet forces are reduced when there is clearance, also referred to as “gap,” which is any space between a workpiece and the surface of a magnet. Gap can be caused by uneven workpieces, rough finish on a workpiece, non-magnetic spacers, and vibration among other things. While much research has been done on magnetic workholding devices for ferrous metals, presently no journal articles can be found on workholding of non-magnetic materials. Some manufacturers use magnets to indirectly clamp non-magnetic materials- but this method is limited and is used case by case.

The purpose of this research study is to investigate the applicability of magnetic workholding of synthetic quartz blocks during high-speed grinding, also referred to as rounding.

In this application, quartz would create a gap between the magnets that would be positioned on both ends of the quartz, holding it in place. Using magnets as work holders for non-magnetic materials presents a challenge because the holding forces are reduced by the gap. However, if this approach is successful there are tremendous benefits for perimeter rounding.

1.1.1 Workholding Overview

Workholding is the method of securing a workpiece; it can be pneumatic, hydraulic, magnetic, and mechanical and so on. Fixturing is a workholding method commonly used in the manufacturing industry (Colvin, F.H., and Lucian L., 1938). It involves the workholding of components and associated planning that is required to properly position, locate, orient and finally clamp a part (Englert, P.J., and Wright, P.K., 1988). Fixturing ensures that all parts produced will maintain a certain level of repeatability, precision, accuracy, interchangeability, and conformity (Henriksen, E.K., 1973). In this study magnets serve as the workholding device or fixture. Workholding methods are limited when it comes to rounding perimeter features of workpieces and for this reason magnetic workholding is valuable. There are two basic functions that a work holder needs to do: securely support a workpiece and allow a cutting tool access to areas of the workpiece that need to be machined (Koepfer, C., 1995). Magnets can accomplish both of these. Pulling forces generated by magnets are uniform across their active areas, unlike conventional workholding methods, the part is held only on the side contacting the magnet, leaving all other sides clear for machining. Fixtures like the magnets serve to reduce working time by allowing quick set-ups and creating a smoother transition from part to part (Colvin, F.H., and Lucian L., 1938).

1.1.2 Synthetic Quartz

Quartz is one of the most abundant minerals in the Earth's continental crust; it is a major component to many rocks and an important rock-forming mineral (Deer, W.A., Howie, R.A., and Zussman, J., 1992). Made up of a continuous structure of SiO_4 (silicon-oxygen tetrahedra) where each oxygen is shared between two tetrahedra. Not all varieties occur in nature, most industry quartz is synthetically produced in autoclaves using the hydrothermal process, which allows for larger, virtually flawless quartz. Synthetic quartz is used because natural quartz is often twinned or in some way distorted (Anthony, J.W., 1997). Quartz is piezoelectric, meaning it develops an electric potential when applied with a mechanical stress, most commonly quartz is used as a crystal oscillator where the resonant frequency of the quartz crystal is changed by mechanically loading it. The first quartz oscillator was developed by Walter Guyton Cady in 1921 (Cady, W.G., 1964). Quartzdyne Inc. (A Dover Company) specializes in the area of using quartz for its piezoelectric properties- its pressure sensor is a *quartz resonator* shown in Figure 1-1.

Figure 1-1: Quartz Resonator

The Quartz Resonator uses the inverse piezoelectric effect to induce the resonator to vibrate at its mechanical resonant frequency when electric fields are applied to its electrodes (Quartzdyne, 2014). Quartz crystal resonators are sensitive to magnetic fields (Brendel, R., 1996). However there is no adverse effect on the quartz when in its basic mineral from.

1.1.3 Abrasive Grinding Overview

The most basic definition of *grinding* is the use of an abrasive to wear away at the surface of a workpiece and change its shape. *Wear* means, the removal of material due to mechanical process under conditions of plowing, cutting or fragmentation. Grinding is in fact the oldest form of material removal (Kegg, R., 1983); as prehistoric man sharpened his tools by rubbing rocks together (Malkin, S., and Changsheng G., 2008). There is no wear without friction or the resistance encountered when one body moves relative to another body with which it is in contact. Grinding fits within the machining classification and it is most often used when a material is too hard or brittle to be machined, such as the quartz mineral. Traditionally it is considered as a finishing process, capable of providing reduced surface roughness values along with narrow ranges of dimensional and geometrical tolerances (Lee, E.S., and Kim, N.H., 2001). It is also a major manufacturing process, which is said to account for about 20-25% of the total expenditures on machining in industrialized countries (Malkin, S., and Changsheng G., 2008).

Hardness of a material can be tested in many ways, for minerals one way is to use the *Mohs Hardness Scale* shown in Figure 1-2. Mohs scale relies on the harder material to scratch the softer material, it relates to the breaking of chemical bonds. At the top of the scale is diamond ranked 10, lowest is talc 1, and quartz is 7 indicating the most efficient way to machine or grind quartz is by using diamond.

Figure 1-2: Mohs Hardness Scale

1.2 Objectives/Goals

This research study is meant to demonstrate and prove the concept or practicality of using magnets to clamp non-magnetic quartz. The purpose is not to implement a single-piece production ready magnetic workholding device- one that will replace Quartzdyne's current batch flow rounding process.

Industry wide magnetic chucks are cutting down set-up times radically when compared to conventional workholding arrangements, like mechanical chucks or vices. To stay competitive manufacturers are on a continuous path to reducing cycle times and cost per part for their products. Users of magnetic clamping devices reduce their cycle times and improve quality per part. Cycle times are reduced due to faster setup times, part loading and part unloading. For Synventive Molding Solutions- one of the world's leading manufacturers of hot runner systems and hot runner components- magnetic chucks reduced their long setup times and increased overall quality, which suffered as a result of multiple fixturing; whenever a part was interrupted sometimes a mark was made in the part (Workholding/Tooling, 2014). Quartzdyne, the principal sponsor of this research study is looking for similar benefits with their grinding batch process which presently uses glue to hold their quartz parts. Their goal is to develop a single-piece magnetic workholding process during rounding, used in the manufacturing of pressure sensors.

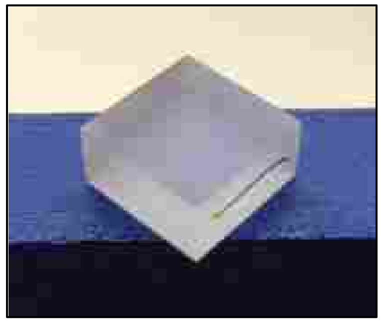


Figure 1-3: Synthetic Quartz Block

Material is received as an individual *synthetic quartz block* shown in Figure 1-3. Currently these blocks are rounded into cylindrical shaped endcaps using a batch process. Before machining quartz blocks are glued and stacked together, although this works it can take up significant non-value added time. Previous single-piece processing efforts involved the gluing of the quartz block to a metal post prior to rounding; this method has long been abandoned due to lengthy setup and cycle times. The quartz blocks are about .625 inches square and .300 inches thick, while the endcaps measure .575 inches in diameter with the same thickness. As stated previously, with batch flow quartz blocks are heated and glued with a special wax; this process is called “stacking”. Figure 1-4 below shows *stacked quartz blocks*.

Figure 1-4: Stacked Quartz Blocks

Stacking takes up a significant time in order to achieve adequate adhesion, over 30 minutes for the first stack, with 9 single quartz blocks per stack. High temperatures are critical for proper adhesion and eventually separation of the stacks, which is done after the blocks are machined. This process is not free of flaws, stacks can come apart during the gluing or more commonly during rounding; therefore it is not uncommon for parts to fracture and get scrapped. Separation is often attributed to inadequate adhesion, inadequate stacking temperature, mishandling, tool wear, poor coolant flow, and misalignment, as well as taper of machine, machine rigidity, and size of cut.

Magnetic workholding for non-magnetic quartz could make single-piece flow possible for Quartzdyne and tremendous benefits would follow. Quartz blocks would no longer need to be glued, heated or cooled, all of which induces fractures. Benefits of single-piece flow will be explored in section 1.2.1 below.

1.2.1 Benefits of Single-piece Flow

Single-piece or what is also called one-piece flow is the concept of moving one workpiece at a time between operations. In contrast batch flow implies producing several parts in one work center then moving them to the next work center once all are completed. While magnetic workholding non-magnetic material is unusual there are clear benefits for companies that are looking to reduce their cycle times and to continue leading in their market segments. Being able to round quartz one-piece at a time would allow Quartzdyne to capitalize on the benefits of single-piece flow effectively keeping out competition and reducing operation costs.

Taiichi Ohno, a prominent Japanese businessman who is considered the father of the Toyota Production System (TPS), known as Lean Manufacturing in the United States, pioneered numerous concepts in said field- many of his notions directly facilitated continuous or single piece flow (Ohno, T., 1988).

“Perhaps the most instructive of Ohno’s insights for us today is the focus on reducing lead time (Liker, J.K., 1997).”

It is said if the emphasis is placed towards reducing the lead time all other processes and measures will follow. This path to reducing lead time is through single-piece flow and where single-piece is not possible then the next best function should be implemented, such as, smaller batches, more frequent changeovers and so on (Liker, J.K., 1997). An objective Quartzdyne greatly values is, how can single-piece reduce lead time? For starters single-piece flow provides a constant product evaluation or a method of building in quality- meaning operators are constantly tracking product performance. When one part is made and moved at a time defects are easier to spot and in most cases it forces an immediate corrective action (Liker, J.K., 1997). Flexibility is also improved, single-piece is faster than batch flow and it is this speed that allows manufacturers to quickly adapt to changing customer orders. Another important benefit is the reduction of inventory, single-piece reduces work-in-process (WIP) and it can also eliminate unnecessary expenditures because manufacturers no longer need to store, move, and manage their inventory; this equates to lower inventory turns. Many of the inherent wastes (like waiting, over-production, rework, motion, over-processing, and conveyance) that come with batch flow are eliminated or at the very least reduced with single-piece flow. JIT (Just-in-Time) manufacturing flourishes in such an environment, an important concept in the TPS. Investopedia, an online dictionary, defines JIT as an inventory strategy that increases efficiency and decreases waste by receiving goods only as they are needed. JIT requires manufacturers to accurately forecast demand. This provides valuable insight on how lead time can be reduced.

If these benefits are not enough, according to the 2013 Liberty Mutual Workplace Safety Index in 2011 overexertion was 25.7% of injuries at the workplace (Liberty, 2013). Implementing single-piece flow reduces the need to move heavy containers of material thus reducing workplace injuries. It can also reduce floor space as work-in-process is reduced. Generally equipment can also be made smaller and cheaper because there is no need for huge batches. Converting to single-piece flow is not without sacrifices, it must be done in gradual steps where proper preparation is made. Quality must improve, changeovers must be reduced and machine reliability must be increased. Single-piece forces manufactures out from hiding behind their buffers of inventory therefore kaizens must be implemented. This is a unique benefit only to single-piece flow, where-in it brings problems to the surface.

1.3 Problem Statement and Hypotheses

The thought is that with sufficient holding forces the quartz would remain static even during high-speed machining and or rounding. However, it is not apparent what holding force (normal to quartz) and shear force (perpendicular to holding force) are required to keep the sample static. If the held sample moves the likelihood of it being out of round is considerably greater, moreover keeping track of the minerals direction is extremely important. Quartz is anisotropic, meaning; it has different properties in its different directions so it is imperative to keep track of its orientation. Some of the anisotropic physical properties in quartz are its hardness, cleavage, thermal conductivity, thermal expansion coefficient, piezoelectricity among others (Akhavan, A.C., 2011). Succeeding processing steps include sealing two quartz endcaps, in order for this to happen the quartz must be heated to elevated temperatures, in which, knowing the direction is vital, if the orientation is off the part could fracture because its different directions expand and contract at different rates. The focus of this research study will be on the relationship between tool feed-rates, the required magnetic holding force and dependent shear force, and lastly size of cuts. In the beginning, it is also essential to recognize the impact of part revolution (RPM) on workholding.

1.3.1 Research Questions

1. Can non-magnetic quartz be held stationary with permanent magnets during rotation in a lathe?
2. Can non-magnetic quartz be held stationary with permanent magnets during grinding of its perimeter while in a live-spindle equipped lathe, with enough precision to create an acceptable part?

1.3.2 Hypotheses

1. A quartz sample sandwiched between two permanent magnets with adequate holding force will remain stationary during rotation (min 250 RPM).
2. A static sample at 350 rpm will remain static when undergoing high-speed rounding of its outside perimeter.

Null hypothesis 1 states, if the quartz sample has adequate holding force it will not move during rotation at 250 RPM (minimum). Alternative for hypothesis 1 is, there is no reasonable holding force that will keep the sample stationary at 250 RPM. For further explanation of "reasonable" in this context means, no currently available permanent neodymium magnet of the required size and shape can apply the necessary force to keep the quartz stationary. No physical contact between the quartz and grinding wheel will occur while testing null hypothesis 1.

Null hypothesis 2 states, if the sample is static at 350 RPM it will remain static when engaging the grinding wheel to its outside perimeter. Essentially holding force will be sufficient to withstand newly introduced tool pressures or applied rotating forces (torque) from the grinding wheel. The alternative is, no reasonable holding force will keep the sample stationary at 350 RPM as the grinding wheel engages the quartz sample's perimeter surface.

Part quality is checked by measuring the roundness; tolerance zone is plus or minus 1 thousandth, suggesting if the machined parts diameter deviates by more than 1 thousandth in either direction it will be considered defective. A static sample is one that did not move from its scribed line during rotation for hypothesis 1 and rotation and machining for hypothesis 2. The magnet sample arrangement has three scribed lines, one line per magnet, and one light line on the quartz block itself. All three entities will be aligned to their scribed lines prior to performing the experiments. Output rotation will be measured between the south pole magnet scribed line and quartz scribed line.

1.3.3 Explanation of Hypotheses Testing

There are two possible outcomes from the hypothesis test:

1. Fail to reject null hypothesis
2. Reject null hypothesis thus accept alternative hypothesis

Failure to reject the null hypothesis does not mean we accept it, it means there was failure to find sufficient proof to reject it- this is because statistical hypothesis testing involves sampling from a population; therefore we cannot be certain about our conclusions (Math n' Stats, 2014).

1.4 Brief Statement of Methodology

Non-magnetic materials can only be indirectly clamped with magnets. Samples will be sandwiched between two permanent cylinder neodymium magnets. Design of Experiments (DOE) is used to test the hypotheses, the three main aspects are: inputs to the process, settings of each input, and the output variable. Experiments will be designed to evaluate which process inputs have a significant impact on the process output and what target settings of the inputs should be to get the desired outputs. Between the two hypotheses four input variables will be used and each input will have different settings. Constant variables will be recognized, which are useful when attempting to replicate experiments, and lastly, one output variable will be used.

When all experiments are completed the data will be uploaded to JMP statistical software, once uploaded, a fit model will be produced from the data. If the model fits the data well (meaning it is statistically significant) the model will be used to predict the behavior of the process inputs. At that point the fitted model could be used to reject or fail to reject the hypotheses. Both the holding and shear force values will be obtained using permanent neodymium magnets, force values will be measured using a Starrett force measurement machine. Both force values will require fixturing in order to hold the magnets and quartz. High-speed rounding experiments will be executed at Quartzdyne's facility using a *Haas OL1 lathe* shown in Figure 1-5. Lathe is equipped with an *NSK live-spindle* and separate controller pictured in Figure 1-6. Live-spindle has a maximum of 60,000 RPM, which essentially converts the lathe into a grinding machine.

Figure 1-5: Haas OL1 Lathe

Figure 1-6: NSK Live-Spindle and Controller

Since quartz is hard, diamond impregnated grinding wheels are used for cutting, more on that will be discussed in later chapters. Samples will be measured using a custom 3D printed fixture that will fit around the magnet. Measurement fixture will have angle depressions around its entire circumference with a resolution of 10 degrees.

1.5 Definitions

Air Gap: Is external distance from one pole of the magnet to the other pole through a non-magnetic material such as air.

Batch Flow: Implies that each unique batch is completed in one work center before the entire batch is moved to the next work center.

Breakaway Force: The force required to detach a magnet from a workpiece surface when the force is applied normal to the workpiece surface and through the center of the magnet. Same as pull force.

CNC Lathe: Numerically controlled machine that rotates a workpiece on its axis to perform various operations such as grinding.

Cross-Feed: The lateral feed of the grinding wheel table.

Electromagnet: A magnet that has a solenoid with an iron core, which has a magnetic field only during the time of current flow through the solenoid.

Endcap: A block shaped quartz sample measuring .625"x.625"x.300".

Ferrous: A material that is the source of magnetic flux or a conductor of magnetic flux. Any ferrous material must have iron, nickel or cobalt.

Gauss: Unit of magnetic induction.

High-Speed Grinding: Grinding at a high-speed.

Holding Value: Magnetic force directly holding a workpiece at zero gap.

In-Feed: Feed of the grinding wheel or tool into the workpiece.

Live-Spindle: Revolving spindle of a machine tool.

Magnet: Object made of certain materials which create a magnetic field. Every magnet has at least one north pole and one south pole.

Magnetic Chuck: Workholding device that is used to hold ferrous parts during machining. It can be permanent or electromagnetic.

Magnetic Circuit: Consists of all elements including the air gaps and non-magnetic materials the magnetic flux travels through.

Material Grade: Neodymium magnets are graded by the magnetic material from which they are manufactured, higher the grade the stronger the magnet. N52 is the strongest grade of permanent magnets available.

Neodymium Magnets: Neodymium (NdFeB) magnets are the strongest permanent magnets in the world. They are members of the rare earth magnet family.

North Pole: Magnet side that is attracted to the magnetic north pole of the earth. By accepted convention, the lines of flux travel from the north pole to the south.

Offshoring: Is the relocation of a business process from one country to another, usually an operational process such as manufacturing.

Outsourcing: Is the contracting out of a business process to another party.

Permanent Magnet: A magnet that retains its magnetism after it is removed from a magnetic field. Neodymium magnets are permanent magnets.

Plating/Coating: Most neodymium magnets are plated or coated in order to protect the magnet material from corrosion.

Pole: An area where the lines of magnetic flux are concentrated.

Pull Force: Force required to pull a magnet free from a flat steel plate using force perpendicular to the surface. It can also be the pull force required to separate two magnets from each other.

Rare Earth: High energy magnet material such as Neodymium-Iron-boron or Samarium-Cobalt.

Rounding: Is the circular or perimeter (edge) machining and or grinding process.

RPM: Revolutions per minute.

Sample Movement: This is the ability of workpiece to move.

Saturation: The state where an increase in magnetizing force produces no further increase in magnetic induction in a magnetic material.

Single-Piece (Lean): Items are produced and moved from one processing step to the next one piece at a time.

South Pole: Magnet side that is attracted to the magnetic south pole of the earth.

Spindle RPM: Spindle speed is the rotational frequency of the spindle, measured in revolutions per minute (RPM).

Stacking: Process of stacking parts one on top of another in preparation for batch flow.

Tool Feed-rate: Rate at which the cutting tool and the workpiece move in relation to one another.

Workholding: Device used to support, locate, and hold a workpiece. Work holder references the tool performing the operation on the part being held.

Workpiece: A part that is being worked on. It may be subject to cutting, welding, forming, machining, or other operations like grinding.

1.6 Significance

According to the Bureau of Labor Statistics, U.S. manufacturing employment has fallen from 19.6 million in 1979 to 13.7 million in 2007. Manufacturing plants have also declined in the last decade, by more than 51,000 plants, or 12.5 percent between 1998 and 2008. The loss of employment is blamed on manufacturing companies who are outsourcing and offshoring jobs abroad. United States Department of Commerce showed that U.S. multination corporations, those that employ a fifth of all U.S. workers cut their work forces by 2.9 million during the 2000s while at the same time increasing overseas jobs by 2.4 million. An unrelated 2012 survey from Duke's Fuqua School of Business showed that nearly three-quarters of respondents indicated labor cost savings as one of the three most important drivers leading to overseas outsourcing.

It is not clear how disruptive overseas outsourcing is on the U.S. economy, in part because data on overseas outsourcing practices is hard to establish, according to the Congressional Research Service; there is no link between employment gains or losses in the United States with the gains and losses of jobs abroad. Furthermore, companies limit the exposure of their outsourcing practices. On the other hand, according to research done by the Hackett Group, the cost gap between the United States and China has shrunk by nearly 50% percent over the past eight years. Despite the shrinking gap, the Duke survey found that

“Only 4% of large companies had future plans for relocating jobs back to the United States (Lach, A., 2012)."

At any rate, the future of U.S. manufacturing is at risk, if not the low cost labor abroad, manufacturing companies can go wayside due to rapidly emerging competition. To keep manufacturing jobs local U.S. companies, especially smaller firms like Quartzdyne are on a continuous track to improving their products and keeping their customers satisfied. Nowadays having quality products, fast delivery and low sale price is the only way in maintaining market share. The rationale is by using magnets to clamp non-magnetic materials such as synthetic quartz, Quartzdyne can attain single-piece flow and as a result gain its benefits. As presented above, this study is particularly important and relevant in this age and time; nowadays manufacturing companies can be made or ruined overnight.

This study is also beneficial to those who are looking at alternative methods of workholding non-magnetic materials. Limited research was found on the use of magnets as workholders for non-magnetic materials. Furthermore, this study contributes to the grinding material removal method, how high-speed grinding of quartz impacts workholding; both the brittle and ductile regime machining is discussed. From the empirical standpoint the study shows how Design of Experiments can be used in determining the reasonableness of a particular method.

1.7 Delimitations

1. Design of Experiments will be done using production synthetic quartz, which has slight variation in size, shape, mass, surface finish and so on.
2. There is confusion in the magnet industry regarding pull force and holding force. Most magnet manufacturers, like K&J Magnetics, treat the holding and pull forces the same, others like Magnetech Corporation say pulling force is not holding force, usually much less. Holding value is the force directly holding a workpiece at zero gap and pull forces are less than holding force because of the inverse proportion of force with the separation between magnets, the closer they are the greater the force. In this study, pulling and holding forces will not be treated the same.
3. Shear force is not pulling force, it is typically less. Shear force is the multiplication of pull force value and the friction factor. To better restrain the sample in the shear direction foam polyolefin rubber bumpers will be used. Aside from increasing the shear force, foam bumpers can prevent possible damage to the quartz and neodymium magnets during the unloading and loading.
4. Rotational force applied on the rotating quartz during grinding will not be measured. This force which is also known as torsion is related to shear force, the larger the shear force the larger the torque is needed to move the sample quartz.
5. Machining speeds will be mostly left out from the study while feed-rates will be included. The interaction between feeds and speeds will also be left out. Authors acknowledge the significance of the speeds and its relationship to feeds, however in order to lessen the complexity of the Design of Experiments constant speeds will be used.

6. Machine stiffness while important will not be measured. Byron Knapp's study on the effects of machine stiffness in grinding brittle materials has shown that an increase in machine stiffness can clearly increase the average grinding forces (Knapp, B.R., 2002). Similarly, cut ability is decreased with increasing machine stiffness (Knapp, B.R., 2002).
7. Surface finish of rounded quartz will not be measured, although important to the production process it is outside the scope. Knapp's study showed surface roughness was independent of machine stiffness (Knapp, B.R., 2002).
8. The study acknowledges the existence and benefit of ductile regime machining; however this method of material removal is outside the scope of this study.
9. Abrasive grinding is an important characteristic of this study, however, due to its many variables this study will keep it constant.

2 LITERATURE REVIEW

The following chapter will review several articles that relate to magnetic workholding of non-magnetic and brittle materials. In general there was a lack of information on the subject, where in most articles focused on workholding magnetic materials such as steel. Only a few sources discussed methods of workholding non-magnetic materials, of which the best source turned out to be a manufacturer of workholding magnets.

2.1 Magnetic Chucks Key to Fast, Efficient Machining

This article gives an example of a real world company that has benefited from magnetic clamping devices. Synventive Molding Solutions, had long setup times and quality suffered as a result of multiple fixturing. After researching alternatives to traditional clamping fixtures they purchased a magnetic workholder. For Synventive the magnetic chucks allowed them to reduce their setup times significantly. Magnetic chucks are also easier and faster to set up than mechanical clamps, and provide uniform support and holding. The solid construction of the magnet dampens machining vibration allowing for faster feeds and speeds, because the chucks use electronically activated permanent magnet holding, they maintain holding power even when disconnected making the chucks portable and suitable for use in off-machine pallet loading applications. For Synventive the process that required two working shifts now takes only four hours. In one operation they can now accomplish what previously took several. The magnetic chuck withstands the forces generated by the milling machine, holding and repeating the required tolerances time and again in the process.

2.2 Magnetic Workholding- Attracting Attention

This article explains how magnetic workholders work, how they are different from other holders, and what applications are best for them. Koepfer explains the two basic things that a workholder needs to do: first, to secure the workpiece and second, to allow the cutting tool to access areas of the work that need to be machined. Magnets are unique in that pulling forces generated by magnets are uniform across their active areas and because the part is held only on the side contacting the magnet, all other sides are clear for machining, as mentioned earlier this concept is important in the application of magnets for rounding quartz. The magnets themselves have a damping effect on the workpiece because they are holding the work over a relatively large contact area.

Two classes of magnets are discussed in detail, first being electro permanent magnets which were first produced in the 1950s, a combination of the permanent and electromagnetic principles capable of being turned on or off. Advantages of electro permanent magnets are portability, permanent magnetism, and no heat generation. Electromagnets are the second type that also provides simple switching of magnetism, either on or off. Electric power is only applied when activating or deactivating the magnets making them portable. Magnets have two poles being the north and south; opposite poles attract while like poles repel. A magnetic workholders surface is comprised of a pattern of north and south magnetic poles. Non-ferromagnetic materials such as stainless steels cannot be used, while mild steels are the most magnetically attractive, hard alloy steels are slightly less attractive and cast iron is considerably less attractive than the mild steel. Irregularly shaped parts can take advantage of magnetic workholding. Compared to conventional general purpose workholders, a 16 by 24-inch magnetic workholder is $7,000, much more expensive than conventional devices. Koepfer adds that magnets never caught on much beyond surface grinding applications.

2.3 Experimental Approach to Electromagnetic Chucking Forces

Similar to the above articles, this journal discusses some of the advantages magnetic workholders have over conventional devices. The common theme is that magnets are used for ferromagnetic materials. With that said there is still benefit in reviewing the article since the same concepts and benefits could be applied to clamping quartz. Furthermore, it discusses applications of magnetic workholders, how clearance and surface roughness affect pull force, as well as how thickness of samples relates to pull forces. Electromagnetic chucks vary with magnetic pole arrangement, workpiece mounting position, thickness, surface roughness, etc. Focus is given in determining the parameters that influence the attraction forces of the electromagnetic chuck. Electromagnets work to a depth, if that depth is a quarter of an inch and the part is half an inch thick then everything above the half point will not be magnetized. If the space needs to be adjusted typically spacers are used to lift the magnetized area. Cheng-liang Liu and Wen-ching Tsai say, the primary advantages of magnetic chucks are the ease of its loading and unloading and the convenience it provides in holding small and or thin parts.

Electromagnetic chucks provide distributed magnetic force to the contact area, and maintain contact with the entire surface of the parts. Regarding material thickness, magnetic flux density is limited, as an example workpieces that have a small cross-sectional area will restrict magnetic flux flow and result in leakage. Thinner samples have less material than thicker samples, which allows magnetic flux to escape. Magnetic force is also dependent upon the contact area, surface roughness, even at the microscopic level can result in *discontinuous surface* *contact* illustrated by Figure 2-1. Think of surface roughness as air gaps or clearance between the materials. Paper was used as gap and results revealed that chucking forces exhibit an exponentially decreasing trend with increasing gap. In the case of this research study the entire quartz block (.300 inches thick) would act as gap.

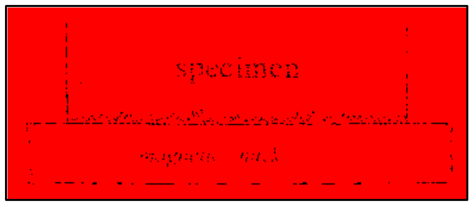


Figure 2-1: Discontinuous Surface

2.4 Magnetic Chucks Attract New Users

Destefani also describes the different types of magnetic chucking classes. He presents a third type, permanent magnet chucks which use ceramic or other magnetic materials embedded in the chuck to provide the force. In this research study forces are obtained using permanent magnets. We also have electromagnetic chucks, mentioned in previous reviews; they exchange electricity for magnetism, requiring a DC power source. Then there are electro permanent chucks which are permanent magnet chucks that are controlled by sending electrical signals to the control magnet, as a result the chuck can be switched on or off by reversing the polarity. Electro permanent chucks actually combine some of the attributes of the other two and once turned on, there is no electricity involved. In addition, the article discusses magnet types, primarily Alnico (aluminum-nickel-cobalt) and neodymium rare earth alloys, which have increased the holding force of permanent magnet chucks.

As important as clamping is, power or the ability to control chuck magnetization and demagnetization is more important, controls are continuously variable between zero and one-hundred percent power for electromagnets and electro permanent magnets. Another important function of controls for electromagnetic chucks is assuring safe operation, most controls have current-sensing features that prevent the machine from being on if the chuck is not already engaged. Magnetization and demagnetization are important for this study since permanent magnets are used, which by default have less control.

2.5 Current Status of Neodymium-Iron-Boron Magnets

This journal discusses the market status of neodymium or more generally rare earth magnets. It states that even when the Japanese market was in recession, the market for neodymium magnets grew due to new applications for the magnets being continually discovered. Neodymium magnets are the most powerful magnets known to man and because they are essential to this research study it is crucial that more understanding about them is gained.

2.6 A Review on the Current Research Trends in Ductile Regime Machining

This article by Neo, Kumar, and Rahman introduces the ductile regime machining (DRM) which is an alternative method of polishing and lapping of brittle materials such as glass, ceramics, tungsten and silicon, to obtain high quality surface finish by ductile or plastic material removal process. Investigation on ductile regime of brittle materials was first suggested back in 1954 (King, R.F., and Tabor, D., 1954). The article reviews the current state of research and development in the field of ductile regime machining. The need for ductile regime machining has risen over the last decade due to increased demands for miniaturized components that have even higher surface finish requirements, higher tolerances, and ultra-precision accuracies. The benefit of ductile regime machining is that unlike other grinding processes that generate micro cracks, it can provide high quality crack-free surfaces. It also allows for machining of brittle materials regardless of their hardness. Finally, due to a higher material removal rate it can provide a better productivity than polishing, as well as being lower in cost.

Unlike brittle regime grinding- where chip formation undergoes brittle fracture mode-deformation in ductile regime machining chip formation undergoes a plastic deformation. A critical parameter in ductile regime machining is the size of the in-feed cut or the chip thickness. It is defined as the value of chip thickness in which the plastic material removal occurs without fracture or cracks occurring. Several papers can be found that have reported equations in determining the critical chip thickness. One such paper is the classical Bifano model for grinding of typical brittle materials and ceramics (Bifano, T.G., Dow, T.A., and Scattergood, R.O., 1991). Bifano, Dow and Scattergood's paper will be reviewed next. Their model is derived from the Griffith fracture propagation criterion and the effective measure of brittleness in the indentation. For elastic-plastic indentation of brittle materials, during light indentation, the region under the indenter behaves as an expanding core with a surrounding uniform high hydrostatic pressure. The shaded region in their model shows the ideal plastic region and the elastic matrix lies beyond that plastic region (Johnson, K.L., 1970). Indentation is then used to evaluate the ductility and the critical measure of ductile regime machining.

Other work in the field of ductile regime machining suggests that the Bifano model is meant for static state machining mode- in real world situations there would also be a dynamic condition (Sun, Y.L., Zuo, D.W., Wang, H.Y., Zhu, Y.W., Li, J., 2011). Therefore a more complex model for chip thickness is proposed which accounts for the deflection of the workpiece and wheel due to elastic deformation. There is also mention about the effects of rake angle and tool edge radius on brittle and ductile regime machining. Lastly, some discussion is presented on the effect of dry/wet cutting conditions for ductile regime machining. The authors acknowledge that brittle-ductile transition of ductile regime machining is still not completely understood due to its complexity, with that, they recommend several studies that would make ductile regime machining more complete.

Quartzdyne desires fracture less quartz resonators for performance related purposes with that said, ductile regime machining loosely relates to the overall goal of this study; more emphasis will be given to it later- if and when the production ready process is considered. Replacing the current brittle regime machining batch process or a forthcoming single-piece process with ductile regime machining may not be feasible because the two techniques have different objectives. Ductile regime machining would be particularly useful as a post machining process, to further improve the surface finish and reduce or eradicate micro fractures. In comparison to brittle regime machining material removal for ductile regime machining is lesser thus driving longer cycle times. Both methods have an appropriate place and time.

2.7 Ductile-Regime Grinding: A New Technology for Machining Brittle Materials

This is the second article discussing DRM of brittle materials. Here Bifano, Dow and Scattergood show why DRM has broken ground, primarily with advances in precision grinding, smaller in-feed rates can be taken which make it possible to grind brittle materials so that the main material removal mechanism is plastic flow and not fracture. Similar to the previous article the critical depth of cut model is discussed and once more, ductile regime machining allows for brittle workpieces to be processed faster than conventional processes such as lapping and polishing.

2.8 On the Use of an Instrumented Spindle to Determine the Effects of Machine Stiffness in Grinding Brittle Materials

Byron Knapp's master's thesis investigates the role of grinding machine stiffness and effect on the relationship between the chip thickness and grinding forces, as well as surface finish and workpiece form. Reviewing Knapp's thesis was beneficial in gaining more insight on grinding variables. At the same time it helped the authors differentiate between important variables and the not so important ones, at least in order to fulfill the purpose of this research study. Unlike this research study, Knapp's study assumed that the predominant mode of material removal is ductile. His instrumented design system addressed the requirements of ductile regime machining for brittle materials. Experiments were done on silicon wafers, which are normally machined using lapping, however ductile regime machining can drastically increase throughput while decreasing cost (Tricard, M., Kassir, S., Herron, P., Pei, Z., 1998). Knapp cites other research in the field of fine grinding techniques that use ductile regime machining which emphasizes that the process of optimization is key to ductile regime machining's success (Pei, Z., and Strasbaugh, A., 2001).

2.9 Magnetech Corporation (Magnet Supplier)

Magnetech Corporation served as the vital source with information on using magnets to clamp non-magnetic materials. It lists the possible clamping methods and in general serves as a worthy source for providing information on magnets, like how they work and what problems you can have with using them. Some material found here was used in the delimitations section.

2.9.1 Four Ways to Directly Clamp a Non-Magnetic Part

1. *Non-Magnetic Part Sandwiched Between Magnet and a Steel Plate*; see Figure 2-2 below. The non-magnetic part is considered a gap. This is not an efficient method unless the part is very thin.

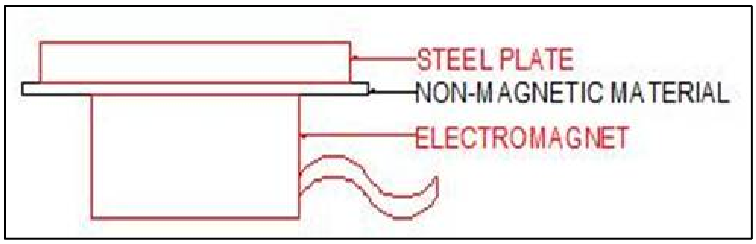


Figure 2-2: Non-Magnetic Part Sandwiched Between Magnet and a Steel Plate

2. A non-magnetic part is sandwiched in between an electromagnet and a permanent magnet. Usually, it consists of a parallel electromagnet and a U shape permanent magnet.
3. *Non-Magnetic Part Sandwiched Between Two Magnets*; see Figure 2-3 below. This is the chosen method for this research study, except permanent magnets will be used instead of labeled electromagnets. Typically the same size magnets are used but it is not required.

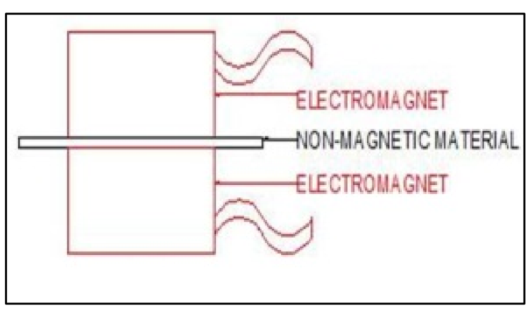


Figure 2-3: Non-Magnetic Part Sandwiched Between Two Magnets

4. *Magnet Directly in Contact with a Steel Plate*, Figure 2-4 below. Attach a bracket to a magnet and use that bracket to clamp a non-magnetic part. For this method any thickness material can be clamped without losing much of the holding power. Clamped material would have to be offset making this clamping method not suitable for turning workpieces.

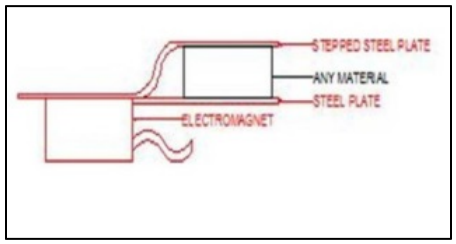


Figure 2-4: Magnet Directly in Contact with a Steel Plate

2.9.2 Direct Contact with an Air-gap

Magnets have less of a holding value in presence of air-gaps between a magnet and a workpiece. Holding value diminishes exponentially with air gaps. Again, in this research study quartz acts as an air gap.

2.9.3 Direct Contact without an Air-gap

Magnets whether electromagnets or permanent magnets have a maximum holding value at direct contact with workpieces.

2.9.4 Reasons for Experiencing Less Holding Values

1. Contact area of a workpiece is smaller than the contact area of the magnet.
2. An uneven surface of a workpiece creating distance between the magnets.

3. Air gaps between magnets and or workpiece.
4. Thin workpieces, like sheet metal, reach magnetic saturation and cannot carry all the magnetic flux through- the stray flux gets wasted. In this case the holding value will be reduced and limited on the flux retained in the thin workpiece.

2.9.5 Pulling, Shear and Peeling Forces

Pulling force is not holding force, usually much less than holding value. Holding value is the magnetic force directly holding a workpiece at zero gap. Pulling force is misunderstood by many users, in which it is thought that an electromagnet pulls or draws a workpiece at gap or distance.

Shearing force is not holding force, usually much less than the holding value. It is the multiplication of the holding value and frication factor or coefficient of friction. Figure 2-5 below shows the *friction force illustration*.

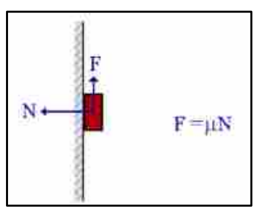


Figure 2-5: Friction Force Illustration

As an example, you might experience that it takes more force to take away a refrigerator magnet than to slide it. Magnets only provide a force normal to the object- be that a steel plate or another magnet- they do not oppose the downward pull of gravity. Only the friction force mentioned earlier keeps the magnet from sliding, this applies to the magnet and quartz arrangement in this research study. This is why foam polyolefin adhesive backed bumpers will be used. The coefficient of friction is an empirical measurement and therefore has to be measured, this will be done later. Figure 2-6 below graphically illustrates the difference between *pull and shear force*.

Figure 2-6: Pull and Shear Force

Peeling force is not holding force; when separating a magnet from a workpiece by opening a corner of contact surface it creates a gap that radically reduces the holding value.

Lastly, leverage force is not holding force. When a magnet holds well and does not slide the weight of the object or another magnet tends to rotate it off the surface it is held onto. The further out from the face the object or magnet sticks out, the more leverage it has to pry the magnet off (KJ Magnetics, 2014). Below Figure 2-7 compares *two leverage scenarios*, lower leverage A and increased leverage B. It would be easier to remove the object from the wall in example B.

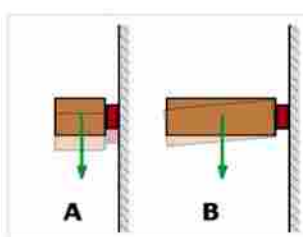


Figure 2-7: Two Leverage Scenarios

3 METHODOLOGY

This chapter will focus on the planning and methods of carrying out the research study hypotheses. Design of Experiments will be used to plan the experiments and all its inputs, outputs and constant variables will be explained. Additionally more details will be provided on the chosen neodymium magnets, like their holding and shear force values and how they will be obtained and measured. Similarly the rounding process will be discussed in depth, including the grinding equipment, rounding program, tool approach, as well as the tool shape and composition.

3.1 Overview

Experiments will be designed to evaluate which process inputs have a significant impact on the process output and what target settings of the inputs should be in order to get the desired output. Design of Experiments results will allow us to determine what parameters if any can keep the quartz stationary during high-speed grinding. Most commonly in scientific experimentation there is independent variables that are deliberately changed, dependent variables that change as a result of the independent variable and constant variables that are left unchanged. For this research study the same applies, there are several variables to consider and in order to keep everything controlled, experiments will be restrained within the Design of Experiments. Inputs (or factors) link to independent variables, target settings are the levels, and the outputs (or responses) are the dependent variables.

Upon competition of the Design of Experiments, results will be uploaded to the JMP (pronounced "jump") statistical software where fit models will be created to better understand the interaction of the variables. Fitting is the procedure of selecting a distribution that best fits the data set. In more ways than not this research study is a process, like any process there are steps to be followed: step 1, plan and create the Design of Experiments using JMP, step 2, complete experiments, step 3, analyze results and step 4, reject or fail to reject the null hypothesis.

3.2 Design of Experiments Variables

There are four input variables between the two hypotheses. Target settings for the input variables range from 2-level up to 8-level. Constant variables will also be used, convenient when attempting to replicate the results. Upon completion, Design of Experiments results will be posted and uploaded to JMP and fit models will be created to better understand the interaction of the variables. Input variables are all continuous, output variables are positive continuous, meaning there cannot be negative values for it. Table 3-1 shows the input variables, its target settings and the single output variable for both hypotheses.

Table 3-1: DOE Hypotheses Variables

[redacted]

North pole rotation is not labeled as an output variable in either of the hypotheses, this is because its rotation is irrelevant to the goal of the research study. Unlike the south pole magnet, the north pole magnet is not clamped and therefore it is expected to rotate whenever the sample breaks loose from the south pole magnet. The north pole magnet should never rotate in respect to the sample quartz unless one or both of them completely fall out during rotation; this was observed from early experimentation. Purchased foam bumpers were used in both Design of Experiments as constant variables because without them considerable rotation was observed, in fact, typically the sample would fall out. Following each experiment the bumpers will also be dried.

There are alignment concerns during the initial loading of the magnet and sample arrangement, if the magnets are not in-line with each other, this will translate to variation during experimentation. Instead of assuming the magnet alignment, plastic *alignment fixture* shown in Figure 3-1 was made, which forces the magnets to be in-line with each other and the quartz block or endcap. As a side note, all hypothesis 1 experiments were done without the alignment fixture; it was implemented after, during hypothesis 2 testing. Another benefit of the fixture is that it sets the tool zero position each time the samples get loaded.

Figure 3-1: Alignment Fixture

3.2.1 Hypothesis 1 - DOE

Null hypothesis 1 states, a quartz sample sandwiched between two permanent magnets with adequate holding force will remain stationary during rotation (min 250 RPM). Two input variables will be used, holding force and part rotation. Two constant variables are the foam bumpers and 1-minute rotation time. Table 3-2 shows the planned hypothesis 1 Design of Experiments created using the custom design tab in JMP.

Table 3-2: Hypothesis 1 DOE

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]

3.2.2 Hypothesis 2 - DOE

Null hypothesis 2 states, a static sample at 350 rpm will remain static when undergoing high-speed rounding of its outside perimeter. Input variable feed-rate was added and part rotation was excluded, which is now 350 RPM and a constant variable along with coolant, grinding wheel rotation 20,000 RPM, and foam bumpers. Table 3-3 shows the hypothesis 2 Design of Experiments created using the full factorial design tab in JMP.

Table 3-3: Hypothesis 2 DOE

Recall that quartz is anisotropic, meaning it has different properties in all of its directions, so it is imperative to keep track of its directions by preventing rotation. Incorrect orientation equates to scrap down the process stream. A static sample is one that did not move from its scribed line during rotation for null hypothesis 1 and rotation and rounding for null hypothesis 2. Magnet sample arrangement will have three scribed lines, one per magnet, and one shallow line on the quartz block itself. All three objects will be aligned to their scribed lines prior to running the experiment. As you would expect the critical rotation is between the south pole magnet scribed line and quartz scribed line. Part roundness will also be checked after each experiment, where the tolerance zone is plus or minus 1 thousandth. Final part diameter must not deviate by more than 1 thousandths or the part will be considered defective.

If the quartz block cannot be kept static during hypothesis 1 testing there would be no value in testing hypothesis 2. Input and control variables ought to affect the samples angle rotation, to be measured using a 3D printed *circular ring gauge* illustrated in Figure 3-2. Resolution for the gauge is 10 degrees. Ring gauge is placed over the magnet and the number of partitions between the two scribed lines is totaled.

Figure 3-2: Circular Ring Gauge

Quartzdyne's current rounding batch per-part cycle time is estimated at 15 minutes. Note cycle time is directly dependent on the linear feed-rate, where a slow feed-rate equates to a longer cycle time and a fast feed-rate means shorter cycle time. For the duration of the Design of Experiments emphases will not be placed on the finish sample size (.575" in diameter) or cycle time. The purpose of this Design of Experiments is to determine what size in-feed cuts are acceptable and once statistically significant results are obtained a new program will be designed that will use a combination of the newly determined in-feeds, holding forces, and feed-rates that are required to machine the sample within the 15 minute allowed time frame. A production process would be indifferent to the size of cuts as long as quality parts are produced in 15 minutes or less.

3.3 Method

Taking into consideration the goal of this research study, to adequately clamp and subsequently grind synthetic quartz, we recognize the best approach is to sandwich the non-magnetic sample between two magnets. Usually this consists of two identical electromagnets or permanent magnets, since this research study is not meant to implement a production ready workholding device, easily obtainable permanent magnets will be used. Quartz samples will be clamped between two axially magnetized permanent neodymium magnets, which are the most powerful permanent magnets in the world (Robinson, A.L., 1984). Neodymium magnets are members of the rare earth magnet family, referred to as NdFeB magnets or NIB because they are composed mainly of Neodymium (Nd), Iron (Fe) and Boron (B). Neodymium magnets are available in different grades, generally higher the grade the stronger the magnet, and according to several magnet manufacturers presently the highest grade of neodymium magnet available is N52 (KJ Magnetics, 2014). Magnet grade relates directly to holding forces. Usually magnets are plated or coated because if exposed to elements the iron in the magnet will rust, nickel plating is the preferred method while some manufactures also offer rubber-coated magnets. Magnets can be purchased in various shapes and sizes like discs, cylinders, blocks, rings, and spheres.

3.4 Pull Force and Gap Calculators

Magnet manufacturers like K&J Magnetics provide calculators to estimate pull force, repelling force, gap, etc. K&J Magnetics states, that the expected pull forces are based on extensive product testing, and the gap is derived from FEA (finite element analysis) of a pair of equal sized cylinder magnets in free space.

Pull force calculator shown in Figure 3-3, estimates the force between two axially magnetized N52 cylinder magnets that are ½ inch in diameter and ½ inch in length. This study is focused around case 3 – magnet to magnet. Calculated force is 18.08-LB, which means theoretically this magnet should lift an object that is 18.08-LB, however since these are laboratory calculations the same pull force would not be achieved under real world conditions.

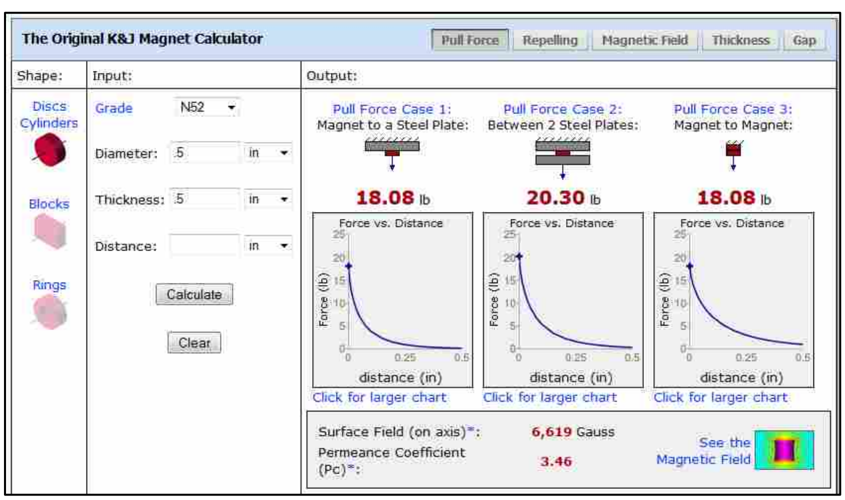


Figure 3-3: Pull Force Calculator

Recall that any gap between magnets will diminish the pull force. The calculator shown above allows the user to enter a distance between the two magnets or a gap. Adding a distance of .300” (sample thickness) to the same N52 magnet reduces the pull force to a meager 2.36 LBF. Using the Starrett the *actual pull force* was determined to be 2.19 LBF, shown in Figure 3-4. Magnet strength and plating variation is the likely reasoning for the small .17 LBF difference.

Figure 3-4: Actual Pull Force

Gap force calculator, shown in Figure 3-5 measures the magnetic field strength in gauss, at the center axis between the magnets. Notice the input column is populated with the same magnets used in the pull force example earlier. The closer the magnets are to each other, the higher the unit of magnetic induction will be. Due to magnet variation no calculator can determine the exact holding and pull force values, such tools are still helpful in estimating sizes and grades for magnets. Also, with a few assumptions, flux density (in Gauss) can be related to the pull force.

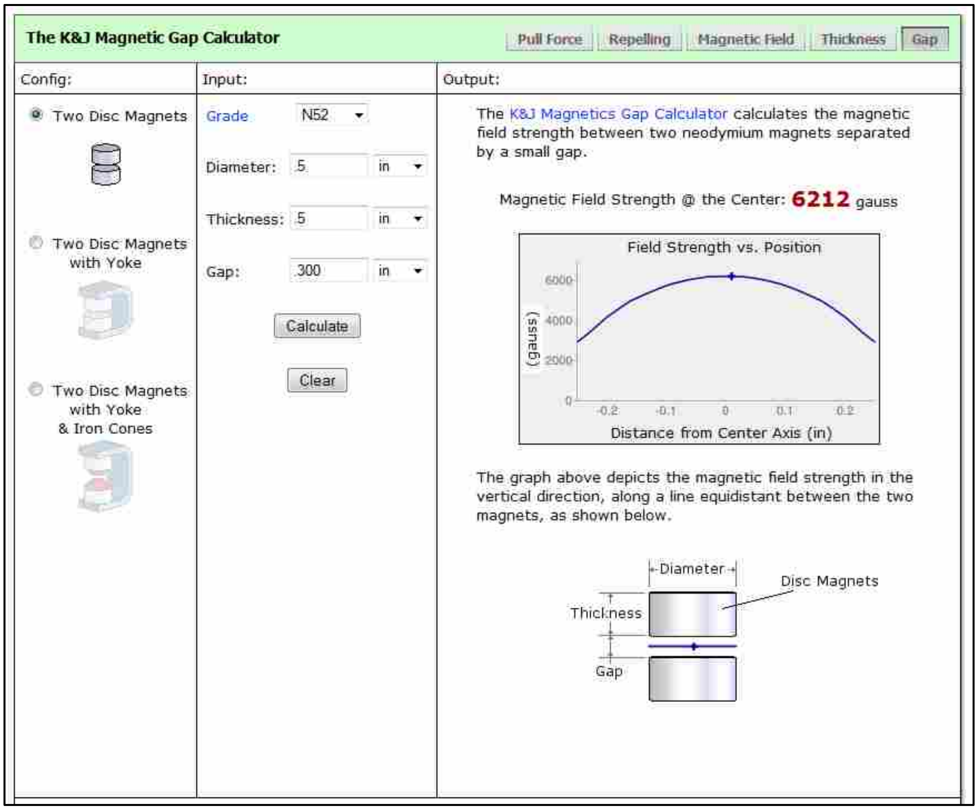


Figure 3-5: Gap Force Calculator

3.5 Holding Force Measurement

Eriez, recognized as world authority in advanced technology for magnetic inspection applications states that, most magnet manufacturers have adopted standard test equipment which measures the holding force of a magnet (Dudenhoefer, B., 2013). They provide pull test kits and instructions on determining the holding values for magnets. In the same way, MDFA (Magnet Distributors and Fabricators Association) gives step-by-step instructions in their Standard MDFA 101 95 (Test Method for Determining Breakaway Force of a Magnet). Test method scope states, “This test method addresses the measurement of the normal force required to detach a magnet from a work load surface. This test method covers both electro and permanent magnets (Integrated Magnetics, 2014).”

They refer to the pull force as the magnet breakaway force, which is determined from the measurement of the holding force of a magnet against a test plate. A gradually increasing load is applied in the direction that is normal to the workpiece and through the center of magnet magnetization. The load that separates the magnet from the test piece is defined as the breakaway force, which is dependent on magnet material, shape, pole material, pole configuration, workload mass, composition, roughness, flatness, air gap, and temperature of the magnet (Dudenhoefer, B., 2013). Air gaps may be introduced by design, which is the case in this research study, also by changes in the surface roughness, by formation of rust, and by coatings such as the nickel plating. Breakaway force diminishes exponentially as the air gap is increased.

In this research study holding and pull force values will be acquired using a Starrett FMS-500-L2 force measurement machine, with a load capacity of 112 ft-lb, well above what the magnets can exert. Measurements would be comparable to Standard MDFA 101 95 mentioned earlier. Two custom non-magnetic stainless steel holders were machined that will attach to the existing posts on the Starrett. *Non-magnetic stainless steel holders* are shown in Figure 3-6, which will clamp the magnets inside their roughly ½” diameter hole by means of a set screw.

Figure 3-6: Non-magnetic Stainless Steel Holders

South pole magnet(s) will be fixed to the platform, quartz block would be centered on it, and north pole magnet will be on the moveable side that contains the load cell. As the north pole magnet moves towards the quartz block it will push on it then retract, producing the holding and pull force values. Measurement machine *program window* for both holding values are shown in Figure 3-7 below.

Figure 3-7: Program Window

3.5.1 Magnet Specification

Cylinder magnets will be used which can be magnetized in two ways, axially or diametrically. Axially magnetized neodymium magnets are better suited due to their greater pull force. Figure 3-8 shows the two *cylindrical magnetization methods*.

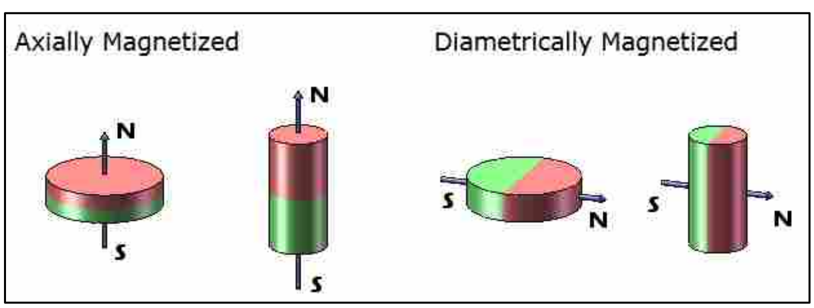


Figure 3-8: Cylindrical Magnetization Methods

Magnets will need to be smaller in diameter than the diameter of the machined sample (endcap) i.e. if the sample is ½ inch in diameter the magnet diameter must be smaller than ½ inch. Thanks to the wide range of available magnet sizes and shapes our research magnets will be purchased off the shelf. As stated earlier different grades of neodymium magnets exist, some are stronger than others, holding forces will be determined by the combination of magnet grade, diameter and length. Not all magnets are created equal, meaning the same size and grade magnet can have different holding values.

3.5.2 Magnet Sizes

Holding values are the most important variable, obtained by mixing and matching different length and grade neodymium magnets of the same diameter. Stacking two or more magnets together will act similar to a single magnet of the combined length. Table 3-4 shows the chosen magnets for hypothesis 1. North pole magnets are bolded.

Table 3-4: Experiment Magnets (H1)

Magnet No.	Low Force	High Force
Magnet 1	½" dia. X 1/8" thick disc, grade N45, Ni plated, axially magnetized	½" dia. X ½" thick cylinder, grade N52, Ni plated, axially magnetized
Magnet 2	[illegible]	[illegible]
Magnet 3	n/a	[illegible]

Larger magnets were used in order to maximize the holding force for hypothesis 2, shown in Table 3-5. North pole magnets are bolded again. Measurements were repeated multiple times and several days apart to verify the holding forces are accurate and repeatable.

Table 3-5: Experiment Magnets (H2)

Magnet No.	Low Force	High Force
Magnet 1	[illegible] dia. X [illegible] thick disc, grade [illegible], [illegible] plated, axially magnetized	[illegible] dia. X [illegible] thick cylinder, grade [illegible], [illegible] plated, axially magnetized
Magnet 2	[illegible] dia. X [illegible] thick cylinder, grade N52, Ni plated, axially magnetized	[illegible] dia. X [illegible] thick cylinder, grade N52, Ni plated, axially magnetized
Magnet 3	n/a	[illegible] dia. X [illegible] thick cylinder, grade [illegible], [illegible] plated, axially magnetized

3.5.3 Resultant Holding Values

Holding values were obtained by measuring four quartz blocks (labeled A, B, C, D), one rounded endcap (labeled E), and the true gap (labeled F). Table 3-6 shows the holding values for hypothesis 1 and Table 3-7 for hypothesis 2. *Magnets with quartz samples* are pictured in Figure 3-9.

Table 3-6: Holding Values (H1)

Sample Label	Dimensions	Low Force	High Force
A	[illegible]	[illegible]	[illegible]
B	[illegible]	[illegible]	[illegible]
C	[illegible]	[illegible]	[illegible]
D	[illegible]	[illegible]	[illegible]
E	[illegible]	[illegible]	[illegible]
F	[illegible]	[illegible]	[illegible]

Table 3-7: Holding Values (H2)

Sample Label	Dimensions	Low Force	High Force
A	[illegible]	[illegible]	[illegible]
B	[illegible]	[illegible]	[illegible]
C	[illegible]	[illegible]	[illegible]
D	[illegible]	[illegible]	[illegible]
E	[illegible]	[illegible]	[illegible]
F	[illegible]	[illegible]	[illegible]

Figure 3-9: Magnets with Quartz Samples

Force versus distance graphs were created for each measurement. Figure 3-10 and Figure 3-11 show the *low and high force graphs* for hypothesis 1. Figure 3-12 and Figure 3-13 show the *low and high force graphs* for hypothesis 2.

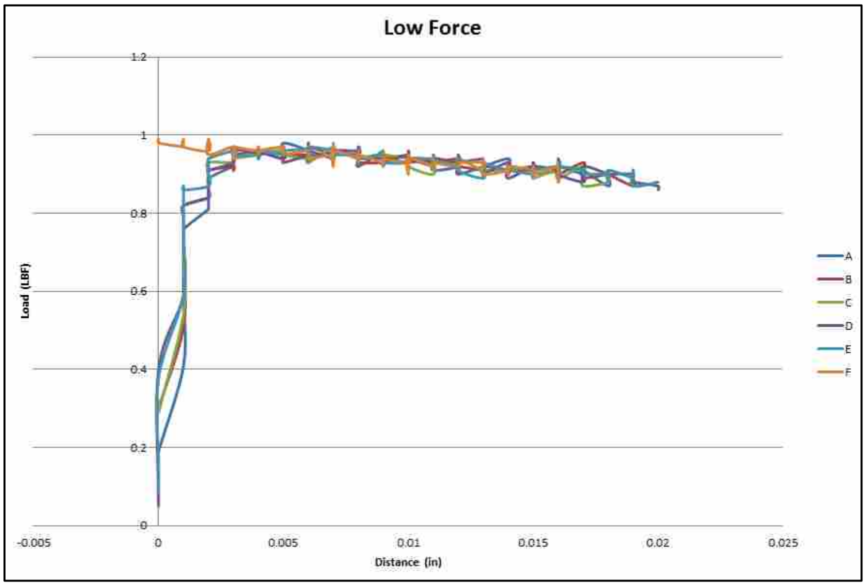


Figure 3-10: Low Force (H1)

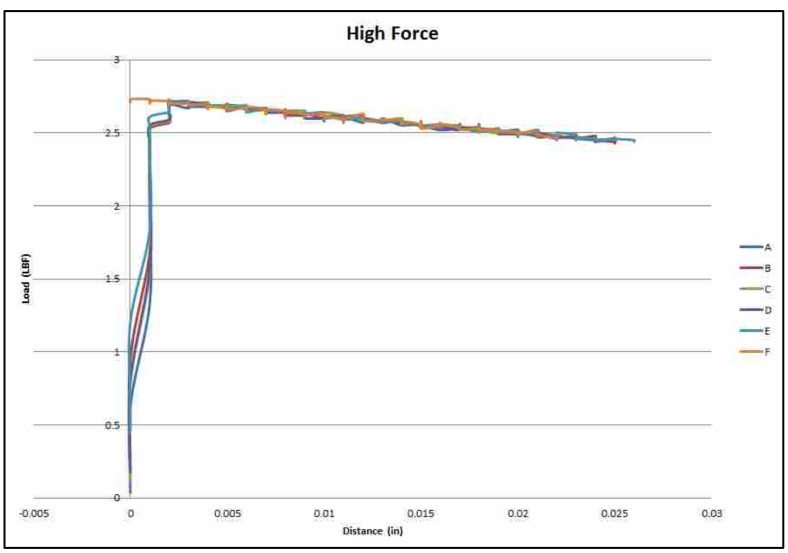


Figure 3-11: High Force (H1)

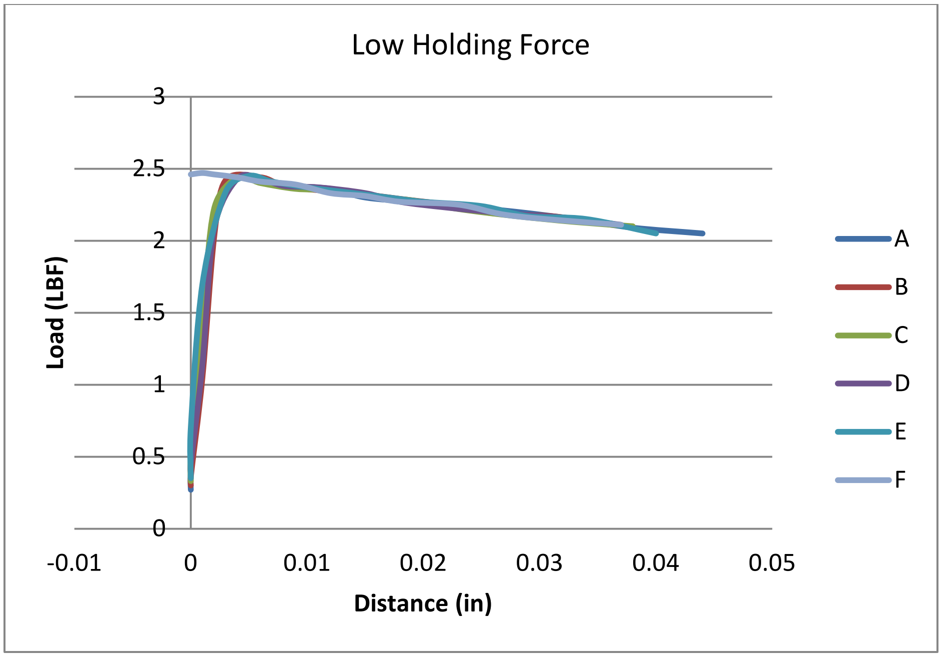


Figure 3-12: Low Force (H2)

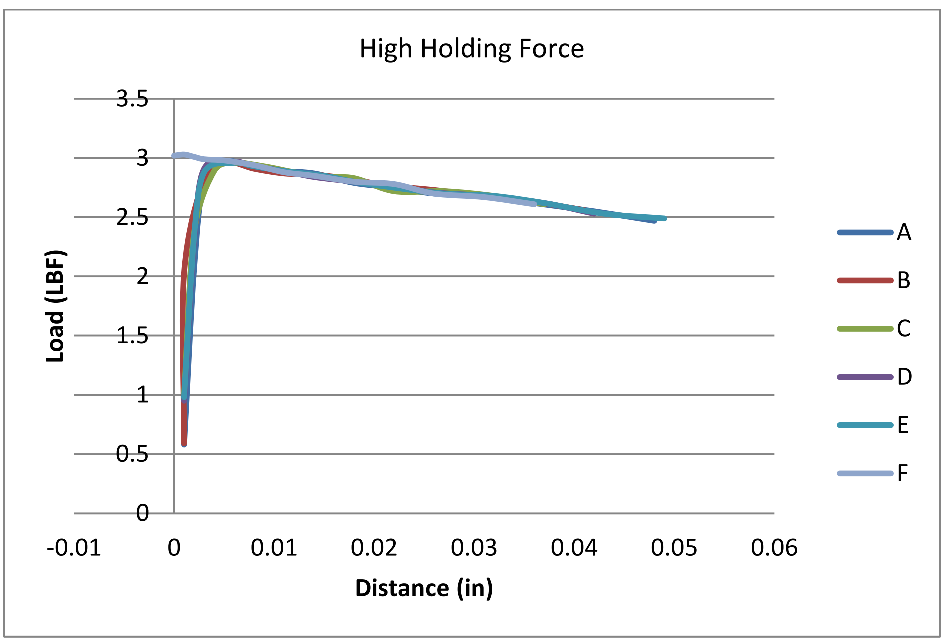


Figure 3-13: High Force (H2)

Notice that in all measurements the quartz sample had no effect on the holding value. For example, sample F produced almost the same holding value despite that no quartz was even used, this confirms that quartz acts as air gap. Measurement average was used as the official holding value.

Not all magnets of the same diameter, length, and grade produce equal holding values, during the low and high force measuring a minimum .10 LBF difference was observed between what appeared to be identical magnets. Starrett machine can calculate the pull force (Lbreak) and holding force (Lpeak). Typically the pull force was 10% less than the holding force. Figure 3-14 and Figure 3-15 show *sample measurement* results from each hypothesis.

Figure 3-14: Sample Measurement (H1)

Figure 3-15: Sample Measurement (H2)

3.6 Shear Force Measurement

Starrett machine was also used to determine the shear force values, which can be calculated by multiplying the holding value by the frication factor. A custom *two-part shear force fixture* shown in Figure 3-16 was designed to orient the magnets perpendicular to the load cell. Labeled moveable part is attached to the Starrett load cell, as it moves up, directly perpendicular to the holding force the shear force value is produced.

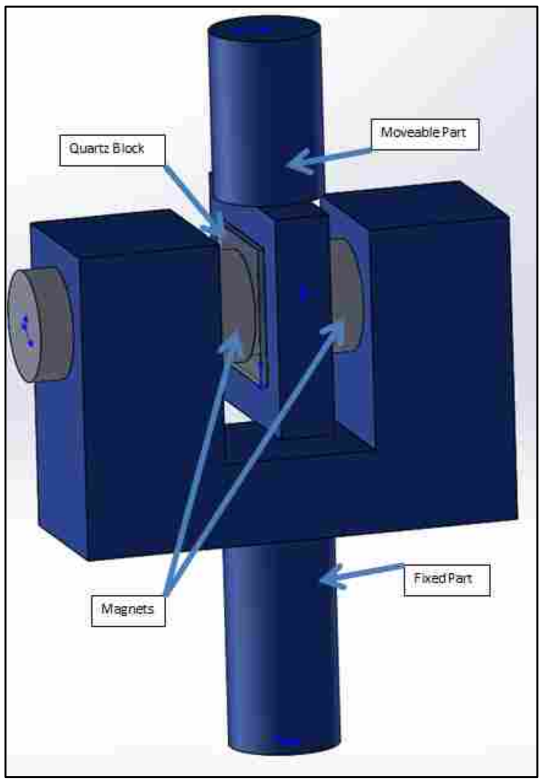


Figure 3-16: Two-part Shear Force Fixture

Starrett shear force program is shown in Figure 3-17. It is designed to pull the quartz away from the magnets at 50 inches per minute to a distance of .275 inches from the center. An average from six measurements was used to determine the shear force. Figure 3-18 shows the *shear force fixture in the Starrett* machine.

Figure 3-17: Starrett Shear Force Program

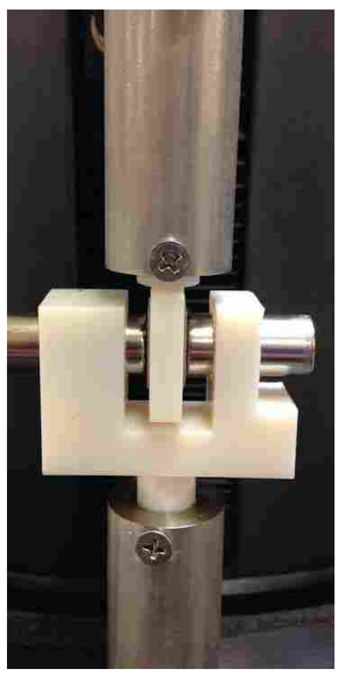


Figure 3-18: Shear Force Fixture in Starrett

3.6.1 Polyolefin Bumpers

To increase the shear force an *adhesive-backed foam rubber bumper* is used, shown in Figure 3-19. Specifically, medium-soft polyolefin ½" diameter and 1/16" thick bumpers with the McMaster-Carr part number 8213K1; bumpers are altered by removing the harder top layer making them thinner. Magnets along with the foam bumpers are then placed on a metal substrate to further reduce the gap by flattening the foam material.

Figure 3-19: Adhesive-Backed Foam Bumper

3.6.2 Resultant Shear Values

The benefit of measuring shear force was realized during preparation for testing null hypothesis 2; therefore no values are presented for null hypothesis 1. Figure 3-20 and Figure 3-21 show the *low and high force versus distance graphs.* Notice values are shown with and without foam bumpers. For the low shear, average with bumper was 2.63 LBF, which is larger than the holding force 2.46 LBF. Removing the bumper drops the force to 1.15 LBF. For high shear, average with bumper was 2.97 LBF, close to the holding force 3.02 LBF. Without the bumper the shear force drops to 1.37 LBF.

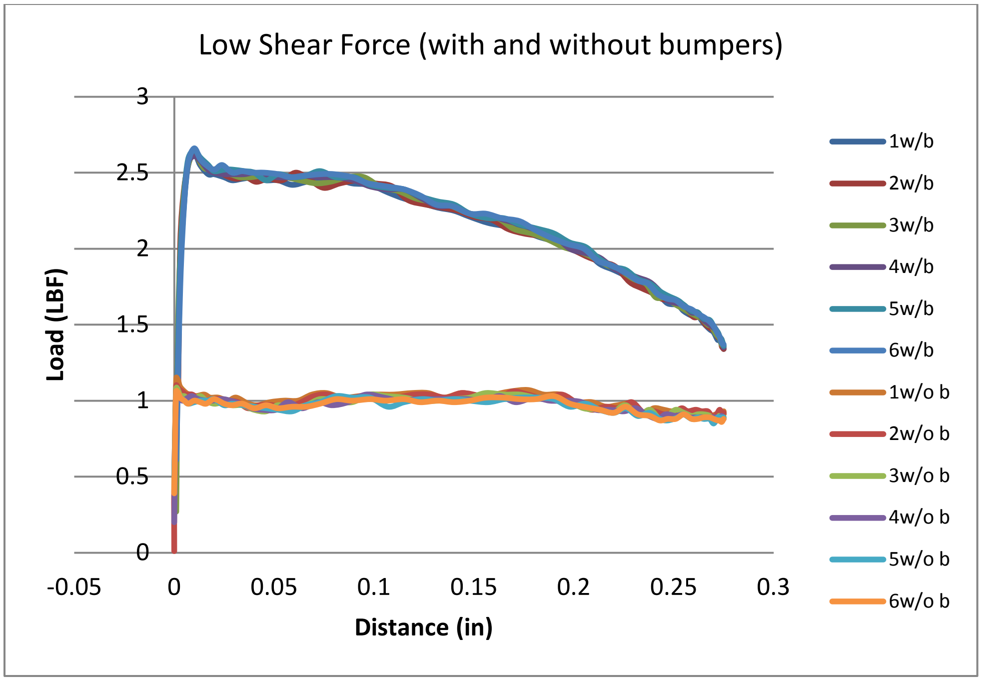


Figure 3-20: Low Force vs. Distance Graph

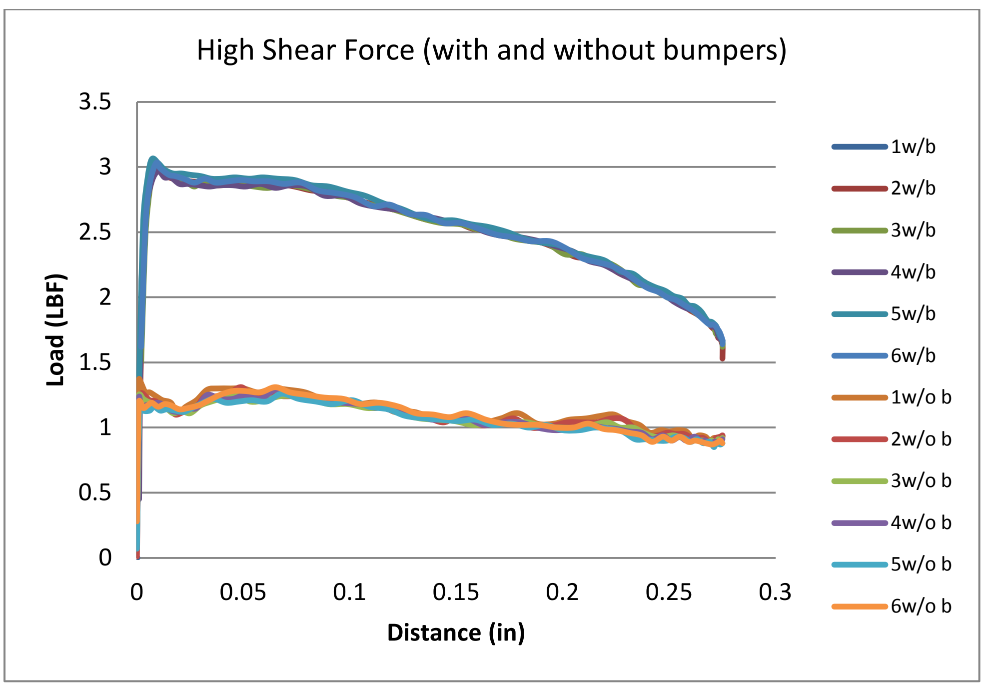


Figure 3-21: High Force vs. Distance Graph

Magnets were positioned in and around the same location in all experiments, in doing so there was minimal variation. By rotating the magnets as much as 1 LBF difference was detected; with that, produced shear force values should be taken lightly. Variation can be attributed to the difference in texture and thickness of the bumpers along the diameter. Further variation can be attributed to alignment issues within the fixture, magnets and the Starrett machine.

3.7 Abrasive Grinding

A brief explanation of abrasive grinding was given earlier in the introduction chapter, as indicated, grinding is the use of an abrasive to wear away at the surface. Society of Tribologists and Lubrication Engineers (STLE) state modern research has presented 12 main types of wear (STLE, 2014). This study will focus primarily on abrasive wear, American Society for Testing and Materials defines it as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface (Standard Terminology Relating to Wear and Erosion, 1987). This wear occurs when either a rough, hard surface or soft surface with hard particles embedded in its surface slides over a softer material (STLE, 2014). There are three common mechanisms of abrasive wear: plowing, cutting and fragmentation. Quartzdyne does forced material removal by cutting and plowing, both of which belong to the *two-body abrasive wear mechanism* shown in Figure 3-22.

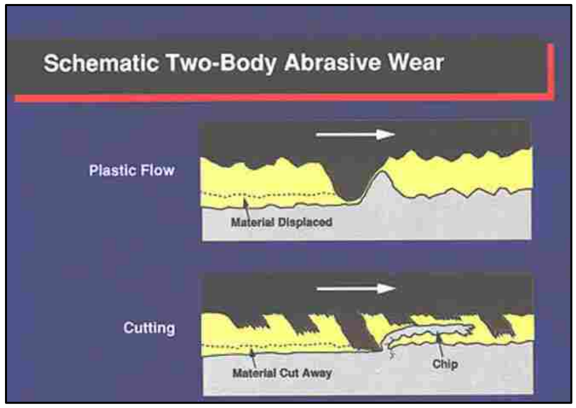


Figure 3-22: Two-body Abrasive Wear Mechanism

With plowing, material is displaced to the side away from the wear particles. Ductile regime machining (DRM) resides in the plowing mechanism of wear; notice the plastic flow label. With cutting material is separated from the surface in the form of microchips, on a microscopic scale the chip formation during abrasive cutting is the same as that found during conventional machining. Cutting is what we would refer to as brittle regime machining, where size of cuts are larger and cracks are expected. Figure 3-23 shows an example of *cutting marble with diamond* (Wang, C.Y., and Clausen, R., 2002). Fragmentation falls under the three-body abrasive wear, where the grit particles are not embedded into either of the surfaces and are free to move.

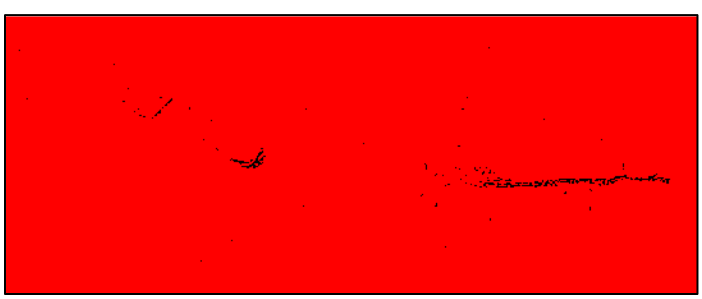


Figure 3-23: Cutting Marble with Diamond

Quartzdyne also does high speed grinding which takes advantage of easier forming of chips, and where cutting forces decrease during the increased cutting speeds because of higher temperature at cutting zones. Chip sizes also get smaller, this means that less thermal energy goes into the workpiece and more thermal energy is taken out by the chips. For high speed grinding, high velocity of coolant is required as well as lots of power from the live-spindle and high stiffness from the grinding machine.

3.7.1 Cutting Fluids

Fluids help with heat removal by minimizing the heat produced due to friction (Eduardo, C.B., Paulo, R.D.A, Anselmo, E.D., Rubens, C.C., 2011). Fluids also help with chip removal, an important and often forgotten purpose of cutting fluids. When abrasive tools are used, a reduction in cutting fluid makes it difficult to keep the grinding wheel pores clean, this is certainly the case with quartz (Eduardo, C.B., Paulo, R.D.A, Anselmo, E.D., Rubens, C.C., 2011). That is why metal bonded grinding tools are often dressed, in order to clean out the pores and to expose fresh cutting edges. Fluids also prevent chemical reactions. Quartzdyne's preferred cutting fluid is a ratio (63:5:1) of water, Rhodes Diamond Kool (Universal Photonics Incorporated) and CSD cleaner.

3.7.2 Grinding Wheel

When selecting a grinding wheel it is important to consider the shape and dimension of the wheel, grit size, diamond concentration and bond, whether resin, vitrified, or metal. A resin bond wheel was chosen due to its degree of elasticity, it promotes relatively low in-feed forces which offers cool running and smooth grinding with superior performance and finishes. Resin bond wheels also offer a high friability property, which is the ability to fracture and self-sharpen;

hence it is unusual for them to need dressing. Scott Smith, VP at Form Grind Corporation, Rancho Santa Margarita, California, stated during his visit to Quartzdyne on August 19, 2013 that there are three main variables that each grinding tool relies on: *grit, glue, and air*, shown in Figure 3-24.

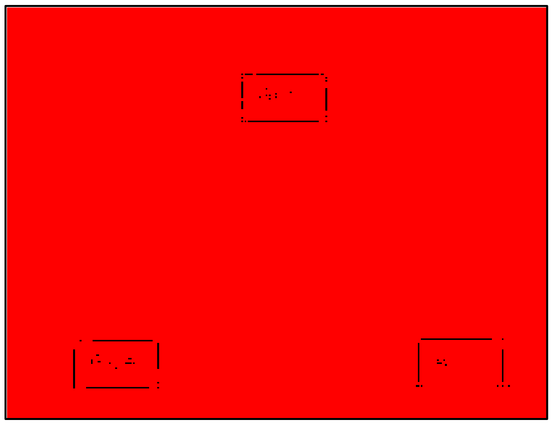


Figure 3-24: Grit, Glue and Air Illustration

If grit size is increased then there is less glue binding the tool, the composition looks different for different bonding agents; you can visualize vitrified or ceramic bonded tools as a smaller triangle in the middle of the larger triangle. Grinding experiments will be completed using an Alpex Wheel Company *resin bond wheel*, pictured in Figure 3-25, which is 2 inches in diameter and .15 inches thick, grit is 150. A coarser wheel would allow for larger in-feed cuts and higher feed-rate but due to design surface finish requirements it is restricted. There are additional factors that affect surface finish besides grit, such as feed-rate, cutting speed and coolant.

Figure 3-25: Resin Bond Wheel

3.7.3 Rounding Approach

In-feed cuts will occur in the perpendicular direction of the rotating sample, more specifically before or after engaging the part, once the in-feed occurs the grinding wheel will move forward or backwards in-line with the collet thus machining the quartz. Figure 3-26 shows the *tool approach*. Blue arrows show the rotation of the part and grinding wheel, notice both are rotating in the same direction, this is an example of climb turning.

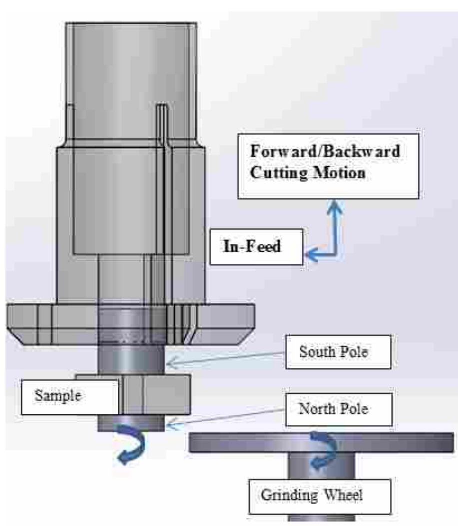


Figure 3-26: Tool Approach

3.7.4 Rounding Program

Design of Experiments for testing hypothesis 2 are indifferent to attaining the finish endcap size .575" and bettering the 15 minute estimated single-piece cycle time. The intent is to define what size in-feed cuts are acceptable and once they are determined an actual numerical control g-code program will be written that assumingly will machine the quartz to the correct size in less than 15 minutes. Experiments will be completed using previously rounded .600" diameter samples. Several ad hoc experiments showed that larger in-feed cuts are possible with square samples because tool pressures are reduced with interrupted cuts. Figure 3-27 shows the *theoretical transition from square to cylindrical shape* on quartz samples.

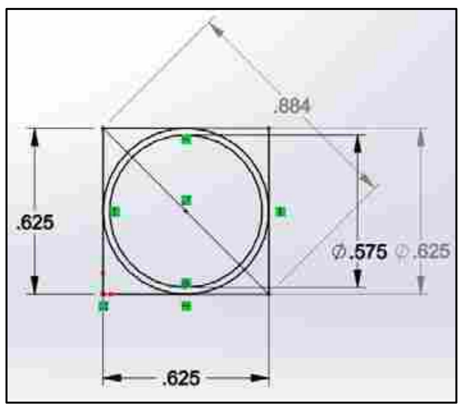


Figure 3-27: Theoretical Transition from Square to Cylindrical Shape

Instead of several different sized cuts down to the finish endcap size, one cut will be made and documented. This method allows for easier, faster, and more accurate angle rotation measurements. Tool offsets will be used to mimic increasing in-feed cuts. Experiments will be completed starting with the lowest holding force, then the lowest feed-rate, followed by the lowest in-feed cuts. Feed-rate, in inches-per-minute, will be .005" for 100%, .0025" for 50% and .00125" for 25% feed.

3.7.5 Speeds and Feeds

Cutting speeds and feeds are two separate velocities that are often considered as a pair because of their combined effect on the cutting. Determining the ideal cutting speed and feed-rate is difficult, that is why this section will provide an overall view. Cutting speed, also referred to as surface speed is the rate at which the material moves past the cutting edge of the tool. In grinding, speeds are measured as peripheral wheel speed in surface-feet per minute (Feeds and Speeds, Abrasive Engineering, 2014). Speed affects the surface quality, material removal rates, and chatter among other factors. To calculate the speed, consider that abrasive grains on the wheel traverse the circumference of the wheel once every revolution, this speed is equal to the circumference times the RPM (Calculation Surface Speeds from Wheel Dimensions and RPM, Abrasive Engineering, 2014). Figure 3-28 below shows an SFM calculator from Abrasive Engineering Society's online site.

Figure 3-28: SFM Calculator

Above calculated cutting speed does not account for the workpiece rotation, recall that in our study both the grinding wheel and part rotate. One must also know what material is being cut, material of the cutter, size of cutter, removal rate that is required, type of cutting fluid used, continuity of cut, type of machine, power output of machine, and so on. Material specific cutting speed charts usually give a large range of values due to all the prevailing variables. Even having what looks like two identical tools can produce differing results during grinding because the tools composition varies. Although cutting speed is important because it can affect sample to magnet rotation, substantial focus will not be given towards it. Existing batch process part rotation (350 RPM) should be sufficient when combined with the 20,000 RPM live-spindle speed, borrowed from an existing process with similar objectives. Further investigation into the ideal cutting speeds would create a more complex Design of Experiments. Note null hypothesis 1 tested part rotation and it relationship to holding force, a characteristic of cutting speeds.

Feed-rate is the relative velocity at which the cutter or in this case grinding wheel moves along the workpiece. It is associated with the z-axis on the lathe. Like cutting speeds, various variables exist for determining ideal feed-rates, like the type of tool, size of tool, surface finish desired, and removal rate desired and so on. Unlike cutting speeds more focus will be given to feeds, hypothesis 2 has feed-rate as an input variable.

4 RESULTS

This chapter explores the results from the Design of Experiments. Results will assist in determining whether to reject or fail to reject the two hypotheses. Moreover, methods of analyzing the data will also be defined within the chapter.

4.1 Results (Hypothesis 1)

Zero rotation was seen from all six experiments, see Table 4-1, all three part rotation settings and both holding forces, as a result we fail to reject the null hypothesis.

Table 4-1: Results (H1)

	[illegible]	[illegible]	[illegible]		[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]

4.2 Results (Hypothesis 2)

We can see from Table 4-2 that several experiments had zero rotation, in fact 19 out of the 42 experiments showed no rotation whatsoever; labeled as "Excellent" in the comment column. An additional 6 experiments were rated "Good" due to their moderately low rotation.

Table 4-2: Results (H2)

[illegible]

4.2.1 Comments Column

Each experiment has a comment description, which is labeled one of five designations: excellent, good, min rotation given, min rotation given where the sample moved, and finally, the experiment was skipped entirely.

- "Excellent" is equivalent to no rotation measured and the endcap stayed stationary.
- "Good" means the endcap did not slide but there was slight rotation, some rotated more than others i.e. experiment 4 had 90 degrees rotation and experiment 26 had 20 degrees.
- "Minimum rotation given" means the sample moved quite a bit and it is entirely possible the recorded rotation is the minimum. As explained in the past without a better method of tracking rotation there is no easy way of knowing when the sample went a full 360 degrees or more past the inscribed line.
- "Minimum rotation given and the sample moved" is comparable to the "min rotation given" but the sample also physically slid and/or moved. The sample would also "pop" back into line virtually centering itself.
- "Experiment skipped" means there was a voluntary decision to skip the experiment because we know the sample will not only rotate considerably but will also move and likely, much more than the previous experiment where the smaller in-feed cut was used.

Results show with each consecutive increase in the in-feed cut there is more rotation and the comment description typically cycles through each type of designation, best to worst. Skipped experiments were given an artificial rotation of 360 degrees; this would be the minimum rotation the sample would see.

4.2.2 Data Fitting

For hypothesis 1, all experiments had zero rotation making it problematic and rendering it meaningless to fit the data. Hypothesis 2 results are more suitable for fitting, however before that can be done it is imperative to determine the distribution for the data set. Probability distributions are tools for dealing with uncertainty, if the wrong tool is used the wrong decision can be made. For example, if the wrong distribution is picked, that is one that does not fit the data well, the calculations will be incorrect. Most often statistical methods need to be used to estimate distribution parameters based on the sample data. Distributions can be classified as either discrete or continuous. If a variable can take any value in some interval, low to high, it is labeled continuous, if it can take only distinct values it is discrete. South pole rotation is positive continuous, meaning the variable can take on any value that is above zero. Knowing that, potential distributions can be narrowed down, for instance exponential distribution also uses a positive continuous response variable. Figure 4-1 shows how the data fits an *exponential distribution*, created using the Distribution preference in JMP.

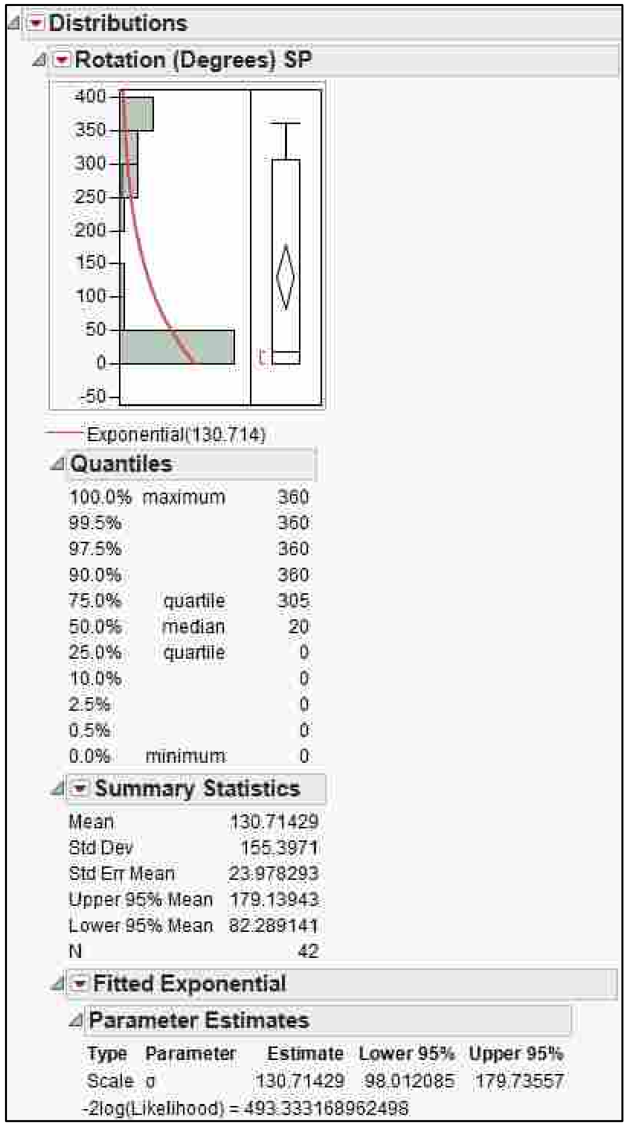


Figure 4-1: Exponential Distribution (H2)

One way to test distributions is by using a goodness-of-fit test; hypotheses are setup such that the null hypothesis reflects that the data comes from the distribution that is being tested, in this case, exponential distribution. The alternative hypothesis is that the data does not come from an exponential distribution. Alpha levels representing the probability of falsely rejecting the null hypothesis are used. Within the Distribution property window in JMP is an option to run a goodness-of-fit test, Figure 4-2 shows the *goodness-of-fit test* for the data set.

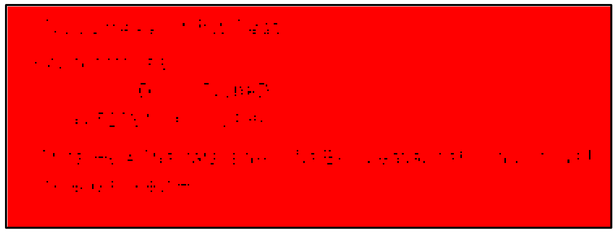


Figure 4-2: Goodness-of-Fit Test (H2)

If the p-value from the Prob>D is small, then the null hypothesis can be rejected, which is the case above. An alternative method is to use the original Kolmogorov-Smirnov goodness-of-fit test; like in the test above it compares the hypothetical distribution with the experimental (Evans, D.L., John, H.D., Lawrence, M.L., 2008). It is primarily intended for use with continuous distributions, making it appropriate on this occasion.

If the D value is greater than the table value then the null hypothesis is rejected while the alternative is accepted. Otherwise, failure to reject the null hypothesis means the exponential distribution fits. Table 4-3 corresponds to the critical values of the Kolmogorov-Smirnov test statistic. Critical values are obtained by matching the number of observations (42) by the chosen alpha .05 (95% confidence interval), this gives an approximate value of .210 and since D (.4524) is greater we still reject the null hypothesis.

Table 4-3: Critical Values Kolmogorov-Smirnov Test Statistic

4.3 Summary of Experiments

4.3.1 Hypothesis 1

Results from testing hypothesis 1 made it possible to fail to reject the null hypothesis - A quartz sample sandwiched between two permanent magnets with adequate holding force will remain stationary during rotation (min 250 RPM). It demonstrated that magnets are capable workholding devices even with non-magnetic materials such as synthetic quartz. Since all experiments had zero rotation, fitting the data was not possible.

4.3.2 Hypothesis 2

Results for testing hypothesis 2 did not make it possible to fail to reject or reject the null hypothesis. Despite the fact that 19 of the 42 experiments had zero rotation the data could not be appropriately fitted to a distribution. In view of that a revised Design of Experiments is planned.

There were a number of wins from the initial experimentation, for example the importance of foam bumpers and their resulting increase on the shear force. Without foam bumpers sample rotation is certain. By the same token, there are issues with the above experiments, mostly regarding the sample rotation measurement method. Right now there is no accurate way to measure the rotation beyond 360 degrees.

4.4 Revised Hypothesis 2

Considering the original set of results could not be fitted with an appropriate distribution the authors elected to repeat the Design of Experiments. In-feed cuts were altered to provide more resolution, while no additional changes were intended. Table 4-4 shows the input variables, its target settings and the single output variable. Notice in-feed cuts are now 8-level with a higher starting point, .0075” instead of .001”. Like the original, a full factorial design (2x3x8) made up of 48 experiments will be used, 6 additional experiments come from the 8-level in-feed cuts. Polyolefin foam bumpers were altered, where its outside edge was trimmed to alleviate possible interference during rotation.

Table 4-4: Revised Variables

Variable Settings	Hypothesis 2	Target Settings
Input	Holding Force (LBF)	[illegible]
	Feed Rate ([illegible])	[illegible]
	In-Feed (IN)	.0075 .010 .0125 .015 .0175 .020 .0225 .025
Output	Rotation (OP Deg)	n/a

4.4.1 Revised Results

Table 4-5 shows the results from the second testing of the null hypothesis 2, compared to the original, one instantly recognizes there are less zero rotation experiments. Part of the reason is the aforementioned starting in-feed size. Notice, comment column was used yet again, it provides more detail into how the experiments faired.

Table 4-5: Results (Revised H2)

[illegible]

4.4.2 Data Fitting

Figure 4-3 shows how the revised hypothesis 2 data fits the *exponential distribution*, created using the Distribution preference in JMP.

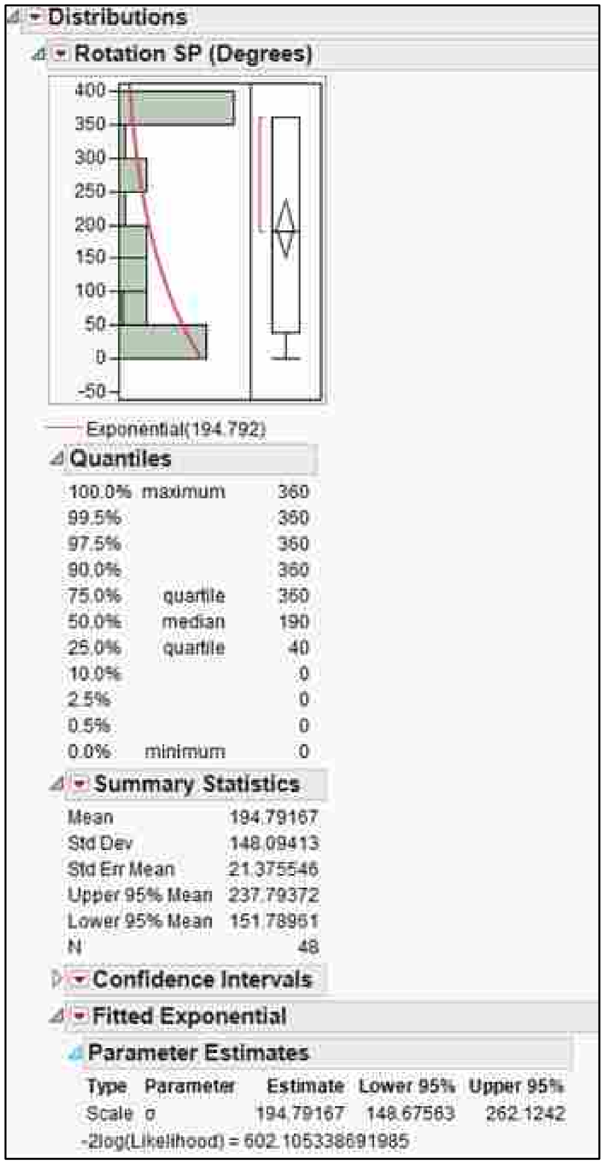


Figure 4-3: Exponential Distribution (Revised H2)

Figure 4-4 shows the *goodness-of-fit test* for the data set. Like before the p-value equals .0100, but this time the D value is much smaller at .1966. Again, Kolmogorov-Smirnov goodness-of-fit test statistic will be used. Matching the revised hypothesis 2, number of observations (48) by the chosen alpha .05 gives a critical value of .196. Strangely values are equal which shows that the data has some signs of exponential distribution. With an alpha of .10 (90% confidence interval) the critical value is .176, well below the .196 D value.

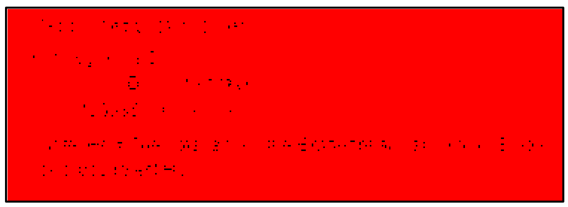
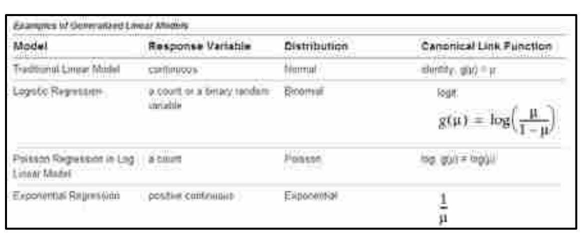


Figure 4-4: Goodness-of-Fit Test (Revised H2)

4.4.3 Generalized Linear Model

Now that the data set fits a distribution we can move towards fitting a model. Generalized Linear Model (GLM) extends ordinary regression to non-normal response distributions, such as exponential distributions; consequently they are more applicable to a wider range of data analysis problems, from the Generalized Linear Models JMP. Figure 4-5 shows *GLM examples*, found via JMP 10.0.2 Help.



Examples of Generalized Linear Models

Model	Response Variable	Distribution	Canonical Link Function
Traditional Linear Model	continuous	Normal	identity, $g(\mu) = \mu$
Logistic Regression	a count or a binary random variable	Binomial	logit: $g(\mu) = \log\left(\frac{\mu}{1-\mu}\right)$
Poisson Regression in Log Linear Model	a count	Poisson	log, $g(\mu) = \log(\mu)$
Exponential Regression	positive continuous	Exponential	$\frac{1}{\mu}$

Figure 4-5: GLM Examples

An exponential regression with the reciprocal link function will be used for the fit model; the reciprocal link function relates the model to the response variable. Figure 4-6 shows the GLM results for the null hypothesis 2.

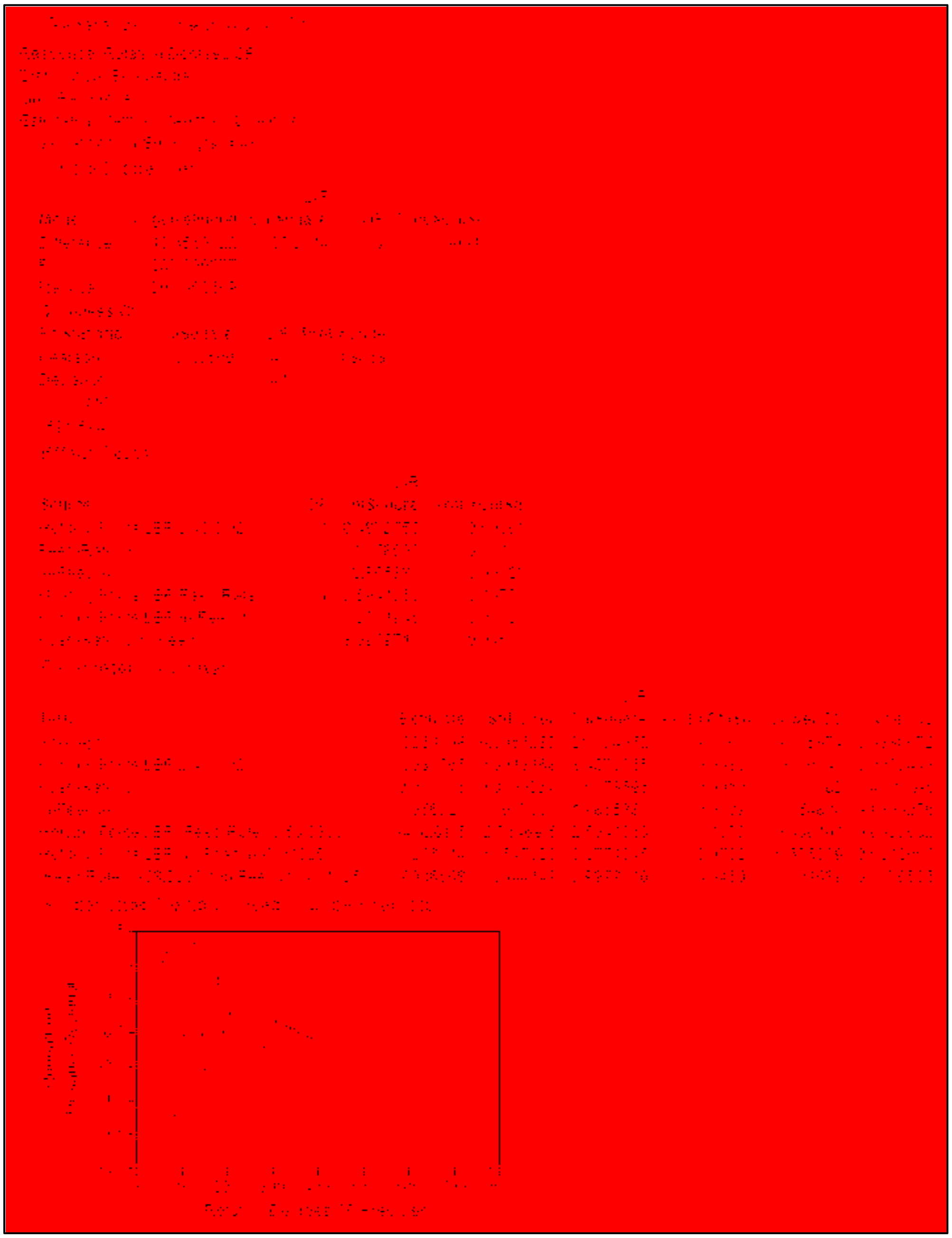


Figure 4-6: GLM Report

Here we have the GLM report window, including the whole model, effect tests and parameter estimates. These tests provide the user with information in comparing the whole model fit to the model that contains only the intercept parameter. The whole model test has three models: full model which contains all effects including the intercept, reduced model which contains just the intercept and the difference model which shows the difference of the log likelihoods from the full and reduced models. P-value in the whole model test is small at .0001 indicating that the model has some predictive capability. An asterisk next to the p-value indicates significance.

Goodness-of-fit test statistic is used again, which tests for the appropriateness of the model. This time it is a chi-square test, used to test if the sample of data came from a population with a specific distribution. Two values are used, an observed value and the expected value, which is calculated based upon the claimed distribution. If the model fits well, our chi-square test statistic should be equal to the degrees of freedom and the p-value should be much larger than .05. The report chi-square is 32 and the degrees of freedom are 41, although not equal they are close. Prob>ChiSq is .8463, much higher than the .05 indicating the model fits the data well.

Effect tests look to see if each predictor or input variable makes a statistically significant contribution to the fit. Looking at the reports window, all input variables are statistically significant contributors to the fit model.

4.4.4 Prediction Profiler

Prediction profiler displays profile traces for each input variable. A trace is the predicted response value as one variable is changed while the others are held constant. It computes the profiles and predicted responses in real time as you change the value of the inputs. Figure 4-7 below is the *prediction profiler legend,* from the Profiler JMP 10.0.2 help.

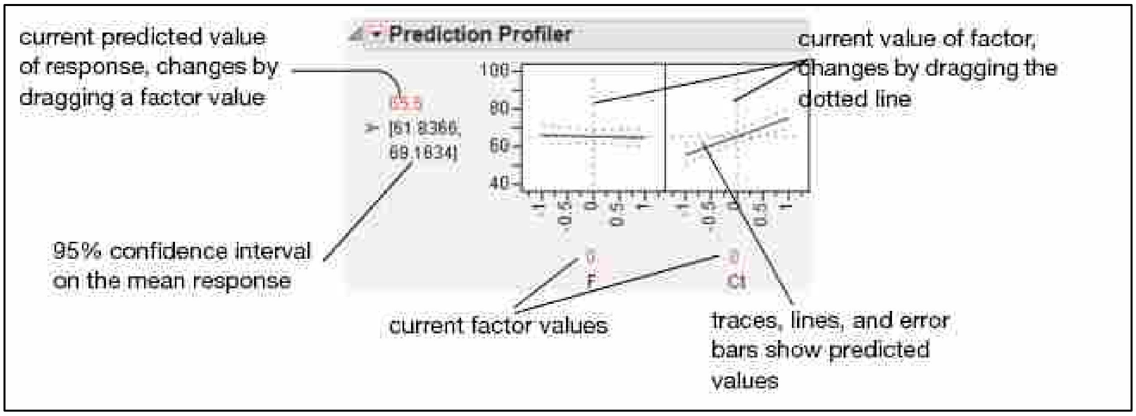


Figure 4-7: Prediction Profiler Legend

- Vertical dotted line (red) shows the current setting of the input variable.
- Value above the input variable in this example F or Ct is the current input value.
- Horizontal dotted lines show the current predicted value for the output variable with the current input variable settings.
- Black lines show how the predicted value changes when you change the current value of an individual input variable.
- Dotted blue lines are the 95% confidence interval for the predicted values.

Importance of the input variable can be assed to a degree by the steepness of the prediction trace. In example, if the prediction model has curvature terms like squared terms then the traces may be curved. When the input variable value is changed its prediction trace will not be affected but the prediction traces of all the other input variables will change. Likewise if there is an interaction effect (or a cross) in the model, prediction traces can shift their slope and curvature as the current values of the variables change. When there is no interaction effect the traces only change in height but not slope or shape, from the Profiler JMP 10.0.2 help.

Within the prediction profiler there is a feature called desirability, it allows the user to set low, medium, and high output or response values which are paired with a desirability number (ranging from 0 to 1) to minimize, maximize or match the target outputs. Sometimes there are multiple responses measured and the desirability of the outcome involves several or even all of these responses. In desirability profiling the user specifies the desirability function for each response. Sample rotation would need to be minimized, to minimize means that the desirability function associates high response values with low desirability and low response values with high desirability, from the Profiler JMP 10.0.2 help. Figure 4-8 shows the desirability settings for the revised hypothesis 2.

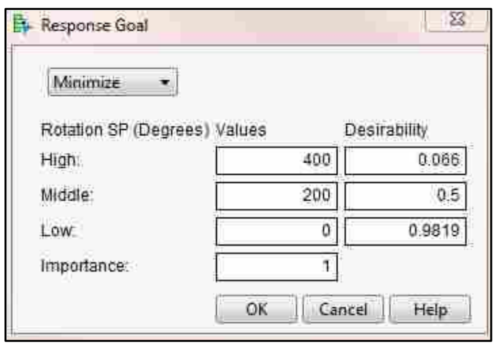


Figure 4-8: Desirability Settings

Having a statistically significant model makes the prediction profiler credible. *Lowest observed rotation* is shown in Figure 4-9, when holding force is set to high, feed-rate to 25% and in-feed to .0075”. In doing so the rotation is estimated at 36 degrees, with the confidence interval ranging from 24 to 64 degrees. Figure 4-10 shows rotation with *50% feed-rate*, rotation increased to 45 degrees with the confidence interval ranging from 31 to 80 degrees. Figure 4-11 shows what happens when the *2.46 LBF reduced holding force* is used, notice the confidence interval widens substantially.

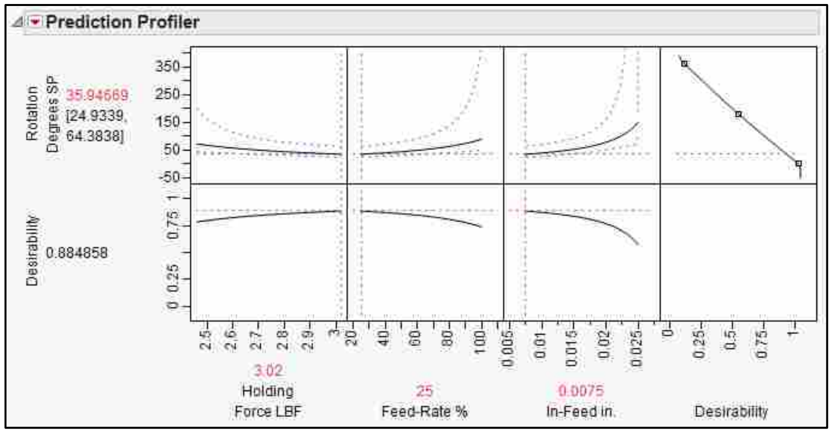


Figure 4-9: Lowest Observed Rotation

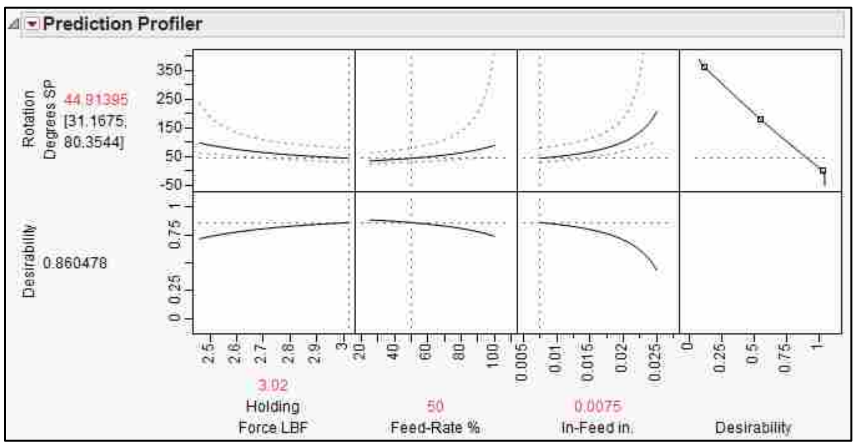


Figure 4-10: 50% Feed-rate

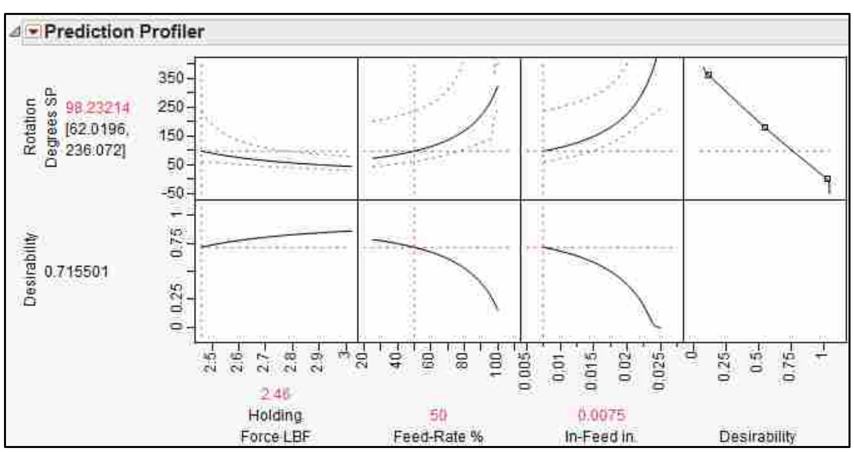


Figure 4-11: 2.46 LBF Reduced Holding Force

4.4.5 Conclusion

How does the original hypothesis 2 compare to the revised hypothesis 2? Looking at the rotation values side-by-side in Table 4-6 it is obvious that the results are not able to be repeated even with identical input settings. This indicates presence of variation between the two sets of experiments, possibly an unaccounted for variable.

Table 4-6: Revised H2 and Initial H2 Comparison

[illegible]

Recall that foam bumpers were trimmed and as a result the shear force values would be less, at the time this was overlooked. In fact, shear force was reduced by approximately 25% for the *low force*, Figure 4-12, and 15% for the *high force*, Figure 4-13.

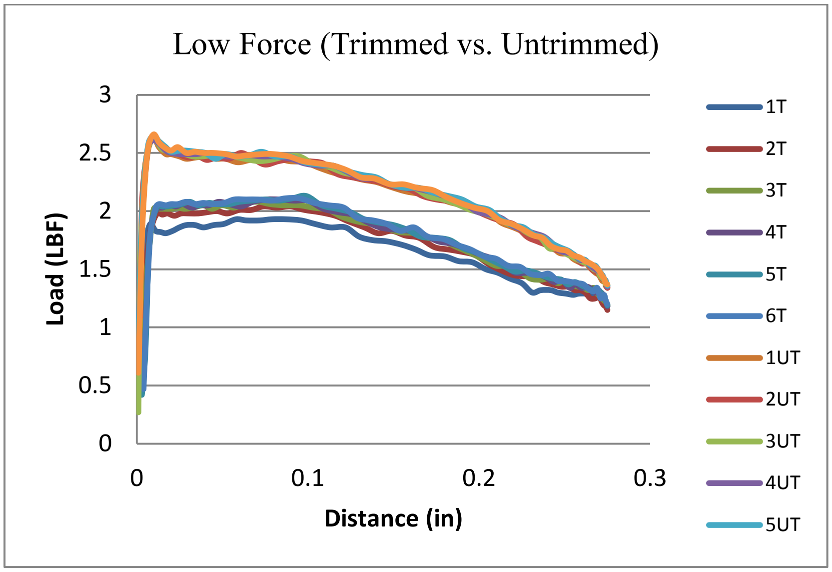


Figure 4-12: Low Force (Trimmed vs. Untrimmed)

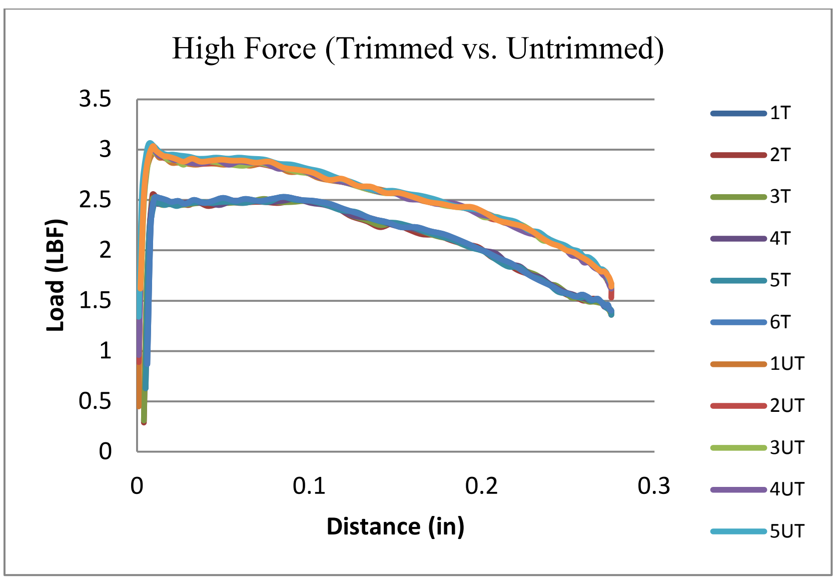


Figure 4-13: High Force (Trimmed vs. Untrimmed)

For the low magnet combination shear force dropped from 2.63 LBF to 1.93 LBF and from 2.97 LBF to 2.53 LBF for the high magnet combination. Figure 4-14 shows the *polyolefin untrimmed vs. trimmed bumpers.* Another difference between the initial and revised hypotheses is the unintentional increase of the grinding wheel speed, from 20,000 RPM to 22,000 RPM. Increasing the RPM will increase the speed or SFM (surface feet per minute).

Figure 4-14: Polyolefin Untrimmed vs. Trimmed Bumpers

4.5 Optimized Rounding Program

Based upon the variation between the initial and revised Design of Experiments an optimized program was arranged. Revised results will be used in selecting the right input parameters that prevent sample rotation entirely. Moreover, this time around finish sample size and cycle time will be taken into consideration. Recall that least rotation was observed using the highest holding force, lowest feed-rate and lowest in-feed cut. Using the higher holding force for the optimized program is clear, however now that there is a time restriction selecting the lowest feed-rate and lowest in-feed perhaps is not realistic. With that in mind, the rounding program should include higher feed-rates and in-feeds that are derived from the prediction profiler.

Overall 15 samples will be machined using a custom g-code program, if the bulk of samples remain stationary during grinding it would be appropriate to fail to reject the null hypothesis, which states a sample at 350 rpm will remain static when undergoing high-speed rounding of its outside perimeter. Program cycle time must be less than 15 minutes; if not attainable the null hypothesis will be rejected.

4.5.1 Program Design

Table 4-6 from earlier compared the amount of rotation observed between the initial and revised tests for null hypothesis 2. A close up of the reduced feed-rate (25%) experiments are shown in Table 4-7 below, there are four from the initial and eight from the revised. Notice that with the higher holding force, 25% feed-rate and .015" in-feed cut zero rotation was observed. Even though the larger .0175" in-feed cut exhibited zero rotation it is considered borderline too aggressive because the following experiment down exhibited rotation. An optimized program is interested in conservative values, such as the .015" in-feed cut mentioned above.

Table 4-7: Reduced Feed-Rate (25%) Experiments

25	+11	3.02	25	0.0075	0	•
26	+12	3.02	25	0.01	0	0
27	+13	3.02	25	0.0125	0	•
28	+14	3.02	25	0.015	0	0
29	+15	3.02	25	0.0175	0	•
30	+16	3.02	25	0.02	40	20
31	+17	3.02	25	0.0225	100	•
32	+18	3.02	25	0.025	90	0

Table 4-8 below shows the breakdown of the proposed g-code program. There are five columns shown, descriptions are as follows:

- Column 1 gives the virtual size of the sample as it is machined; recall that the quartz transitions from square to cylindrical at around .625”.
- Column 2, x-position or location of the grinding wheel in relationship to the sample, this relates to the setup of the grinder itself.
- Column 3 is the in-feed size cut.
- Column 4 is the feed-rate in ipm (inches-per-minute)
- Column 5 is the feed-rate in relationship to each other.

Table 4-8: Program Breakdown

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

It might be surprising to see the larger .055”, .025” and .020” in-feed cuts at the beginning, but recall from the previous section that larger cuts are possible when the sample is still square. This is advantageous since the goal of the optimized program is to keep it as short as possible.

Figure 4-15 shows the *graphical representation of the proposed program*. It shows all 15 in-feed cuts that will be used in the g-code program.

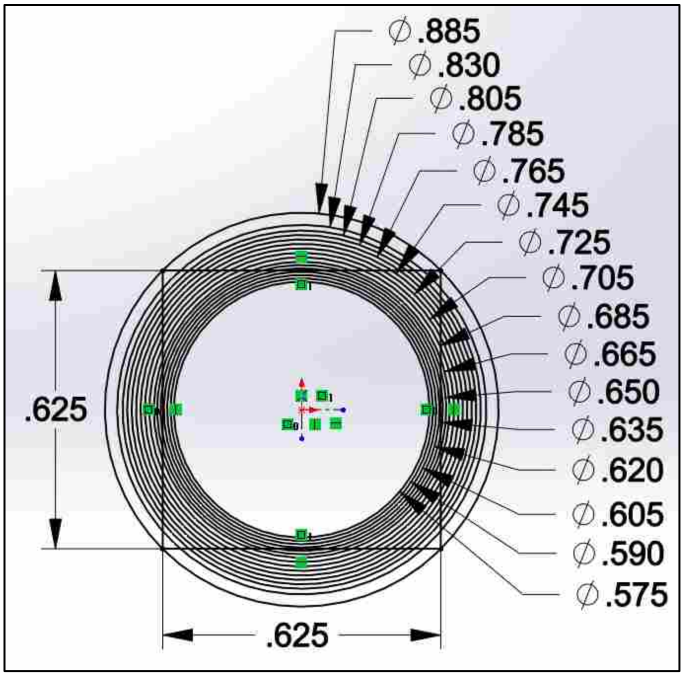


Figure 4-15: Graphical Representation of the Proposed Program

Program breakdown table was used to create the *g-code program*, shown in Figure 4-16 below. Cycle time for program is 7 minutes and 58 seconds (with 25% rapid), well below Quartzdyne's current estimated per piece cycle time of 15 minutes.

```
%
O00001
(Rounding Optimization)

T6
N52
M08
G00 G54 X0. Z4.
X-2.885
S350 M03

G00 Z0.01

G01 Z-0.470 F0.015
G00 X-2.830
G01 Z-.140 F0.005

X-2.835 F0.05
Z0.01

G00 X-2.805
G01 Z-0.35 F0.0025

X-2.810 F0.05
Z-0.470

G00 X-2.785
G01 Z-0.140 F0.0025

X-2.790 F0.05
Z0.01

G00 X-2.765
G01 Z-0.35 F0.0025

X-2.770 F0.05
Z-0.470

G00 X-2.745
G01 Z-0.140 F0.0025

X-2.750 F0.05
Z0.01

G00 X-2.725
G01 Z-0.35 F0.0025

X-2.730 F0.05
Z-0.470

G00 X-2.705
G01 Z-0.140 F0.0025

X-2.710 F0.05
Z0.01
G00 X-2.685
G01 Z-0.35 F0.0025

X-2.690 F0.05
Z-0.470

G00 X-2.665
G01 Z-0.140 F0.0025

X-2.670 F0.05
Z0.01

G00 X-2.650
G01 Z-0.35 F0.0025

X-2.655 F0.05
Z-0.470

G00 X-2.635
G01 Z-0.140 F0.00125

X-2.640 F0.05
Z0.01

G00 X-2.620
G01 Z-0.35 F0.00125

X-2.625 F0.05
Z-0.470

G00 X-2.605
G01 Z-0.140 F0.00125

X-2.610 F0.05
Z0.01

G00 X-2.590
G01 Z-0.35 F0.00125

X-2.595 F0.05
Z-0.470

G00 X-2.575
G01 Z-0.140 F0.00125

X-2.580 F0.05
Z-0.01

G00 X-2.885
Z0.01

G00 Z4.
M09
M05
M30
%
```

Figure 4-16: G-Code Program

4.5.2 Optimization Results

Results are outlined in Table 4-9 below. Notice two samples saw slight rotation and it is not clear why. Despite the rotation all 15 samples were on size and entirely round.

Table 4-9: Optimization Results

Sample No.	Run Date	Rotation Degrees	Finish Size	Cycle Time
1	5/20/14	0	575	7 min 58 sec
2	5/20/14	0	575	7 min 58 sec
3	5/20/14	0	575	7 min 58 sec
4	5/20/14	0	575	7 min 58 sec
5	5/20/14	0	575	7 min 58 sec
6	5/21/14	0	575	7 min 58 sec
7	5/24/14	0	575	7 min 58 sec
8	5/24/14	0	575	7 min 58 sec
9	5/22/14	10	575	7 min 58 sec
10	5/24/14	0	575	7 min 58 sec
11	5/24/14	0	575	7 min 58 sec
12	5/24/14	0	575	7 min 58 sec
13	5/24/14	5	575	7 min 58 sec
14	5/24/14	0	575	7 min 58 sec
15	5/24/14	0	575	7 min 58 sec

Polyolefin bumpers were untrimmed and also dried between each run with paper towels; folded over paper towels were clamped between the magnets without the quartz 2-3 times, essentially absorbing the residual coolant. The grinding wheel was dressed throughout the machining due to visible quartz particles embedded within it; without dressing it would be more difficult to grind the quartz thus rotation would become more probable. Figure 4-17 shows the *wheel before and after dressing*, image was taken right after rounding sample 13. Tool wears from dressing so occasional and minor offsets were made to uphold the precise finish size for the endcap.

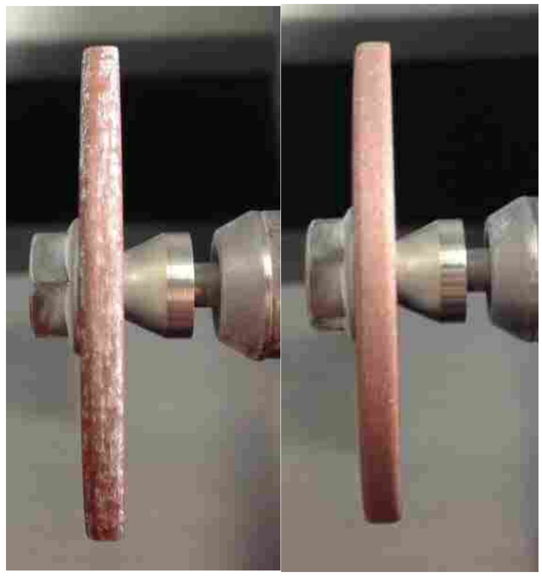


Figure 4-17: Wheel Before and After Dressing

Irrespective of the two samples that had minor rotation the optimized program has permitted most of the samples to remain static during machining. This shows that magnetic workholding non-magnetic material during precision grinding is feasible, therefore the study fails to reject the null hypothesis 2.

5 CONCLUSIONS AND RECOMMENDATIONS

This chapter will summarize the key findings from the thesis. It will also review how and why this study was done. Later a more detailed interpretation of the findings; starting with the initial problem statement, research questions and hypotheses, and ending with the results and supporting data is presented. Lastly, recommendations for action and further study are explored.

5.1 Summary of Findings

Below are the some of the key findings from this research study. Detailed findings can be found in the section 5.3

- Zero rotation was observed from all six experiments during null hypothesis 1 testing; this made it unnecessary to fit the data to a model.
- 15 samples were machined for the optimized program; only 2 samples had minor rotation.
- Optimized program cycle time was 7 minutes and 58 seconds.
- The largest in-feed size cut used during the optimized program was .015” in diameter for cylindrical quartz.
- Larger in-feed size cuts are possible while the quartz is square in shape, as it becomes cylindrical in-feed cuts were reduced to experimental levels.

- Variation was noticed while quantifying the shear force; it is attributed to the polyolefin foam bumper and its inconsistent coefficient of friction.

5.2 Overview

Users of magnetic clamping devices reduce their cycle times due to faster setup times, part loading and part unloading, and improve quality per part. Quartzdyne, the principal sponsor of this research study was looking at developing a single-piece magnetic workholding process for rounding quartz used in the manufacture of pressure sensors. Magnetic workholders can assist in making single-piece flow possible. Readers should recognize that the output for the study was not to implement a single-piece production ready magnetic workholding method but rather to investigate the applicability of magnetic workholding of synthetic quartz blocks during high-speed grinding. Magnetic workholding devices clamp ferrous metals - the difficulty arises in using magnetic workholding devices on non-magnetic materials - such as quartz, and depending on the circumstances it is not clear if this approach is feasible. Magnet forces are reduced when there is clearance, also referred to as “gap,” which is any space between a workpiece and the surface of a magnet. While research has been done on magnetic workholding devices for ferrous metals no journal articles were found on workholding of non-magnetic materials.

The thought was that with sufficient holding force the quartz would remain static even during high-speed rounding. However, it was not apparent what holding force (normal to quartz) and shear force (perpendicular to holding force) are required to keep the .300” thick quartz static. If the sample moved the likelihood of it being out of round was considerably greater, as mentioned before keeping track of the minerals direction was important to Quartzdyne. Emphasis was placed on the relationship between tool feed-rates, required magnetic holding forces and dependent shear forces, and lastly, size of cuts. Moreover in the beginning it was essential to recognize the impact of part revolution (RPM) on workholding.

Below were the proposed research questions, along with their corresponding hypotheses, that confirmed magnets are suitable for workholding non-magnetic quartz during grinding:

1. Can non-magnetic quartz be held stationary with permanent magnets during rotation in a lathe?

   Hypothesis 1 - A quartz sample sandwiched between two permanent magnets with adequate holding force will remain stationary during rotation (min 250 RPM).

2. Can non-magnetic quartz be held stationary with permanent magnets during grinding of its perimeter while in a live-spindle equipped lathe, with enough precision to create an acceptable part?

   Hypothesis 2 - A static sample at 350 rpm will remain static when undergoing high-speed rounding of its outside perimeter.

Null hypothesis 1 states, if the quartz sample has adequate holding force it will not move during rotation at 250 RPM (minimum). Alternative for hypothesis 1 is there is no reasonable holding force that will keep the sample stationary at 250 RPM. Further explanation for "reasonable" means, no currently available permanent neodymium magnet of the required size and shape can apply the necessary force to keep the quartz stationary.

Null hypothesis 2 states, if the sample is static at 350 RPM it will remain static when engaging the grinding wheel to its outside perimeter, essentially holding force will be sufficient to withstand newly introduced pressures or applied rotating forces (torque) from the grinding wheel. Alternative is no reasonable holding force will keep the sample stationary while the grinding wheel engages the quartz sample's perimeter surface.

Null hypothesis was tested, from that we had two possible outcomes, either to fail to reject the null hypothesis or to reject the null hypothesis thus accepting the alternative hypothesis. Failure to reject the null hypothesis does not mean we accept it, it means we failed to find sufficient proof to reject it, this is because statistical hypothesis testing involves sampling from a population; therefore we cannot be certain about our conclusions.

5.2.1 Methodology

Non-magnetic materials can only be indirectly clamped with magnets. Samples were sandwiched between two permanent neodymium magnets of opposing poles. A Design of Experiments was used to test the hypotheses, it has three main aspects: inputs or factors to the process, settings of each input, and the output variable. Experiments were designed to evaluate which inputs have a significant impact on the output and what target settings of the inputs should be to get the desired output. Between the two hypotheses four input variables were used and each input had different settings. Holding force, used in both hypotheses, stretched from .98 LBF to 3.02 LBF. Both hypotheses also had specific inputs; for 1, it was part rotation ranging from 250-1000 RPM (500 RPM as the in-between) and for 2, it was the feed-rate percentage ranging from 25-100% (50% as the in-between) and in-feed cuts starting as low as .001” and going up to .030”.

Upon completion results were uploaded to JMP and fitted with a model. Statistically significant models were used to predict the behavior of the process inputs. By now the fitted model could be used to reject or fail to reject the hypotheses. Both the holding and shear force values were obtained using permanent neodymium magnets, measured using a Starrett machine. High-speed rounding experiments were executed at Quartzdyne’s facility using a modified Haas OL1 lathe.

5.3 Detailed Interpretation of the Findings

This section will review the findings from the study, specifically answering the research questions by rejecting or failing to reject the two hypotheses.

5.3.1 Hypothesis 1, 2 Initial, and 2 Revised

Design of Experiments results for testing null hypothesis 1 made it possible to fail to reject the hypothesis - A quartz sample sandwiched between two permanent magnets with adequate holding force will remain stationary during rotation (min 250 RPM). Zero rotation was observed from all six experiments, this made it unnecessary to fit the data to a model. Having such encouraging results made it fitting to advance to testing the null hypothesis 2, which involves actual contact of the quartz sample with the grinding tool.

Two Design of Experiments results and one optimized program were required to make it possible to fail to reject the null hypothesis 2 - A static sample at 350 rpm will remain static when undergoing high-speed rounding of its outside perimeter. For the duration of the initial Design of Experiments, 19 out of 42 samples had zero rotation, but the data could not be fitted to a distribution. The authors then elected to repeat the experiments. During the revised Design of Experiments, in-feed cuts were expanded to provide more resolution. While the data was properly fitted with a distribution there was visible variation between the initial and revised results, which used identical input settings, therefore an optimized program was generated from the revised model. Variation was largely owing to the unintentional alteration of the polyolefin foam bumpers while conducting the revised Design of Experiments, the bumpers outside edges were trimmed to alleviate potential interference during rotation, and as a result the shear force was less.

An alternative to repeating the Design of Experiments was to use the revised Design of Experiments prediction profiler to create an optimized program, which allowed the authors to fail to reject the null hypothesis 2. This time around finished sample size and cycle time were taken into consideration. Least rotation was observed using the highest holding force, lowest feed-rate and lowest in-feed. Overall 15 samples were machined with a custom g-code program, 2 samples showed minor rotation, not enough to reject the hypothesis. It is not clear why these samples rotated, despite the rotation all samples were in specification, both in size and roundness. A stipulation was that the program cycle time must be less than 15 minutes, the optimized program cycle time was much less at 7 minutes and 58 seconds. Polyolefin foam bumpers were left untrimmed, which matched the original hypothesis 2 Design of Experiments. Bumpers were also dried between each run with paper towels, folded over paper towels were clamped between the magnets without the quartz approximately three times, essentially absorbing the residual coolant. In conclusion the optimized program results showed that magnetic workholding non-magnetic synthetic quartz during precision grinding was feasible.

A number of ad-hoc experiments showed that larger in-feed cuts are possible while the quartz was still square in shape, as it becomes cylindrical in-feed cuts were reduced to experimental levels. Due to the amount of material being removed, the grinding wheel required dressing, otherwise rotation is expected. Furthermore, variation was noticed while quantifying the shear force; it was attributed to the polyolefin foam bumper and its inconsistent coefficient of friction. On a positive note all optimized program samples were perfectly round, even the two that had slight rotation. Resin bonded grinding wheel held up well during the course of the experiments, minimal offsets were made, perhaps around .003” overall.

5.3.2 Recommendations for Action

Demonstrating that zero rotation samples can be produced using the magnetic workholding method is different from considering it production tested. Machining several dozen quartz blocks cautiously over the course of several weeks is not the same as doing several dozen in a work shift. More experiments would equate to greater confidence that magnetic workholding is in fact feasible for everyday use. Before that several concerns will need to be addressed and resolved.

Neodymium magnets by nature chip with little effort. Magnets could be placed and protected using a stainless steel sleeve. This was trivial when likened with the variation that comes from using the polyolefin foam bumpers –used to increase the shear force. A more suitable material should be found, one that provides a repeatable and much higher coefficient of friction. Recall the polyolefin foam bumpers get modified prior to being used. This process inherently hurts the repeatability of the material. An increased coefficient of friction would equate to a larger shear force permitting for larger in-feed cuts and in general a more robust workholder.

By the same token the holding force should be increased for the production process. There were three valid methods in achieving that, two had to do with the physical size of the magnet and the third has to do with the grade. Increasing the magnet diameter would make the biggest impact but there is limited space, the difference between the magnet and finished part was .075” in diameter, half that in radius. A protective sleeve would further diminish the limited space. That said, even 15 to 20 thousandths of an inch can make a difference because magnet diameter has the greatest bearing on its strength. Magnet length should also be increased and unlike its counterpart it has space to grow.

Recall that this research study kept the aspect of shaping the quartz or abrasive grinding as a constant. This was done because including it would require a much larger Design of Experiments, which would take away from the main goal of proving that magnets are useable for holding non-magnetic materials. Grinding tools bring a great deal of intrinsic variation from how they are made to what materials are used in them. Unlike what most people think the industry of making grinding tools is not exactly standardized. With that said, it would be advantageous to turn more focus on how different bonding agents, grit sizes, diamond concentrations and so on, affect the rotation of the quartz. Perhaps with a different type of grinding wheel, larger in-feed size cuts could be taken.

To end, quartz orientation will need to be addressed. Regardless if the process reaches Six Sigma levels, direction would need to be known after the machining. Using a fixture during the initial loading that orients the parts to a specific feature would be appropriate. Most modern lathes are equipped with a rotational axis, allowing the programmer to create a point of reference or origin, which can be used to mark the direction of the quartz. That said, if loading and unloading becomes time consuming it defeats the point of using the magnets as workholders.

5.3.3 Conclusion

Based upon the findings, the authors consider magnetic workholding a worthwhile method of clamping non-magnetic materials even when challenged with the task of heavy material removal at high-speeds. As described in the beginning of this broad research study using magnets for workholding non-magnetic materials, such as quartz, is a novel innovation because to date this has not been researched nor written about extensively.

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