Determining Material Properties Responsible for Grinding Performance

A Major Qualifying Project
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Abstract

This project, prepared for the Saint-Gobain Abrasives group, will determine the effects of work material properties on grinding performance. Working with previous data, the team designed the parameters for a surface grinding test that employed two different grinding wheels as well as three different steel types (304 Stainless, 4340, D-3 Tool Steel). The data from this surface grinding test showed that hardness, elasticity and ultimate tensile strength have unexpected effects on grinding performance.

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1. Introduction

Steel and other specialty metals are some of the most commonly used materials in the world. Everything from the structural supports of large buildings to computer hardware requires steel to function properly. Because of its wide variety of uses, there are thousands of different grades and alloys of steel, each having different physical properties that are dependent upon the raw materials that make up the steel.

In order for these steels to be transformed from raw stock into a usable product, it must be cut, shaped and polished. While other metals were traditionally used to accomplish this transformation, grinding wheels are becoming more and more commonplace in the modern processing of steel. Being able to adjust the various properties of the grinding wheel allows these tools to be tailored to any variety of tasks, ranging from cement cutting to fine precision polishing. Due to this wide range of grinding wheel use, there are literally hundreds of thousands of variations in grinding wheel models to meet all the different needs that the customer may encounter.

Saint-Gobain is a market leading supplier of grinding wheels of all shapes and sizes. The company manufactures over 250,000 different variations which take into consideration the material being processed and the job that the wheel must accomplish. Due to this wide variety of grinding wheels, a variety of test methods have been designed and implemented by Saint-Gobain in order to determine how to optimize the performance of different abrasive grains. The overall goal of current on-going research is to gain a broad knowledge of how a range of abrasives react differently when used on a specific steel. However, the amount of research being done on how specific grains react when grinding different types of steels is somewhat limited. With knowledge of both of these research areas, Saint-Gobain can improve the time it takes them to create a grinding wheel designed for a specific customer's application.

The completion of this project, ultimately result in cost savings for Saint-Gobain, will require four distinct phases. A complete material investigation of the steels and abrasives being used will first be completed. Then, data from previously completed surface grinding tests will be analyzed to determine what additional tests would be beneficial to this study. With this information, a Design of Experiment will be proposed to run further tests aimed at determining how steel properties effect grinding performance. After these tests have been run at the Higgins Grinding & Technology Center in Worcester, MA, the data outputs will be statistically and analytically analyzed. Through the completion of this project, an understanding of how steel properties effect grinding performance will be developed in order to assist Saint-Gobain in creating more efficient grinding wheels for their customers.

2. Nomenclature

MRR' - **Material Removal Rate.** This is the normalized rate at which material is removed from the steel during grinding. For our calculations, MRR was normalized so the width of the grinding wheel does not have an effect on the MRR used for our calculations. Its units are in^3/min/in

WWR'- **Wheel Wear Rate.** This is the normalized rate at which material is removed from the grinding wheel during grinding. For our calculations, WWR was normalized so the width of the grinding wheel does not have an effect on the WWR used for our calculations. Its units are in^3/min/in

Unit Power- **Unit Power** is the normalized amount of power that is required to spin the grinding wheel during the grinding process. Its units are hp/in.

G-Ratio- **G-Ratio** is equal to the normalized MRR' divided by the normalized WWR'. As a result, this term is dimensionless. It is used in determining the efficiency of the grinding wheel of removing material from the steel.

SGE - **Specific Grinding Energy.** This is equal to the total power divided by the material removal rate. This term is used in understanding how much power is needed to grind a certain unit of material from the steel. Its units are HP min/in^3.

Surf. Finish- **Surface Finish.** This number describes how smooth the finish of the steels are. It is measured in µin and the smoother the surface, the smaller the number.

D3- **D3 Tool Steel.** This is one of the steels that were used during testing for this project.

4340- **4340 Steel.** This is one of the steels that were used during testing for this project.

304- **304 Stainless Steel.** This is a stainless wheel, which was used during testing for this project. The properties of these different steels can be seen in Appendix A at the end of this report.

UTS- **Ultimate Tensile Strength.** The point on the stress strain curve where plastic deformation ends and failure of the part begins. Its units are pounds per square inch.

3. Background

Steel has been a crucial building block in industry ever since its inception hundreds of years ago. Without steel and other types of metal, our society would be much less capable and adept. At its first discovery, there were few, crude versions of iron and steel. As time passed, the ability to produce higher quality steels became studied and practiced. This lead to a diversifying steel market which contains thousands of grades of steel and other high performance metals. This increase in metal quality led to a change in the types of industry they were being used for. As higher quality metals were created, new industries and products were created and past products and technologies were improved upon. For example, when steel was first produced, people around the world realized it was significantly stronger than iron, which was used previously, and could be used as a building material. This simple discovery gave birth to the structural steel industry that is used today in the creation of multilevel steel frame buildings, skyscrapers and bridges.

With direct proportionality to the increase of steel performance was the development of high specification products. The development of better quality steel occurred in conjunction with products being developed that require higher tolerances and requirements. As the products being produced for the world market were requiring higher grades of metal with higher tolerance values, the machines used to produce and shape the metals also had to increase. Therefore, these industries worked in a positive feedback loop. As higher versions of steel were created, products were created that were more technologically advanced. This led to even higher specifications for the metals being produced which were used in products with even higher technological advances.

One type of product that is used in the production and finishing of steels and other metals are grinding wheels. Grinding wheels come in thousands of different shapes and compositions, which are all dependent on the stock material and the use of the wheel. As the steel grades change and the tolerances of the steel for the finished product increase, the grinding wheels must be redesigned to meet these needs. As a result, the increasing technology that causes newer products to become invented also drives the research and development of new grinding wheels to enable high quality products to be made.

3.1. Saint Gobain Information

Saint-Gobain was created by Louis XIV and Colbert in the year 1655 as a way to save the failing French economy. The company began by doing something that no one else had yet done; manufacturing glass in an industrial setting. Prior to Saint-Gobain, glass manufacturing was largely privatized. When glassware casting was invented in 1688 Saint-Gobain grew in leaps and bounds, creating a modern monopoly of the glass making business in 17th century Europe. The 19th century saw Saint-Gobain begin to expand itself into the industrial powerhouse it is today. Additional sites were opened in Germany (1857), Italy (1889) and Spain (1904). The first half of the 20th century saw the development of the Saint-Gobain that we know today, with the diversification of products produced. One of the most significant events of the 20th century was the company's 1970 merger with Pont-à-Mousson, the world leader in cast iron piping.[1] This along with other mergers began to form the many groups of the modern Saint-Gobain Group.

Saint-Gobain has formed locations on this side of the Atlantic since 1831 when they opened a glass sales depot in New York. 1920 saw investments in several cast glass companies that began to build Saint Gobain's reputation as an industrial supplier. Norton Company was acquired in 1990, and today the reputation of the company as a whole continues to grow. Today the company strives for "A Balanced Growth Strategy", focusing on:

- Prioritizing development of construction and housing related businesses, in particular through bolt-on acquisitions in Building Distribution and Construction Products sectors
- Pushing ahead with R&D and innovation initiatives, particularly in High-Performance Materials and Flat Glass sectors
- Stepping up expansion efforts in emerging countries for all businesses[2]

The sales figure for the company as of 2005 are illustrated in Figure 1:

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[1] "History of the Saint-Gobain Group."

[2] "Saint-Gobain Group Strategy."

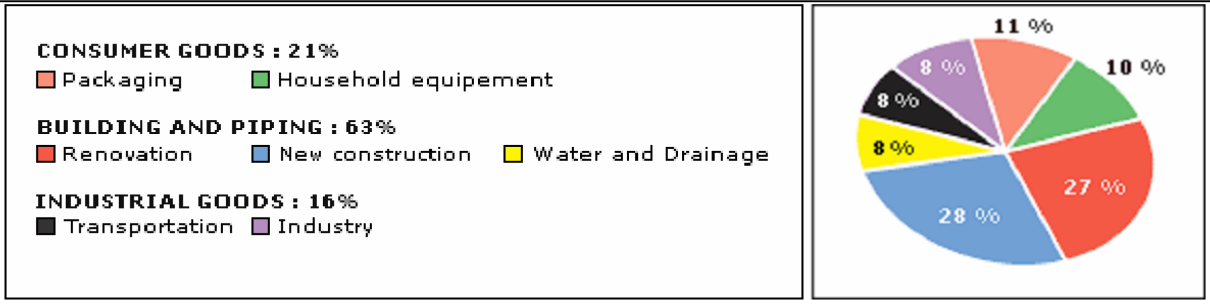
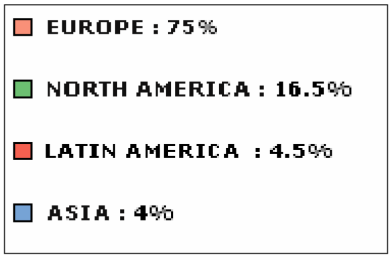


Figure 1: Breakdown of Sales by Market in 2005[3]

Saint-Gobain is a worldwide company; a table of their sales by region in 2005 is illustrated to the right. The company is divided by the types of products certain divisions produce. An illustration of the various Saint-Gobain Business Sectors is shown in Figure 3.


🟧 **EUROPE : 75%**

🟩 **NORTH AMERICA : 16.5%**

🟥 **LATIN AMERICA : 4.5%**

🟦 **ASIA : 4%**

Figure 2: Regional Sales Figures in 2005

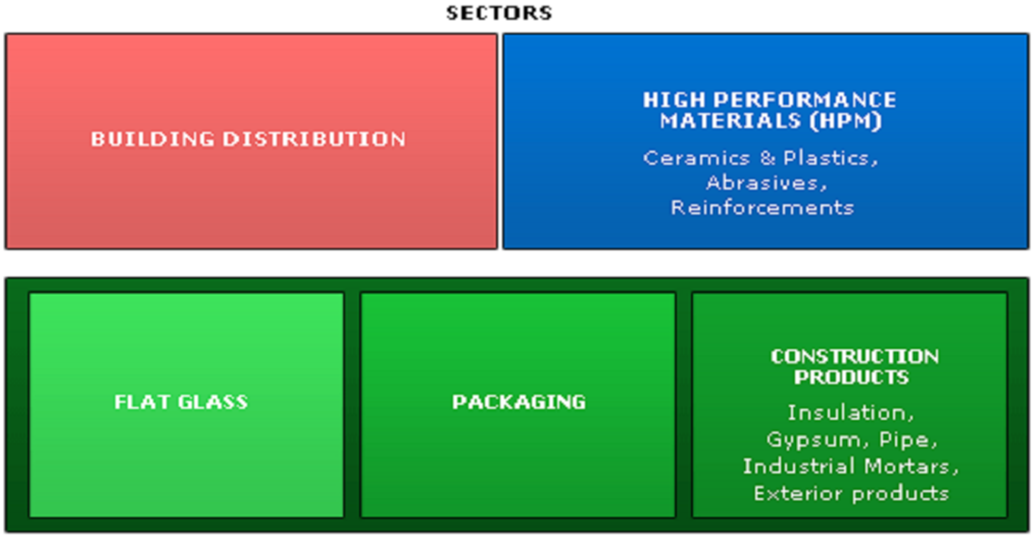


Figure 3: Saint Gobain Business Sectors[4]

The company prides itself on being a world leader in its various business sectors. Shown below is a table of their placement in the each of these sectors.

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[3] "Saint-Gobain Products' End Applications Market."
[4] "Saint-Gobain Business Sectors."

Industry	Placement
BUILDING DISTRIBUTION	N°1 worldwide in tiles distribution
	N°1 in Europe in building materials distribution and in industrial carpentry
CERAMICS AND PLASTICS	N°1 worldwide for thermal and mechanical applications
ABRASIVES	N°1 worldwide
REINFORCEMENT	N°1 worldwide
FLAT GLASS	N°1 in Europe
	N°3 worldwide
PACKAGING	N°1 in Europe
	N°2 worldwide
INSULATION	N°1 worldwide
GYPSUM	N°1 worldwide
PIPE	N°1 worldwide in cast iron pipe
INDUSTRIAL MORTARS	N°1 worldwide in wall coatings and glues for tiling
EXTERIOR PRODUCTS	N°1 in US for sidings
	N°3 in US for roofing products

Figure 4: Industry Placement

Our particular project works with the High Performance Materials group, comprised of Refractory Ceramics, Plastics and Abrasives businesses. The specific group we are working with is Abrasives, and their sales figures for 2004 and 2005 are shown in Figure 5.

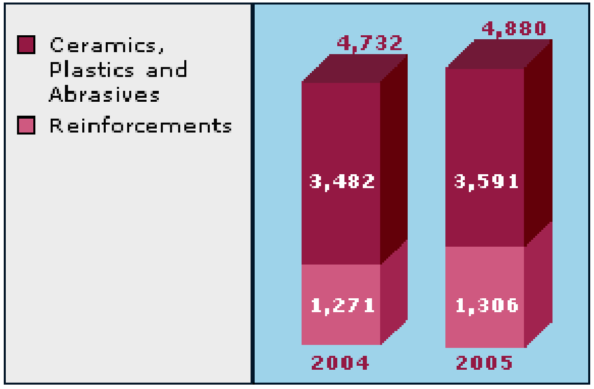

Figure 5: Sales in Millions of Euros

Saint-Gobain in Worcester and Northboro Massachusetts is primarily comprised of abrasive product production and Research and Development departments to support the various production facilities that the company has. Our project deals specifically with abrasives, which is also broken down into certain sectors based on the product type. These groups fall into three distinct categories: Bonded Abrasives, Coated Abrasives, and Super Abrasives.

Coated Abrasives are what people commonly think of as sandpaper. They are made with a variety of backings that have a layer of abrasive grains bonded to them with a glue-like substance. Similar to all types of abrasives there are different types of grains used for different types of materials. There are grains made from any variety of materials from alundums to zirconias. Coated Abrasives are used for a variety of things from belt sanders to films used to micro-polish crankshafts. They are mainly used to sand wood products with belts, but can also be used in a sanding disc for orbital sanders. St-Gobain produces over 30,000 types of coated abrasives.

Super Abrasives utilize diamond or cubic boron nitride as the abrasive grains. They are used for cutting some of the toughest materials, which are found mainly in the construction industry. The wheels are made using a metal center that has the abrasive material bound to it with a vitrified resin. SuperAbrasives are used mainly for cutting concrete and asphalt.

Our project specifically deals with Bonded abrasives. Bonded abrasives are formed by combining the abrasive grains and a bonding agent, either organic or vitrified. A vitrified bonded wheel has a glassy porcelain like bond material, while organic bond wheels contain a bond resin that is made from natural materials. The mix is pressed into the desired shape ranging from a flat disc 76" in diameter to a 3" diameter cup wheel. After the desired shape is achieved the wheel is either fired or cured, depending on the bond type. The wheel goes through various quality checks to ensure that the bond is holding and that the wheel is perfectly balanced. Bonded abrasives are used for the widest variety of applications including ID wheels (precision applications), LDCO (Large Diameter Cut-Off), and BZZ (large industry rough grinding). St Gobain produces over 250,000 variations in size and type of bonded grinding wheels.

3.2 Grinding Wheel Industries

With such a wide variety of abrasive products, the industries in which they are used are diverse. Grinding wheels are used in industries ranging from home repair to shipbuilding. Grinding wheels in general are divided up into three categories, which are distinguished by their shape and composition. These three categories are grinding wheels, thin grinding wheels and superabrasives.

Grinding wheels are used in both rough and precision grinding and can be used to sharpen tools and materials. They are typically used in the aerospace, automotive, metal processing, mechanical bearings, and the iron and steel industries. As of 2005, the largest competitors to Saint Gobain in this field are Carbo plc, which is based out of UK, Noritake in Japan and Tyrolit in Austria.

Thin grinding wheels, on the other hand, are used primarily for cutting and trimming material. They are typically found in the metal processing, maintenance, energy, iron and steel, construction and home improvement industries. For this type of wheel, SAIT in Italy and the US, Tyrolit, and Comet located in Slovenia are the key competitors to Saint Gobain.

The last types of grinding wheel produced by Saint Gobain are the superabrasives. They are used in industries requiring high precision in their parts, such as the aerospace, automotive, cutting tooling, mechanical bearings and construction materials industries. The key players in this market are Asahi in Asia, Diamant Boart in Belgium, Noritake in Japan, and Wendt Boart in Belguim.[5] As one can see, the companies producing grinding wheels are located all over there world, as are their products.

3.3 Grinding Wheel Process

The first step to the production of any grinding wheel is to prepare the products used in the wheels: mainly abrasive grain and some sort of bond to hold the grains together. The main function of the bonding agent is not only to hold the wheel together, but once grains have become dull, the bond is designed to release these dull grains. This measurement of the strength of the bonding agent is called the grade of the bond. There are two main types of grinding wheels and the main difference between the types is the bond that is used in the wheels. The difference in wheels is so great that the Worcester Saint-Gobain manufacturing facility has two separate plants for the two different types.

The first type is a vitrified bond, which is actually made of animals, yielding quite a unique smell to the facility in which these wheels are manufactured. Vitrified bonds are described as glassy and very hard/brittle. This type of bond is not affected by the heat that is generated in grinding. When these wheels are heated to achieve final hardness they are fired in a kiln at 2300 F. The high hardness of this wheel also makes it prone to breaking. These wheels can fracture by being dropped on the ground alone. Because of this they are not used in thin cut-off wheel applications, nor can they be used at a speed above 6500 s.f.p.m. The second type of bond is organic bond. This bond is much less brittle and hard, and more resilient. These bonds are not limited to being run at 6500 s.f.p.m, but can be run

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[5] Bazon, Benoit.

upwards of 10,000 s.f.p.m. This type of bond is affected by heat, and will soften to release dull grains when the bond reaches a certain temperature. Organic bonds are cured in an oven cycle that reaches only 500 F.

Abrasive grains can be made of a variety of materials, but the two main types that Saint-Gobain uses are Silicon Carbides and Aluminum Oxides. These grains, although made differently, are made in a batch process, and then made into the proper size grain, also referred to as the grit size number of the grain. The grains are either made in a liquid mixture and extruded through a mesh screen that is the proper size, or larger grain pieces are made, and then broken down to proper size by rotary impact crushers. The grit size of a grain is determined by sieving grains through mesh that has a specified number of holes per inch, or the grit size number.

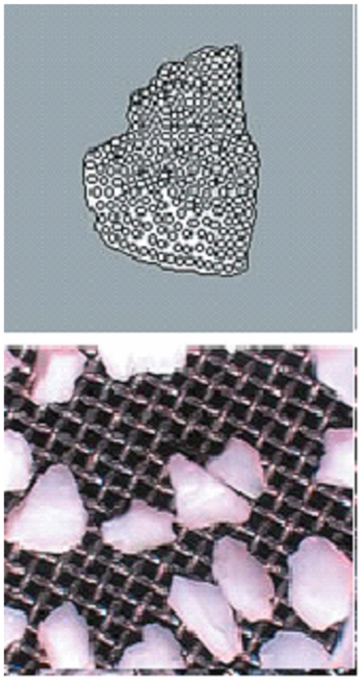

Figure 7: Seed Gel Grains

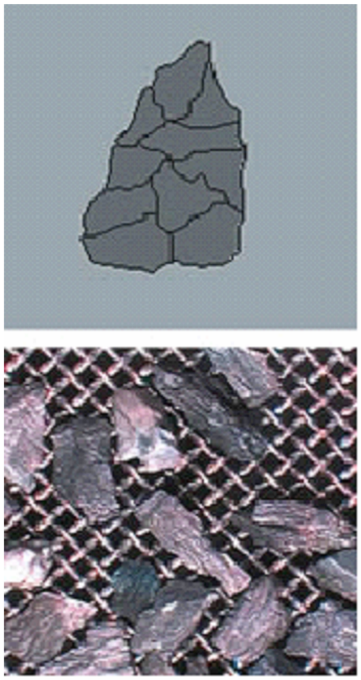

Figure 6: Norzon Grains

There are five properties that quickly determine the work material that is suitable for different grains. The first one of these properties is the hardness of the abrasive. This is easily thought of as the ability of the grain to penetrate the metal. The second property is the body strength, often known as the toughness of the grain, is its ability to withstand fracturing during the grinding process. Once the grain does fracture the next important property of the grain is the nature of that fracture. Depending on the microstructure of the grain and the grinding conditions, the fracture can leave a sharp or a dull edge. This is especially important because if a grain is used improperly this dull edge will lead to glazing and greatly affect the performance. The chemical nature of the abrasive is also an important property and is often linked with the solubility effect. To understand this effect it can be useful to think of it as the relation of salt on ice that is below freezing. When the salt is rubbed on the ice the tips of the salt crystals will wear down.[6] Although, this will happen much quicker in the example then in the interaction with the grinding wheel and the steel, it is still an important factor. The last property that will be discussed is the ease of fracture. The ease of fracture of an abrasive directly correlates to its body strength. This is measured by the Tukon tester that is similar to that of the Rockwell hardness test that is used for metals. If the body strength is too low then the grinding wheel will waste away, however if it is too high the grains will dull. The ideal body strength will allow the grains to fracture only when they have begun to dull.

Although, Silicon Carbides and Aluminum Oxides are the two main abrasives that Saint-Gobain uses, Aluminum Oxides are the abrasives are used when grinding steel. Within aluminum oxides, a wide range of property values may be obtained by preparing the abrasive grains different ways. For example two common aluminum oxides that Saint-Gobain uses are Norzon and Seeded-gel. Seeded-gel is a high purity aluminum oxide made by the Sol-gel process, which is displayed in Figure 7. In simplified terms, this process involves the alteration of a liquid, "Sol", into a solid "gel". Seeded-gel grains are less aggressive than Norzon and therefore require less pressure to prevent glazing. Soft metals, such as aluminum and some carbon and stainless steels, are usually good candidates for aluminum oxide grain products. Norzon, displayed in Figure 6, which is a Zirconia alumina abrasive, can also be made by the Sol-gel process but it differs from seeded-gel when the aluminum oxide is fused together with zirconium oxide. A common problem with Zirconia grains is glazing, which occurs when the grains dull from insufficient grinding forces. Rubbing the dulled grains causes the metal to adhere to the tips of the grain. To reduce glazing heavier grinding forces are required to fracture the grain and enable re-sharpening. Therefore, zirconia lends itself to the higher temperatures and heavier pressures that are present in high-stock-removal applications. The basic steps involved in processing these grits can be seen below in Figure 8.

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[6] Norton CO, Lectures on Grinding

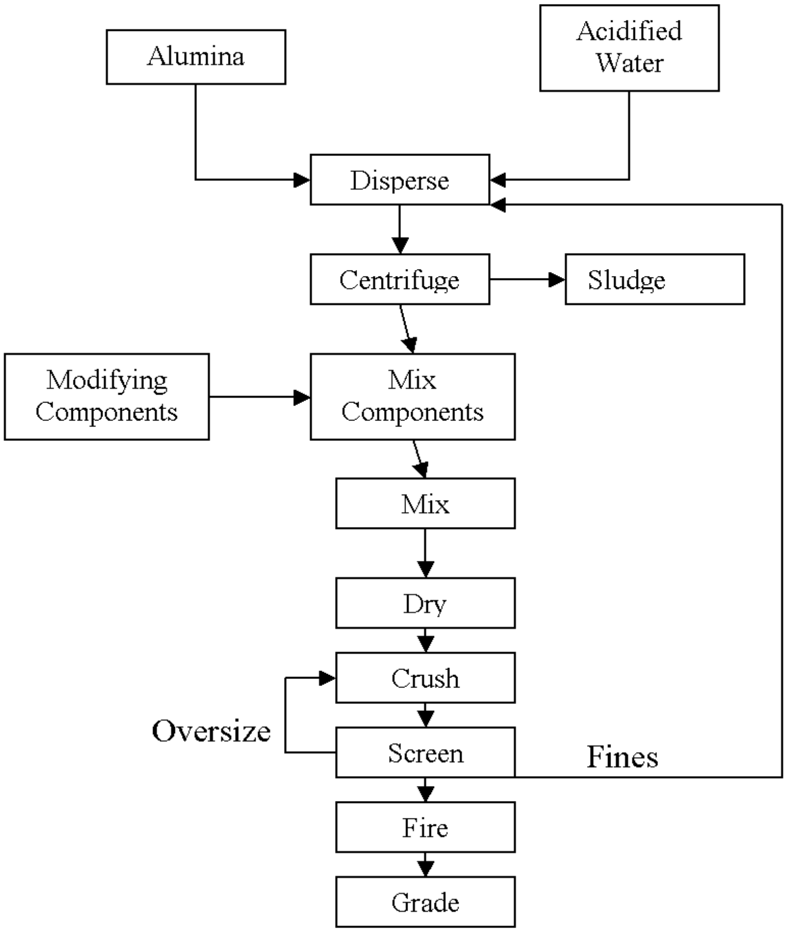

Figure 8: Steps to Make Abrasive Grains[7]

Once the grains are made, the next step in the creation of a grinding wheel is that the grains and bonds are weighed to an amount that depends on the size of the wheel and the ratio of grain to bond. The pre-measured grains and bond are sometimes mixed along with small amounts of other materials that aid in wear prevention and heat dissipation. The grains are then placed into a form of what shape the wheel will eventually be. The form is inserted into a hydraulic press and pressed under high pressures one or two times. Now that the wheel has its rough shape, it must be hardened to withstand the high forces of grinding. Organic wheels are cured in an oven and vitrified wheels are fired in a kiln. After the firing and curing cycles are complete it is time to fit the wheel to its final dimensions. The process of precision finishing the wheel to these dimensions is called truing the wheel.

At this point, construction of the wheel is complete and it now needs to be checked before shipping in order to ensure that the proper quality is achieved. The grade of the finished bond is first checked using a sand blast penetration test, modulus of elasticity, and

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[7] Patent 4,314,827

displaced weight. Next the wheels are tested for their balance. In this test, the wheels are basically run at high speeds in an enclosed room until a speed at which they reach catastrophic failure. After these two major tests have been completed, along with a variety of batch checks, the product can be packaged and shipped to the customer.

3.4 Grinding Technique for Processing Different Steels

There are three types of interaction that occur between an abrasive tool and the work piece, which are cutting, plowing and sliding.

3.4.1. Cutting

Cutting a clean chip is the main interaction. Ideally, the abrasive grain is sufficiently exposed to penetrate the work piece material and curl a single defined chip. In this condition, there is sufficient clearance between the grain, bond and work piece for the chip to be removed from the area by either a coolant material or simply by the movement of the wheel itself.

3.4.2. Plowing

Plowing is another type of interaction that happens during the grinding process. This occurs when the abrasive grain is unable to get adequate penetration into the material to lift a chip. Instead, it pushes the material ahead of the abrasive edge similar to plowing snow along a road with a removal vehicle.

3.4.3. Sliding

The third cutting zone interaction is sliding. This interaction type can occur due to several conditions being present. Too shallow of a cut depth can cause the abrasive grain to slide across the work piece surface without digging in or removing any material. A lack of clearance between the abrasive grit and the work piece can trap the chip, causing it to slide on either the grinding wheel or the work piece. In cases where grit stays bonded to the wheel too long, the binder can come into contact with the work piece and create slide marks on the surface. Because there are so many cutting edges at work in a grinding operation, all of these interactions can be considered to be happening at once during the grinding process. Grinding process control is an effort to balance these interactions.[8]

Selecting the right type of grinding operation parameters involves consideration of a multitude of factors, which are machine tooling, work material, wheel selection and operational factors.

3.4.4. Machine Tool Factors

The coolant delivery system is important because it is the main method for maintaining interaction site temperature, providing lubrication and removing chips. Important machine specifics that affect the overall performance of the grinding operation are the machine's rigidity, precision and dynamic stability. A machine that cannot mechanically provide the precision and accuracy with adequate tolerances will not be able to deliver the desired outcome. Machine controls, power and speed capabilities and settings, as well as the truing and dressing mechanics are important for some grinding operations. They give the operator the ability to see how well the grinding wheel and work piece can be positioned on a repeatable basis.

3.4.5. Work Material Factors

Defining aspects of the working material that influence the grind are especially critical to successful cutting. Work piece characteristics include the material's mechanical properties, its machinability, thermal stability, abrasion resistance, its microstructure and chemical resistance. Also the material’s percent elongation at break has an effect on grinding performance. This is the area that we will be most concerned with, as these are the types of variations in the grinding process that we want to learn the effects of with regard to changing the type of grinding wheel.

Example:

Cutting steel with diamond where the abrasive/work piece contact pressure is high cannot be done because of the chemical reaction that occurs between the carbon in both.

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[8] Koepfer, Chris

Low pressure grinding techniques like honing can be done on steel with diamond cutting materials because the pressure is not great enough to initiate the chemical reaction. The shape or geometry of the work piece is also important. Tight corners or extremely sharp radii are difficult to grind and require special consideration. Feature tolerances and surface finish requirements dictate the types of grinding wheels to be used and the various other parameters of the process that need to be varied.

3.4.6. Wheel selection factors

Selecting the correct abrasive composition is an important factor in grinding. Grain composition types, properties, size, distribution and concentration need to be properly selected in order to produce the right outcome. The matrix properties for these grains (bond) are an equally important factor. Bond characteristics can be classified by their type, hardness, stiffness, porosity and thermal conductivity. [9]

3.4.7. Operational factors

These factors include fixturing, wheel balancing, the frequency of truing and dressing, the application of coolant, and whether the part is gauged in-process or off-line.

3.5. Grinding Interactions

When grinding with abrasive wheels, there are multiple interactions occurring simultaneously. For the majority of the grinding wheels history, it was believed that the interaction between wheel and piece was purely mechanical. It was compared to cutting with a knife or using a lathe. There have always been suspicions that there was some interaction occurring on the molecular level, but until recently there was no clear-cut evidence to prove the assumption. More and more phenomena began to be uncovered that could not be explained by simple mechanical analysis alone. One of the most important of these was the observation that Silicon Carbide abrasives and Aluminum Oxide abrasives performed very differently under the same grinding conditions. For example, it was observed that aluminum oxide is superior for grinding steels. This led people in the early 1900s to believe that Aluminum Oxide was the superior abrasive, and was suitable for

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[9] Koepfer, Chris.

materials with a high tensile strength, while Silicon Carbide should be used for materials with low tensile strengths. Researchers then discovered that in grinding other materials, Silicon Carbide was the superior abrasive. This led to the still ongoing study of what factors effect the performance of a grinding wheel on a specific material. The grinding interactions discussed here will be:

- Abrasive – Metal Interaction
- Abrasive – Atmosphere Interaction
- Abrasive – Bond Interaction
- Metal – Bond + Environment Interaction
- Bond – Environment Interaction

3.5.1. Abrasive – Metal Interaction

The interaction between the abrasive and the work material is the most important interaction discussed. This interaction is the reason that grinding interactions began to be closely studied, and one of the major parts of this project. One of the first and most notable points on this topic is that most measurements indicate that the temperature where the two surfaces come in contact during grinding is at or near the melting point of the metal. This temperature obviously varies based on grinding conditions, but when grinding ferrous metals these high temperatures can change the microstructure of the abrasive, causing it to lose hardness. Another problem created by the high temperatures observed during grinding is the adhesion of the metal chips to the abrasive wheel, or back onto the metal itself. This phenomenon is caused by a "built up edge" and is known as re-welding. This occurs when the interaction site temperature rises to a point where the chips are hot enough to re-adhere to either the wheel or the freshly ground surface.

Chemical reactions also have a great effect on certain materials that are likely to react with each other. Specifically grinding Iron with Silicon Carbide produces interesting results that are unique to this combination. It is believed that the Silicon Carbide reacts rapidly with small amounts of SiC in the iron to form carbides and silicates that can significantly affect the grinding process. The oxidation of metals while being ground can also have a significant effect on grinding performance. [10]

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[10] Coes Jr., Loring.

3.5.2. Abrasive – Atmosphere Interactions

It has been determined that with oxide abrasives any interaction with the atmosphere is of negligible effect. There is one exception, the wear rate of aluminum oxide on steel has been observed to be higher in humid air then in dry air and is less under oil than in dry air. This has been attributed to a secondary chemical reaction. However, with carbide abrasives, these interactions are significant. SiC specifically forms a silica film on the top of the surface being ground, which provides some level of protection against oxidation of the ground surface.

3.5.3. Abrasive – Bond Interactions

Abrasive – Bond interactions can be both physical and chemical in nature. Bond chemicals can have a detrimental and beneficial effect on grinding performance. Cryolite is an excellent example of this. This additive melts at around 950 deg, F, and because of this greatly improves grinding performance on stainless steels. The opposite is true when grinding carbon steels however, due to oxygen preventing loading in the case of carbon steels but not when grinding stainless steel. [11]

3.5.4. Metal – Bond + Environment Interactions

The main topic of interest here is the oxidation of the metal being ground after material has been removed. This rate of oxidation is a function of the composition of the metal. For most metals, the oxidation rate is fast enough that re-welding to the abrasive, bond, or metal is effectively prevented. Materials like stainless and low alloy steels, however, do not have a sufficiently fast oxidation rate to prevent re-welding. Because this is known, other substances that are known to react more quickly with freshly ground surfaces then oxygen are added to the bond mixture, therefore effectively preventing re-welding. Another common problem that can be solved by using fillers is extreme heat in grinding operations. Cut-off applications are one specific example in which extreme heat is generated, due to the sides of the wheel as well as the face grinding the material. In cases such as this, active fillers are used to combat the problem. Active fillers like this can be used for a variety of things from decreasing side friction to extending wheel life. [12]

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[11] IBID.

[12] IBID.

3.5.5. Bond – Environment Interactions

While this may seem to be of little importance to the grinding process, there are a few important interactions that occur in this medium. When using organic bonds, the major concern is oxidation of the bond. This is mainly a concern in big industry type applications when either high power is being used, contact area is large, or where heat conductivity of work piece is low. These high heat and high stress applications cause the bond to oxidize, resulting in what is known as wheel burn. This weakens the bond, and eventually causes the bond to disintegrate and the wheel to fail. Similarly, this can be solved by the use of active fillers. [13]

3.6. Steel Properties

Up until now we have talked about the different aspects of grinding wheels and how their characteristics determine how they perform in a grinding situation. The other key aspect to understanding how grinding wheels will perform is the material that they are processing. The type of metal that is being processed is a huge factor in the selection of the perfect grinding wheel. Everything from the simple mechanical and thermal properties to the microstructure of the steel has an influence on how it responds to grinding.

3.6.1. Mechanical, Thermal and Physical Properties

For our project, we looked into three types of steel, which are 4340 steel, 304 stainless steel, and D3 tool steel.

4340 steel is a low alloy, heat treatable steel known for its toughness. This alloy also has the unique ability to develop high strengths in the heat treated condition, while at the same time retaining good fatigue strength. Typical uses for this steel are in structures, such as in aircraft landing gear and power transmission gears and shafts. Machining of this steel is best when the steel is in its normalized and tempered condition. The element composition by weight percent and the properties of this alloy can be seen in Appendix A at the end of the report.

304 Stainless Steel is used significantly because of its ease of welding and machining, as well as its resistance to oxidation. A low carbon version of this steel, which is commonly used in heavy gage components, is created so there is no need for post weld annealing. The

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[13] IBID.

high carbon version, on the other hand, is particularly useful at elevated temperatures. The element distribution as well as the different properties relating to each of these versions can be seen in Appendix A.

D3 tool steel is a high carbon/chromium tool steel with very high wear characteristics. This particular alloy is deep hardening and has a very high compressive strength. This tool steel is used in applications which require a very hard steel along with a high degree of accuracy. A few examples are draw dies, forming rolls, and powder metal tooling. D3 tool steel is oil quenched steel and is very sensitive to slight changes in the tempering and annealing conditions. The element composition by weight percent and the properties of this alloy can be seen in Appendix A at the end of the report.

3.7. Microstructure of Material

The microstructure and grain distribution within the work material will have an effect on the grinding power required, as well as the chip size and shape that is formed. There are likely many other effects that we hope to investigate and clarify. There are six common microstructures, also referred to as phases, which can be present in a steel specimen. They are Ferrite, Cementite, Pearlite, Austenite, Martensite, and Bainite.

These 6 microstructures are commonly present to some degree in most steels. The steel types that we will be analyzing will also have some of these different phases present within them. Each microstructure is explained briefly below.

3.7.1. Ferrite

Ferrite is a generally soft and ductile phase, and is a primary phase in softer steels. Ferrite is the crystal arrangement for pure iron. It exists as a body centered cubic structure. Ferritic metals are usually easy to grind, but the grinding wheel must be chosen carefully to avoid interaction that causes either plowing or sliding due to the softness of the ferrite.

3.7.2. Austenite

Austenite (gamma phase iron) is a metallic non-magnetic solid solution of iron and an alloying element. This phase is present when the steel exists above the critical eutectoid temperature. In some dual phase steels, or some high strength steels, austenite is purposely retained in small amounts to help achieve the desired properties. Austenite has a face-centered cubic (FCC) structure, which has more open space than the body-centered cubic structure, which allows it to hold a higher proportion of carbon in solution.

3.7.3. Pearlite

Pearlite is a phase mixture consisting of alternating platelets of ferrite and cementite (α + Fe3C), which grows by conversion from austenite. A steel containing 0.77 wt% carbon can consist solely of pearlite if cooled sufficiently slowly from austenite (see Figure 9). Under the microscope it can have an iridescent mother of pearl appearance, hence the name.

3.7.4. Bainite

Bainite is one of the hardest of the 4 phases, and consists of cementite and ferrite in a lamellar structure similar to pearlite. Bainite is formed when austenite (a solution of carbon in iron) is rapidly cooled past a critical temperature of about 723°C.

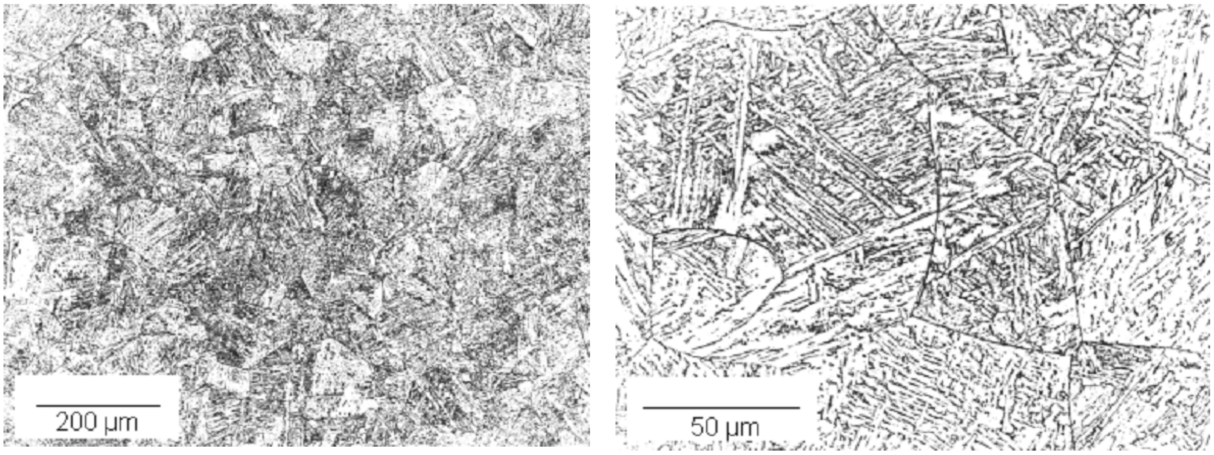

Figure 9: Bainite Matrix with Prior Austenite Grain Boundaries[14]

3.7.5. Martensite

Martensite is primarily like a ferrite phase saturated with extra carbon. The extra carbon makes the structure much harder and thus this phase is found more often in super high strength steels. Martensitic ferrite is similar in crystal structure to austenite, but has a

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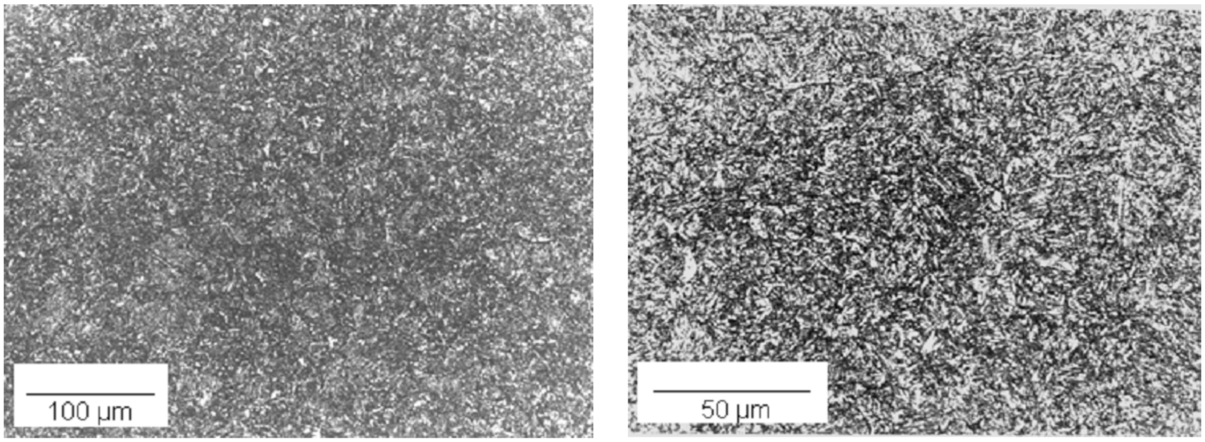
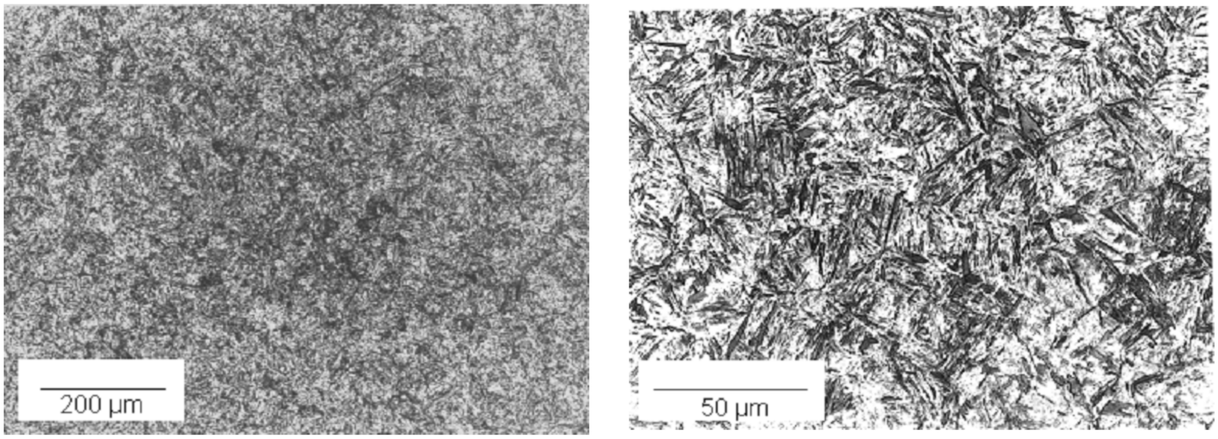
[14] Dr. James Marrow. British Steel.

lower density. Martensite is usually considered to be a grain structure not a phase. It is only distinct from ordinary ferrite in that its transition between the stable phases relies on displacive transformation rather than diffusion and nucleation.

Quenching can be difficult to control in martensite because most steels are quenched to produce an overabundance of martensite and then tempered to gradually reduce its concentration until the right structure for the intended application is achieved. Too much martensite leaves steel brittle, too little leaves it soft. Pictures showing the difference between quenched and tempered martensite can be see in Figure 10.



Quench and Tempered Martensite



Water Quenched Martensite

Figure 10: Martensitic Structures[15]

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[15] Dr. James Marrow. British Steel.

3.7.6. Steel Micrographs Showing Various Phases

More often than not, steels are forged and heat treated to include a multitude of the different phases within their microstructure. This is to combine the positive traits of different phases while lessening the limiting characteristics that they both have. Shown below are photos displaying the microstructure of steels with more than one microstructure.

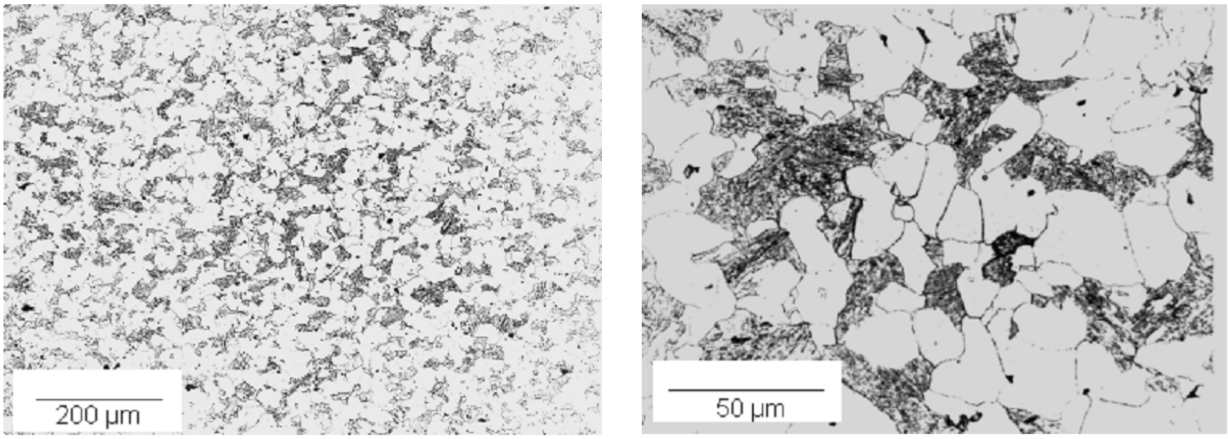

Figure 11: Mixed Microstructures Ferrite, martensite, and bainite.[16]

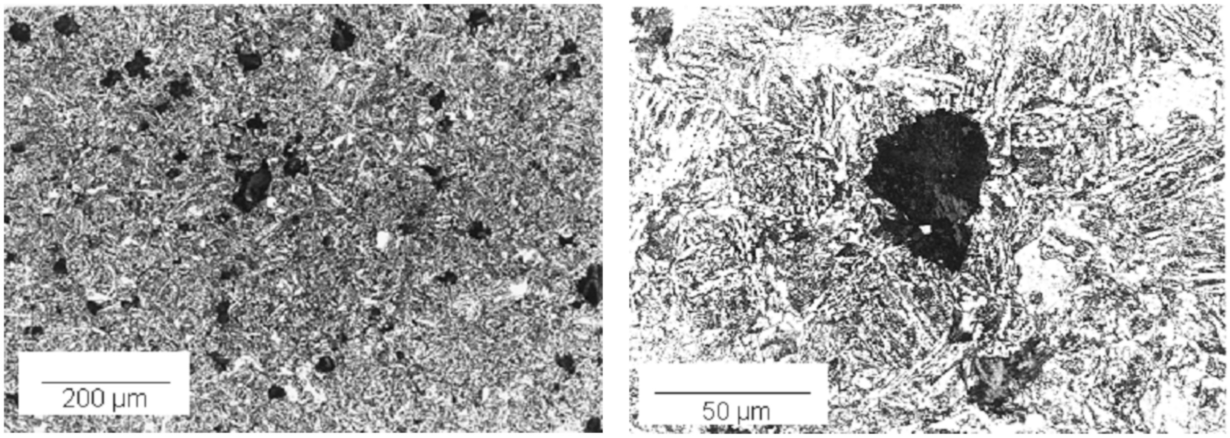

Figure 12: Mixed Microstructures Bainite, martensite, and pearlite[17]

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[16] IBID.

[17] IBID.

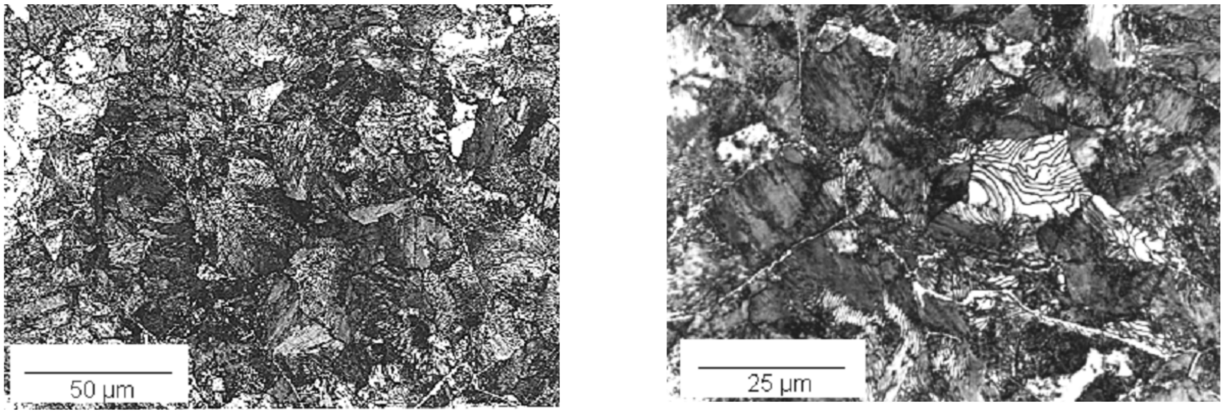

Figure 13: Pearlitic Matrix with Cementite on Grain Boundaries[18]

3.8. Effects of Heat Treatment on Steel

Although there are only six main types of steel that we are analyzing from this test method, the properties that the steel hold can differ greatly depending on the amount that the steel is heat treated. Heat treating steels alter the mechanical and physical properties that can give the steel desired characteristics that are not present under normal conditions. The first qualification for hardening heat treating, which is most common, is that there is sufficient quantity of carbon and alloying materials. If these are both not present, the surface of the material must be carbon enriched to allow heat treating to occur.

There are three basic types of heat treating, which are normalizing, quenching and tempering. During normalizing, the steel is heated to 900^{0}C into the Austenitic region and then allowed to cool slowly in the air. By raising the steel to this temperature, the microstructure transforms from a body-centered cubic structure to a face-centered cubic structure. This process allows the steel to form a microstructure of pearlite and ferrite. Pearlite gives the steel its strength, while ferrite is soft and allows the steel to be ductile and tough. As the percentage of carbon in the steel increases, its strength also increases because the amount of pearlite increases.

When steel is quenched to increase its hardness, the steel is quenched in water or oil immediately after heating the steel up into the Austenitic region. This process forms a Martensitic microstructure. This microstructure is extremely hard and brittle because carbon is trapped in the microstructure due to the rapid quenching. In order for it to be useful, it

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[18] IBID.

must be tempered. During tempering, the steel is heated up to 200^0C for an hour. This allows the trapped carbon atoms to diffuse out of the steel. As a result, the tempered steel is less brittle and thus tougher than the quenched steel. It is also harder and stronger than the normalized steel, but it is somewhat less ductile. [19]

As stated earlier, it is important to have an adequate amount of alloying elements in the material before heat treating because the full hardenability of steel is based upon the amount of alloying elements present. Although the full hardenability is based upon the amount of alloying elements present in the steel, this does not affect the maximum hardenability of the steel. In fact, the maximum hardenability of steel is the same for different alloys as long as they both contain the same percentage of carbon. The depth of the full hardness, however, is dependent on the amount of alloys present. For this reason, the purpose of adding alloys to steels is not to add to its strength, but rather to add to its hardenability.

Under normal conditions, when hot steel is quenched, most of the cooling occurs at the surface, thus leading to a high hardenability at the surface. The hardness eventually propagates into the steel. The addition of alloying elements to the steel helps in the ease of obtaining full hardness in the steel. Without alloying elements, the steel would have to be quenched extremely rapidly in order to transform the entire part to Martensite. With the addition of alloying elements, such as Molybdenum and Chromium, rapid quenching is no longer needed to obtain similar if not better mechanical properties.

3.9. Alloying elements present in steels

While most of the weight percent of steels is made up of iron, pure iron is generally not a desirable material by itself. In its pure state, iron is weak, soft, ductile and doesn't respond well to heat treating. For that reason, additional elements are commonly alloyed with iron to give it the characteristics that are desirable. Carbon, which is added to up to 4.5 weight % strengthens the material and allows it to be considerably heat treated. Other elements are added in miniscule amounts, usually less than 1 weight %. One additional element that is added is nitrogen, which also strengthens the material. Sulfur and phosphorous are added in larger quantities to improve in the machinability of the steel. High quantities of sulfur tend to lead to "hot forming," so small quantities of manganese are

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[19] Marrow, James Dean. Heat Treatment of Steel.

added to offset this. Silicon is an additional element that is added to increase the strength of the ferrite and increases its oxidation resistance. Cr, Mo, W, and V are all added to steels with high carbon contents because they create carbides, which increase the creep resistance of the steels and allow it to be used as a cutting tool. Therefore, although additional elements can be added to the steels to obtain its desired properties, the underlying goal is to increase the hardenability of the steel. [20]

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[20] Meier, Mike.

4. Methodology

This project aims to assist Saint-Gobain Abrasives R&D to determine what steel properties effect grinding performance. The team will draw general conclusions from previously conducted surface grinding tests, propose conditions for additional testing, and then analyze all gathered data to determine key steel properties affecting grinding performance. The main objectives of this project are:

- Complete material investigation on both the steels and the grinding wheels to be used in the test.
- Analyze data from HGTC surface grinding tests to determine where the holes are in understanding the effects of material properties on grinding performance.
- Propose Design of Experiment based on previous data from the HGTC.
- Analyze all results to compile comprehensive understanding of material property effects on grinding performance.

Our research was compiled from data collected from a surface grinding test located at the Higgins Grinding & Technology Center in Worcester, MA at the Saint-Gobain facility.

4.1. Gathering Key Properties of Steels Used

A key aspect to being able to determine why steels behave in certain ways when ground is to understand all the properties of the steels that affect its grinding performance. Every aspect of the steel, whether it is the density and mechanical properties of the steel, or how it is made up at a microscopic level, all play a role in determining how the metal reacts when subjected to grinding tests. Therefore, it is crucial for us to fully understand every aspect of the materials including the different heat treatments that could have an influence on the metals performance when subjected to grinding conditions.

4.1.1. Material's Physical Properties

The first step in understanding how a metal will react when subjected to different situations is to understand its mechanical and thermal properties. To accomplish this, various properties of the different steels that we will be analyzing were researched. These steels are 4340 steel, 304 stainless steel, and D3 tool steel. These steels have quite a diverse range of usage, and therefore will have diverse material properties. Even though there are only three steels that we have to look into, each one of them can have a multitude of different properties depending on the way that they are heat treated. To gather the most comprehensive set of data possible, steel websites were looked at, as well as a materials selection program known as CES4. Through these two sources, the material properties on these different steels, was gathered, as well as their heat treated counterparts. A spreadsheet was created to easily house all of this information. By collecting all of this data, links could be developed between material properties and grinding performance in the test bed.

4.1.2. Material's Composition

Once the properties relating to how the steels perform were understood, it was important to determine how the steels were created. One of the major factors determining a steels performance is the type and quantity of alloying elements added to the material. If no alloys were added to the steel, the material would remain 100% iron, which is a brittle non-desirable metal. Once carbon and other additional elements are added in small quantities (on average less than one weight percent), the performance of the steel drastically increases.

4.1.3. Material's Microstructure + Heat Treatment

The next step in determining how steel performs under grinding was to explore their microstructures. Depending on the type and quantity of alloys, the configuration of the steels atoms at a microscopic level will be different. The positioning of these atoms, although seemingly unimportant, can determine how steel fractures and its' wear rate. In addition, steels are made up of a multitude of different phases, each of which has different properties that are suitable for different applications. To fully understand this, research was done on the different ways in which steels are heat treated and the types of effects that heat treating has on the material properties. The different types of phases present in steels, was also researched. These are characteristics that each steel has and common combinations of them are present in steels being used in this surface grinding test. This was accomplished using materials books as a reference, as well as various internet sites, specializing in heat treatment and phases of steels. Some of this information is included in Section 2.6- 2.7.

4.1.4. White Alundum and Seeded Gel Grains

The choice of the abrasive used to grind the steel is a crucial step in making sure the grinding wheel accomplishes its desired task. For this project, the data that will be analyzed will be focusing on White Alundum and Seeded Gel Grains. White Alundum is the trade name that the Norton Company uses for one of their aluminum oxide grains. The particular Alundum abrasive that we will be dealing with in our test is 38A or 38 Alundum, and is made from chemically treated unfused alumina. This grain is made by heating the base materials to a specified temperature in an arc furnace, and then pouring the product into molds. This process gives the grain its' distinctive white color. Seeded gel is the trade name for one of Saint-Gobain's ceramic aluminum oxides. Seeded gel is made by crushing alumina gel that has been dried. It is especially important because it has the ability to re-fracture at the sub-micron level. This information along with the information that was provided in the background on these grains is publicly available and found at reputable sites on the Internet. In addition, patent information was found for 3M and Saint-Gobain, which also gave us valuable information relating to these grains. In addition to the specific properties of these grains, research was done on how in general grinding wheels and the grains specifically act while under stress.

4.1.5. Grinding Interactions

Now that a thorough understanding of the steels properties and microstructure has been developed, it is important to also understand the interactions the steel has when exposed to grinding. To do this, the multitude of interactions that occur between the grinding wheel, the material being processed and the environment surrounding them were all researched. These are separated into five categories, which are abrasive-metal interactions, abrasive-environment interactions, abrasive-bond interactions, metal-bond-environment interactions and bond-environment interactions. Each one of these categories represents a different way in which the grinding of the steel is affected, whether in a positive or negative way. To accurately determine why grains grind certain steels better than others, it is important to have a thorough understanding of what exactly is happening at the site of interaction between the grains and the steel. This information was found in books that were recommended to us from a Saint-Gobain Abrasives employee based on their past experience on where they found useful information on the subject.

4.2 Design Of Experiments

4.2.1 Preliminary Data Analysis

In order to determine what the nature of our experiments would be, it was necessary to conduct some initial analysis on the data that was given to us by Saint-Gobain's grinding center. The data that we were provided with had a wide range of input selections. There were variations in the downfeed, crossfeed, grain types, grain size, bond type, bond grade as well as variations in the material being ground during the test.

To better understand the effects of varying inputs, a multitude of plots were generated that showed the effects of changing these various inputs of the test. Also, by examining the amount of data for similar input parameters, it was determined where more data would aid in forming functional correlations between the inputs and the outputs of the data.

4.2.2 Trends and Assumptions from Previous Data

Some assumptions need to be made when analyzing the data that we have already been given. For instance, in the following sample portion of the data, there appears to be 2 types of grain in the abrasive wheel on the selected rows. However, there is no grain type listed under the Grain Type 1 column. In this case it is assumed that grain type 1 is the same as grain type 2.

Grit 1 Size	Grit 2 Size	% Grain 1	% Grain 2	Grain Type 1	Grain Type 2
54	54	30	70	XG	57A
54	54	30	70	XG	57A
54	54	30	70	XG	57A
54	54	30	70	XG - MR1	57A
54	54	70	30		SG
54	54	70	30		SG

A similar situation was encountered with another portion of the data. Below, there are two types of grains listed, but there is no value under Grit 2 size on the selected rows in the figure below, which is a sample section from the original data set with which we were provided.

Grit 1 Size	Grit 2 Size	% Grain 1	% Grain 2	Grain Type 1	Grain Type 2
54		30	70	SG	38A
54		30	70	SG	38A
54	54	30	70	SG	38A
54	54	30	70	SG	38A
54	54	30	70	SG	38A
54	54	30	70	SG	38A
54		30	70	SG	38A
54		30	70	SG	38A

In this situation, it was assumed that the grit sizes are equal, meaning that in rows 1,2, 7, and 8 of the above figure, the value of grit 2 size is 54.

As a part of the results from this project, there will be many graphs which attempt to correlate the outputs of the testing to the inputs we have provided. Additionally, a few outputs will be plotted with respect to each other. For example, if wheel wear rate is plotted vs. power, one would expect to see an upwardly curving concave up type of relationship.

With other output parameters plotted vs. power, different relationships will be observed, which will in turn generate differently shaped curves. Some of these shapes are considered to be common and expected when plotting those two parameters with respect to each other. These relationships have been documented in previous studies and grinding mechanics handbooks. By comparing these known results to the shapes of our graphs (which will be generated from the data produced through the designed experiments), the accuracy and appropriateness of the test method can be evaluated.

These plots will have a significant importance as part of the expected results, because they will allow the group to assess the accuracy of the information that the tests are producing. If the plots do not provide a shape in the form that is expected, then it is obvious that either the assumptions that were made are incorrect or that something may be wrong with the data. If the plots are in the expected form, then the plots can be used to show that the data is accurate.

4.3 Design of Experimentation

Through discussion with a representative from St. Gobain, it was determined that there would be a limited number of test runs available to us. This was due to long wait-lists for use of the testing equipment. A test plan was needed that would allow for the most information gathered from the fewest number of test runs.

Through preliminary data analysis a few specific tests were pinpointed that would be necessary in order to have enough related data to gain useful results. Our initial plan was to conduct more testing with the same steels and vary the input parameters, such as wheel speed, downfeed, or others.

Our final Design of Experiment that was submitted to St. Gobain was as follows:

February 3, 2007

Steels:

D3 Tool Steel
4340 Steel
304 Stainless Steel

Wheels:

38A60 K6 B40
SG60 K6 B40

Constant Test Conditions

Vw=600
Vs=7500
Wheel Width~.5"
Wheel Diameter~5"
Total Infeed- .05
Crossfeed - .48

Varying Test conditions

Downfeed This will be either .001 or .003

Experiment1)	SG wheel, D3 Steel, .001 downfeed

Experiment 2)	SG wheel, D3 Steel, .003 downfeed
Experiment 3)	38A wheel, D3 Steel, .001 downfeed
Experiment 4)	Re-Run Experiment #3
Experiment 5)	38A wheel, D3 Steel, .003 downfeed
Experiment 6)	SG wheel, 4340 steel, .001 downfeed
Experiment 7)	SG wheel, 4340 steel, .003 downfeed
Experiment 8)	38A wheel, 4340 steel, .001 downfeed
Experiment 9)	38A wheel, 4340 steel, .003 downfeed
Experiment 10)	SG wheel, 304 stainless steel, .001 downfeed
Experiment 11)	SG wheel, 304 stainless steel, .003 downfeed
Experiment 12)	38A wheel, 304 stainless steel, .001 downfeed
Experiment 13)	38A wheel, 304 stainless steel, .003 downfeed
Experiment 14)	Re-Run Experiment #8

Table 1: Design of Experimentation

4.3.1. Surface Grinding Tests

Due to limited availability of equipment, the designed tests were run at the Higgins Grinding & Technology Center at the Worcester Saint-Gobain facility. This facility has been conducting a variety of grinding tests on a wide variety of abrasive wheels for years now, so there were no concerns about the proper implementation of the surface grinding tests. Pictured below in Figure 14 is the actual surface grinder used for these tests.


03/26/2007

Figure 14: Surface Grinder

In order to be able to analyze the data outputs from these tests, it is necessary to understand how the tests are run by the operator. The grinding wheels used in these particular tests measured five inches in diameter by one-half inch thick. Although a coolant nozzle can be seen in the picture, these tests were run dry. The wheels are fixed to the spindle seen below using a screw type attachment. The spindle described is shown in detail below.


03/26/2007

Figure 15: Surface Grinder Spindle

The steel billet being ground is attached to a movable plate, located below the spindle above. Before the test begins the operator takes precise measurements of both the wheel and the steel. This is done so that after the grind is complete, the same measurements can be taken, therefore determining how much material was removed from the billet, and how much of the wheel has worn away. Initially the operator begins spinning the wheel at the speed specified in the test specifications. During the grind data is collected on the power consumed, and normally on the horizontal and vertical forces as well. Unfortunately, during our test runs the FIS system that collects the force data was not operational; therefore no force data was obtained. Another important parameter collected after the grinding is complete is the surface roughness of the finished billet. The first grind begins at the back corner of the billet and travels lengthwise until the other side is reached. The wheel, or in this case the fixture actually, jogs over the specified in-feed length, for this test 0.050 inches. The other change after one pass is in the down-feed, or the height of the grinding wheel relative to the billet. The change in down-feed for this test was a height of 0.0005 inches. The fixture that the billet is attached to is shown below.

Figure 16: Surface Grinder Fixture

4.3.2. Determine which steel properties affect grinding performance

Once the results are collected from the grinding test that was submitted to the Higgins Grinding & Technology Center, they will have to be analyzed in order to determine what properties present in the steel affected the outputs of the tests. This can be accomplished in a graphical way by comparing the graphical outputs to specific steel properties or by graphing parts of the test data and identifying on the graph what properties each of the three different steels possess.

There are many different variables that can be plotted to gain an understanding for how the different steels affect grinding performance. Since only three steel types were used, it is possible to graph data with all variables constant except for the steel type. By doing this, it was determined if a specific steel property could have affected the data outputs. For example, if 4340, 304, and D3 steel have a linear slope in a specific graph and 304's line was above 4340, then it becomes clear if specific traits in the steel were higher for the 304 than the 4340. If so, this trait could also be a cause for the steels grinding performance.

When comparing the preliminary data, as well as the grinding test, the same data was plotted in multiple ways. One method was plotting material removal rate (MRR) vs. power, which ideally should produce a line. Another graph plotted was wheel wear rate versus power, which should result in an exponential curve. Another graph that should produce a liner line was specific grinding energy versus the inverse of wheel wear rate. A different type of graph that was utilized was G-Ratio versus power, which will produce a bell shaped curve. Unfortunately, the data does not have a very large range, and therefore, will probably only have data that falls on one side of the bell curve or the other. Using these graphical methods allows one to compare how specific steel properties effect the placement of the different steels on each of the graphs.

5. Results & Analysis

The main deliverable for our project was to graphically show correlations between steel properties and grinding performance. This was reached by first developing an understanding of the properties in steel that could have the possibility to affect the steels surface grinding performance. We then conducted preliminary analysis on data collected from past organic surface grinding tests to determine any assumptions that could be made with the data and preliminary correlations reached through this data. We then designed a grinding experiment to test how different steels perform while subjected to identical grinding test specifications. This data, along with the correlations reached through our preliminary analysis on surface grinding test data was used to determine which properties in the steels affect their grinding performance.

5.1. Surface Grinding Data Correlations

In order to identify what reactions each of the different variables in the surface grinding test has on the output data, graphical analysis had to be completed to show each test parameter's affect on grinding performance. In the database provided us, the downfeed, or increment that each grinding pass penetrated into the steel varied between .0001" and .02" depending on the test. Our first step was to understand how this linear change in downfeed height affected the test data. We gathered a group of data from the database where all test conditions were held constant except for the downfeed. In the graph below, 4340 steel is tested with a total infeed of .05" and a crossfeed of .48". The grinding wheel used for this comparison was a 38A80K6B40 wheel, which, with the exception of the grain size, is identical to one of the grinding wheels used in our experiment. As can be seen in Figure 17 and Figure 18, a linear increase in the downfeed causes the material removal rate(MRR), wheel wear rate(WWR), Transverse Forces (Ft), Normal Forces(Fn) and the Power to increase at a linear rate. This linear increase in the downfeed height also causes the Specific grinding energy(SGE) and the G-Ratio to decrease at a liner rate. This agrees with present grinding theory which states that as the amount of material that is removed with each pass of the grinding wheel increases, the power necessary to remove that material increases. This also leads to higher wheel wear and larger forces at the interaction between the wheel and work material. By understanding this linear relationship between the downfeed and test output data, we can now vary additional test conditions to determine what their affects on test conditions are.

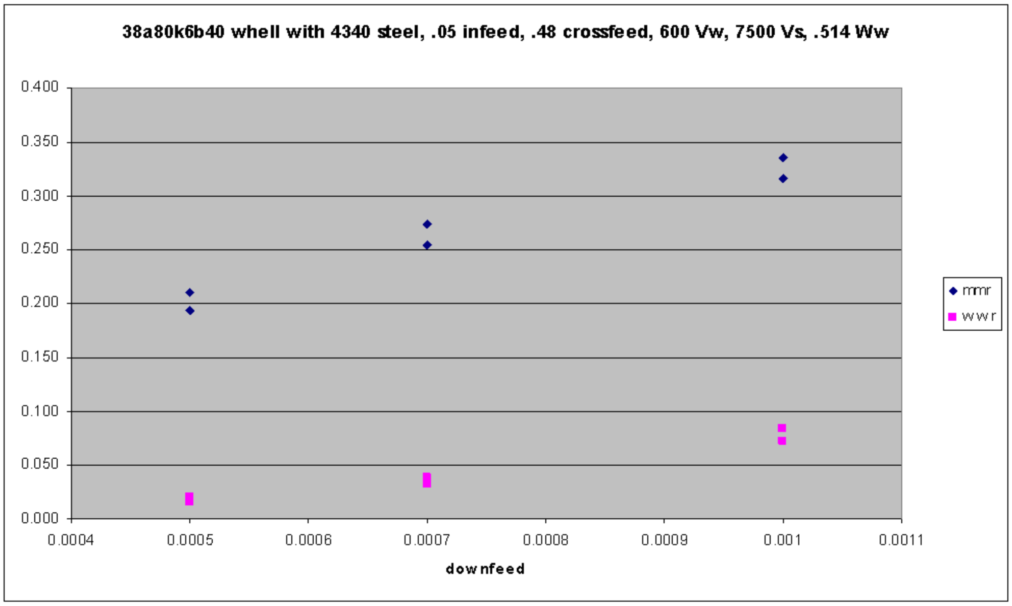


Figure 18: Down feed Effects on 4340 Steel with 38A80K6B40 Wheel

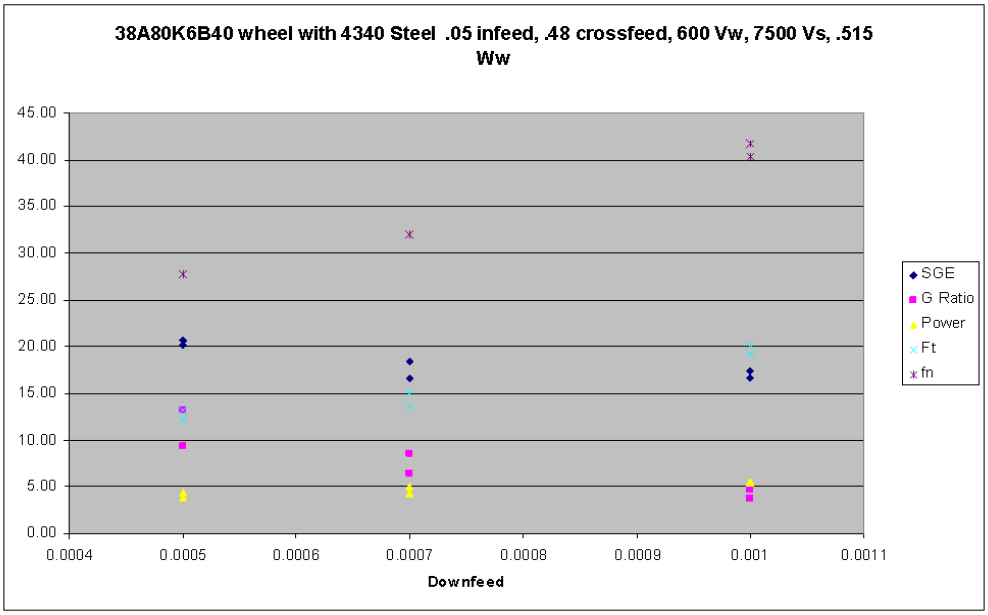


Figure 17: Downfeed effects of 4340 steel with a 38A80K6B40 wheel

In the operating procedure information section of the database, the wheel diameter (Ds) is not constant like the downfeed, crossfeed and infeed tend to be. The wheel diameter ranges from 4.13 to 5.0 and from 6.85 to 7.0, which is caused by the wheel wear during the testing. The width of the wheel also ranges from .196 to .22 and from .5 to .515, which is caused by variances in the making of the wheel. All of the output data is normalized with respect to the wheel width, therefore removing the wheel width as a possible factor in the affects of the grinding test. To determine the effects that the wheel diameter has on the output data, a set of data was collected that had all variables held constant except for the wheel diameter. Shown below in Figure 19 and Figure 20, 4340 steel is testing with a SG54I6B40 wheel with a total infeed of .05", downfeed of .005", crossfeed of .18", and a wheel width of .203". From the graphs, it is evident that the wheel diameter has no effect of the G-Ratio and Unit Power, but causes a liner decrease in the MRR and WWR and a linear increase in SGE when the diameter increases. When the wheels diameter increases, the surface of the wheel travel slightly slower than it did previously, which causes less material to be removed and less wear to occur on the grinding wheel. Since SGE is a calculated ratio of the total power divided by the total MRR, simple algebra would supports the findings that an increase in wheel diameter would cause the increase in SGE. From this test, it was discerned that wheel diameter is an important factor to consider when looking at the MRR, WWR and the SGE outputs of all surface grinding tests.

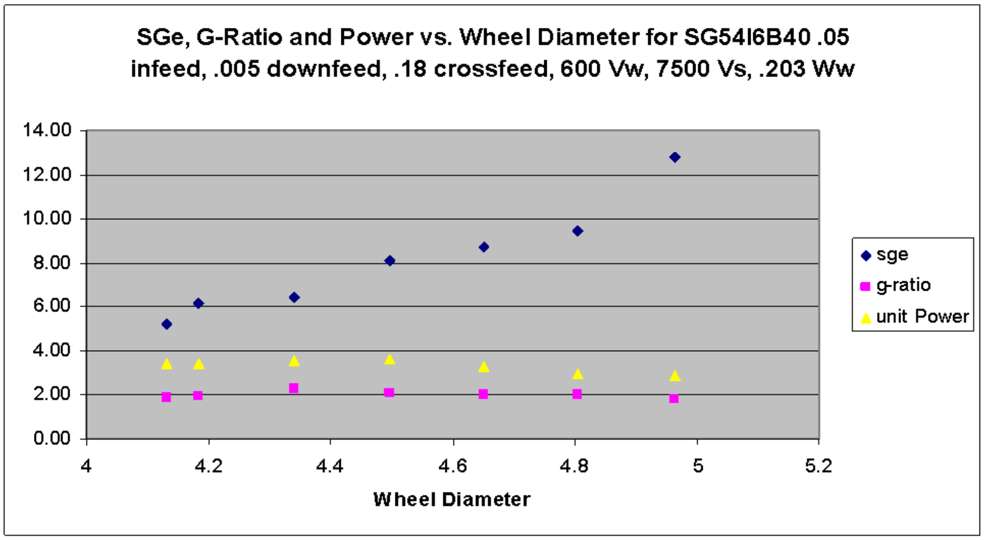


Figure 19: Wheel Diameter effects on test data

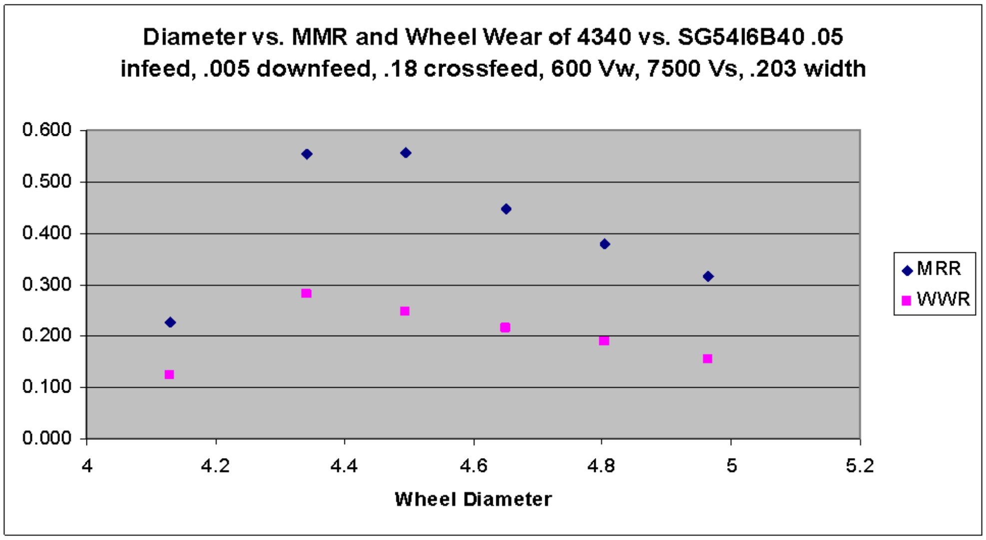


Figure 20: Wheel Diameters effects on Test Outputs

Now that an understanding of test conditions effect on the output data has been developed, it is important to make the same determination relating to the abrasive and bond properties. In the designed experiment, two different wheels were tested, which used a Seeded Gel(SG) grain and a white alundum(38A) grain. Before the data is analyzed, it is important to develop an understanding of how each grain behaves under similar test conditions. To test this, all variables were held constant except for the grain type. D3 tool steel was tested with a total infeed .05", crossfeed of .18", and a wheel width of .203". In one wheel, 100% SG grain was used, while the other wheel used 30% SG and 70% 38A grain. Both wheels used 54 grain size with a B40 bond and I6 grade and structure. In Figure 21 and Figure 22, the wheel with 70% 38A grain has

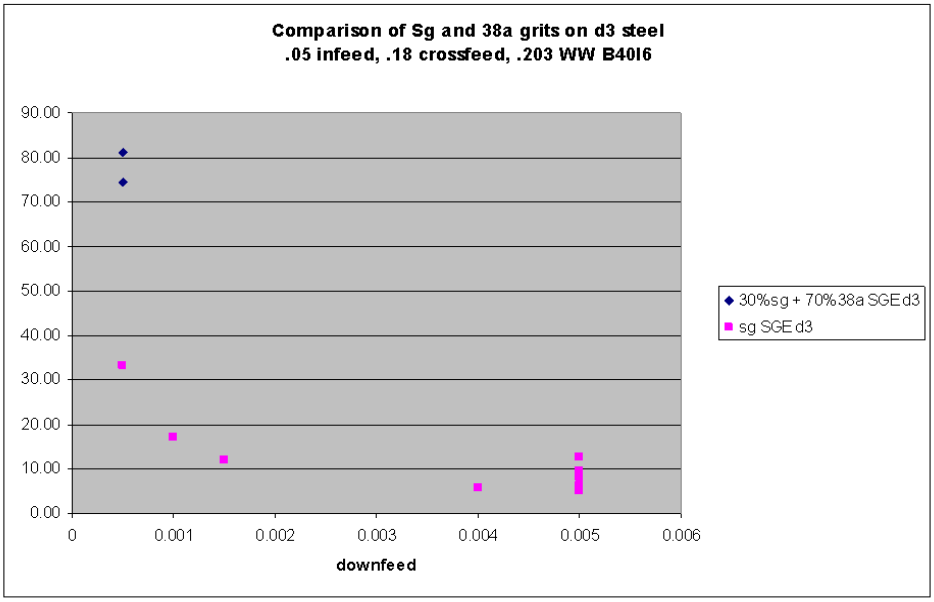


Figure 21: Grain effects on test outputs

a significantly higher SGE compared to the SG grain wheel. Also, the G-Ratio is relatively constant with both wheels. These finding just give further understanding as to how each parameter affects the overall grinding performance of the steel.

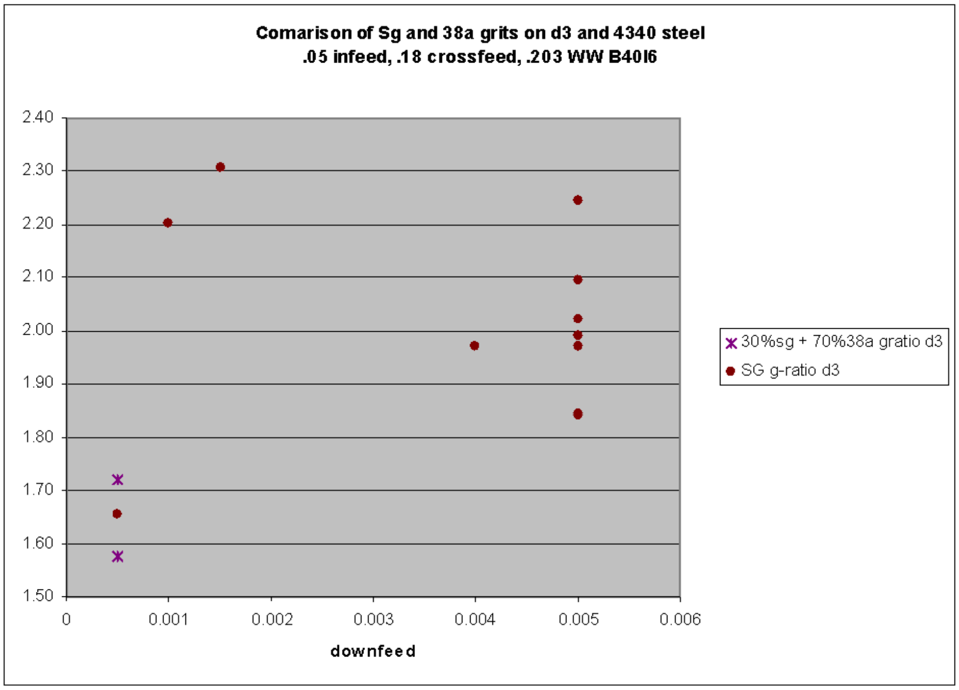


Figure 22: Grain effects on test outputs

For the grinding experiment, both of the wheels had B40 bonds in them, and the preliminary analysis that was conducted on the previously collected grinding data also had the B40 bond for the tests. Because of this, it was not necessary to determine how different bonds affect the grinding performance of steel since only one bond was used.

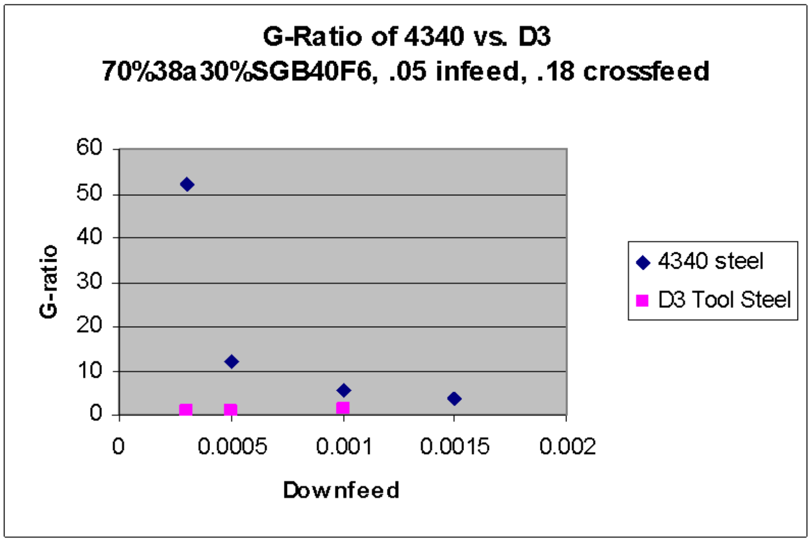


Figure 23: Effects of steel type on G-Ratio

Now that the variables in the grinding test and their effects on the test data is understood, it is necessary to begin to determine how grinding performance of 4340 steel and D3 tool steel changes when run with the same test conditions. This was determined by finding a group of data with the same test conditions where both steels were tested. Shown in Figure 23 and Figure 24 below are the outputs of tests taken with an infeed of .05", crossfeed of .18" and a 70%38A 30% SG B40F6 grinding wheel. It is evident that the G-ratio is higher and the SGE is significantly lower when testing the 4340 steel compared to D3 tool steel. This is determined by the different physical properties of the steel being tested. The exact causes for the 4340 steel to be easier to grind in comparison to D3 Tool steel will be discussed later in this section.

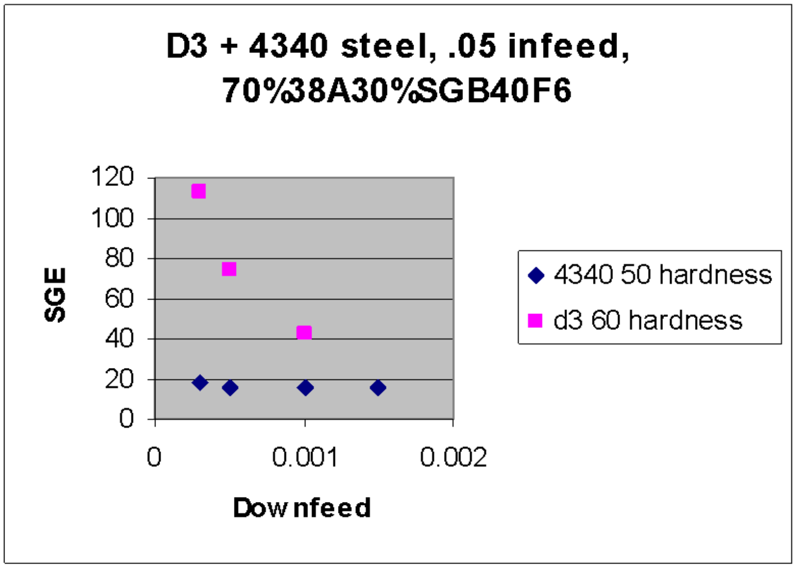


Figure 24: Effects of steel type on SGE

5.2. R^2 Analysis

While there are many ways to interpret data, one of the most simple and effective is to look for direct correlations between data points. In its simplest form, this project would represent just that; material properties comparing perfectly to outputs of the grinding test. While this did not occur exactly as expected, there are still some relationships that correlate quite well. These relationships, how they were calculated, and what significance they have will be introduced here.

The table below this section shows a variety of parameters on both the top and the bottom of the chart, and a numerical value at the intersection of each of these columns. The values in the cells were obtained using Microsoft Excel software. Each R^2 value in the cells below represents a graph comparing one of the terms on the y-axis to a term on the x-axis.

The resulting graph had three data points, which a trend line was added to, and from this, the R^2 values were calculated and displayed in the graphs. Rather than display each and every one of these graphs, only this correlation value has been displayed. It is important to note that each of these graphs had three data points on it, due to the use of three different steels in the test. In order to produce a trend line, three points is the minimum number of points required. This may lead to questions of the statistical relevance of the data presented, however with limited amount of steels and test times, this data did allow for some very logical correlations. It is not easy to predict how these correlations would have turned out had the test used ten steels, however these correlations due support logical interpretations of their meanings. In the table, values of above 0.87 were cited as "good" correlations, and highlighted to indicate so. The values of "1" down the middle of the table are obviously correlating individual properties to themselves and were therefore not included in the "good" correlations category.

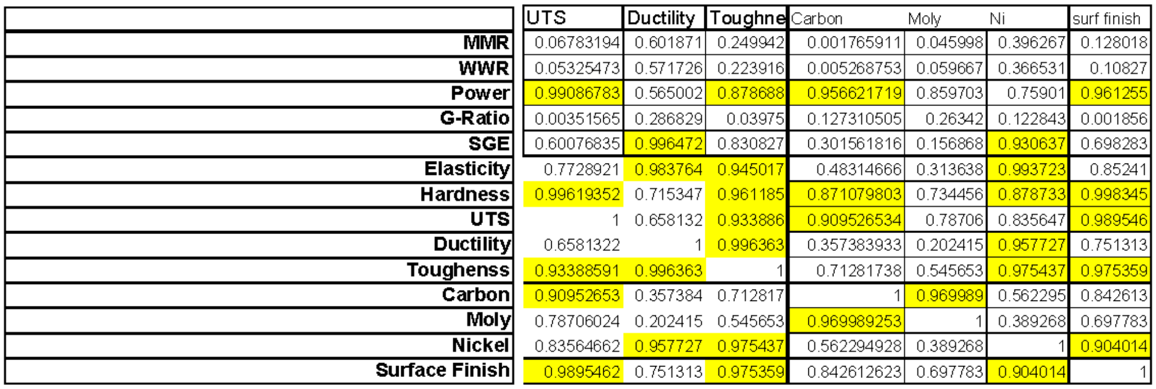
It becomes obvious when looking at the chart and having an understanding of the surface grinding tests that some correlations have very high values. For example, the top right corner has two values that both correlate two each other with values of 0.99, Material Removal Rate and Wheel Wear Rate. This makes a good deal of sense because these two depend on each other; if a certain amount of metal is removed from the billet, then a proportional amount of the grinding wheel will be worn away, and vice versa. This also leads to the comparison of G-ratio to each of these properties. Because G-ratio is a comparison of Material Removal Rate to Wheel Wear Rate, it follows logically that both of these will correlate well to the G-ratio. One of the major data outputs of this test that was studied was the power consumption, and in this chart some very logical correlations to power are shown, especially to material properties. One of the first is the hardness of the material; basically the harder the material is, the easier it is to make the initial grinding penetration, therefore consuming less power. For materials that have a low hardness, the steels will naturally deform under the penetration forces which will cause more power to be needed to grind off the initial material. This logic works as well with the Ultimate Tensile Strength of the material. The higher the UTS, the less power will be required of the surface grinder to cause the breakage of the chip away from the billet. Although toughness is more of a general property, dependent on the area under the stress strain curve for the material, the same relationship seen for Hardness and UTS is present for Toughness. Power also correlates well to the % carbon of the steel, which is the main alloying element responsible for the hardness of the material.

Specific grinding energy is another interesting property (P/MRR) that has some significant correlations in this chart. This property seems to correlate very well to the elasticity of the material. As the elasticity of the materials increases, the SGE also increases, so as the materials tendency to be deformed increases, so does the amount of power used per amount of material removed. There is also a correlation between the SGE and the ductility of the material. This is logically explained by the two parts of the grinding process, the important one here being plowing, or chip removal. The ductility property affects the abrasives ability to remove a chip once it has been initially broken away from the rest of the block, and the fact that this property increases linearly with SGE results in such a high correlation.

Another important measured output of the grinding test is the surface finish of the metal. Basically, after the grind is complete, a machine measures the average of the height difference between the peaks and valleys of the metal surface. A simple way to look at this would be to say that it is a measurement of the wheels ability to remove chips at an even rate across the billet. Hardness would affect this because the harder a material is the easier it becomes to remove chips evenly, hence the high correlation. The same idea is true for both the UTS and toughness. Another very interesting correlation to look at would have been to compare the microstructure of the steel to surface finish. If the steel had a large amount of very close grain boundaries, then it would seem obvious that the Surface finish would be quite low, however if the grain boundaries were not so defined and there were few, the surface finish would most likely be very high. This is one reason for our later recommendations to complete research on the materials microstructure.

	MMR	WWR	Power	G-Ratio	SGE	Elasticity	Hardness
MMR	1	0.99906302	0.027885	0.8993626	0.65919991	0.4748321	0.10209105
WWR	0.999063018	1	0.018695	0.9170236	0.62989806	0.4443222	0.08430984
Power	0.027885444	0.0186953	1	0.0238442	0.50575474	0.6882002	0.97541545
G-Ratio	0.899362556	0.91702355	0.023844	1	0.34196609	0.1794311	5.7992E-06
SGE	0.659199907	0.62989806	0.505755	0.3419661	1	0.9653639	0.66031677
Elasticity	0.474832055	0.44432218	0.6882	0.1794311	0.96536395	1	0.8224133
Hardness	0.102091048	0.08430984	0.975415	5.799E-06	0.66031677	0.8224133	1
UTS	0.6018709	0.05325473	0.990868	0.0035156	0.60076835	0.7728921	0.99619352
Ductility	0.601947568	0.57172593	0.565002	0.2868292	0.99647208	0.983764	0.71534666
Toughenss	0.249941673	0.22391557	0.878688	0.0397503	0.83082676	0.9450171	0.96118528
Carbon	0.001765911	0.00526875	0.956622	0.1273105	0.30156182	0.4831467	0.8710798
Moly	0.045997571	0.05966677	0.859703	0.26342	0.15686795	0.3136383	0.73445569
Nickel	0.396266605	0.36653087	0.75901	0.1228433	0.93063678	0.9937225	0.87873329
Surface Finish	0.128017986	0.10827034	0.961255	0.001856	0.69828259	0.8524103	0.99834548

Figure 25: R^2 Table



	UTS	Ductility	Toughne	Carbon	Moly	Ni	surf finish
MMR	0.06783194	0.601871	0.249942	0.001765911	0.045998	0.396267	0.128018
WWR	0.05325473	0.571726	0.223916	0.005268753	0.059667	0.366531	0.10827
Power	0.99086783	0.565002	0.878688	0.956621719	0.859703	0.75901	0.961255
G-Ratio	0.00351565	0.286829	0.03975	0.127310505	0.26342	0.122843	0.001856
SGE	0.60076835	0.996472	0.830827	0.301561816	0.156868	0.930637	0.698283
Elasticity	0.7728921	0.983764	0.945017	0.48314666	0.313638	0.993723	0.85241
Hardness	0.99619352	0.715347	0.961185	0.871079803	0.734456	0.878733	0.998345
UTS	1	0.658132	0.933886	0.909526534	0.78706	0.835647	0.989546
Ductility	0.6581322	1	0.996363	0.357383933	0.202415	0.957727	0.751313
Toughenss	0.93388591	0.996363	1	0.71281738	0.545653	0.975437	0.975359
Carbon	0.90952653	0.357384	0.712817	1	0.969989	0.562295	0.842613
Moly	0.78706024	0.202415	0.545653	0.969989253	1	0.389268	0.697783
Nickel	0.83564662	0.957727	0.975437	0.562294928	0.389268	1	0.904014
Surface Finish	0.9895462	0.751313	0.975359	0.842612623	0.697783	0.904014	1

Figure 26: R^2 Table

5.3. Penetration Aspect of the Grinding Process

Now the that a basic understanding of the effects of the different parameters of the grinding process is known, it is important to analyze the results from the DOE and determine what material properties affect the test outputs. The first step to do so will be to determine what properties affect the initial penetration aspect of the grinding process. In Figure 27 and Figure 28, Power vs. MRR is graphed and the threshold power values are displayed. In Figure 27, the values recorded during the grinding tests for each of the three steels are displayed. A trend line was then added for each of the steels as shown below. As can be seen, the slope and placement of these lines are dependent on the steel type and the grinding wheel that it is being tested against. In both of these figures, 304 stainless steel required the most amount of power for a given material removal rate. D3 and 4340 steel required less power per MRR than the 304 steel, but their performance in relation to each other is dependent upon the grinding wheel used. With the 38A wheel, the D3 steel required more power to grind than the 4340 steel, while the power needed during grinding using the Seeded-gel wheel was a lot closer.

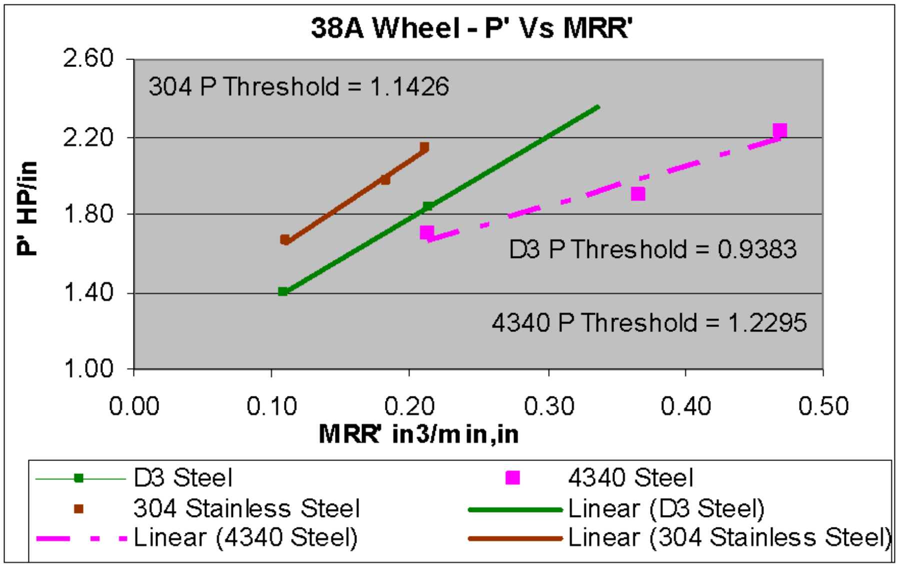


Figure 27: Threshold Power - 38A Wheel

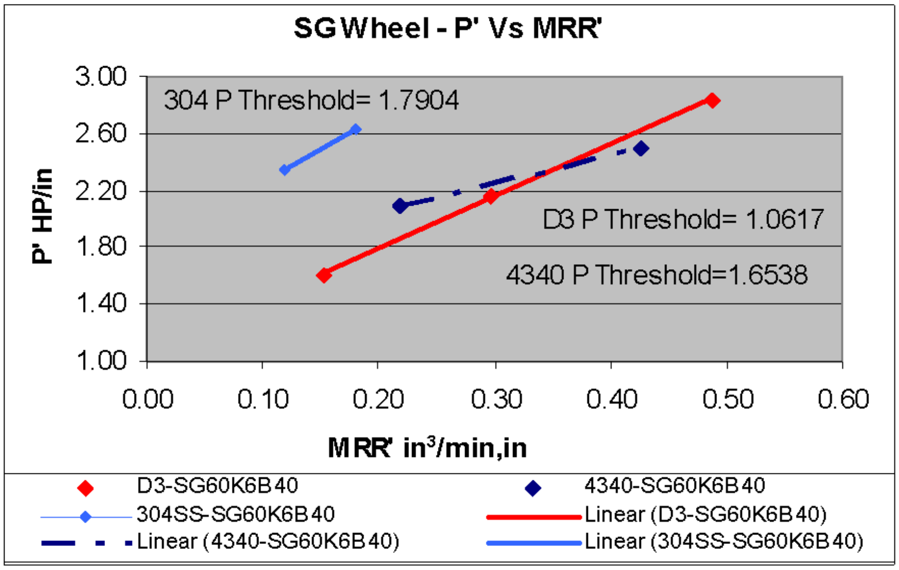


Figure 28: Threshold Power - SG Wheel

After looking at these graphs, it was evident that there were several different properties that influenced this performance. All of the material properties of the three different steels used in these experiments can be seen in Appendix A at the end of this report. Some of the more notable properties to notice is that D3 Tool Steel has a carbon content higher than the other steels which allows the tool steel to be heat treated. As a result, the D3 steel has a hardness and ultimate tensile strength that are much higher than the other two steels. The 304 stainless steel is easily the softest of the three and has the lowest ultimate tensile strength, while 4340 steel has UTS and hardness values that fall between the other two steels.

Some of the other important properties to consider in the two steels are the elongation at break and the fracture toughness of the materials. The 304 stainless has an elongation of 44% and a fracture toughness of 158 ksi.in^1/2, which are both significantly higher than the other two steels. Due to this, 304 steel during surface grinding is much more likely to plow and plastically deform instead of fracturing easily, which is what D3 steel does. Since D3 has an elongation at break of 14% and a fracture toughness of 18.1 ksi.in^1/2, it takes much less energy to fracture this steel.

Type of Steel	Density (lb / cu. in.)	Young's Modulus (10^6 psi)	Hardness Vickers (HV)	Ultimate Tensile Strength (psi)	Elongation at Break	Fracture Toughness (ksi*in^1/2)
304	0.289	28.5	190	81945	44	158
4340 quenced 800C, 480C temper	0.284	30.31	396.25	192000	13%	65
D3 high carbon, high chromium, cold worked tool steel	0.278	30.53	610	333500	14.00%	18.1

Table 2: Material Properties Table

These properties are possibly a contributor to the different threshold power reading for these steels. When R^2 values were created comparing the grinding test outputs to the material properties, both hardness and ultimate tensile strength had an almost exact relationship to the power. Therefore, hardness and UTS are two possible causes for the performance of the various steels. To make these conclusions more accurate, more test runs must be conducted and more steels must be tested. By increasing the data points that these values are created from, higher statistical relevance can be obtained and hardness' and UTS' effect on threshold power can be supported.

In this case, the D3 Tool Steel, which has the highest hardness and UTS values, requires the least amount of power to start the grinding process. Initially one would assume that the harder steels would require significantly more power to start the grinding process. In this case however, it appears that the softer steels have higher threshold power values, which could be contributed to their tendency to deform when being ground. Since they are not as hard, they are more apt to elastically or plastically deform, which would increase the power required by the grinding wheel.

In the figures above, the slope of the linear line also gives us insight into the grinding process. When the slopes are steep like the D3 and 304 steel, it can be deduced that increasing the material removal rate greatly increases the power required by the grinding wheel. On the other hand, the gently increasing slope of the 4340 steel shows us that changing the MRR has little effect on the total power required by the grinding process. Therefore, it is evident that the 304 and D3 steels are significantly harder to grind than the 4340 steel and their grinding performance is greatly dependent upon the MRR set by the operator of the machine. For 304 and D3 steel, if the grinding wheel attempts to remove too much material at one time, the power required for the grinding process will skyrocket.

5.4. Grinding Wheels Effect on Grinding Performance

The grinding wheel chosen to process specific steels is an exacting process. Many steels grind relatively well with one type of grinding wheel, while performing quite the opposite with another. Therefore, before any conclusions are made on determining what properties affect the grinding process, it is important to know how the grain choice affects grinding performance.

In Figure 29, a graph displaying D3's performance with both grinding wheels is shown. Since G-Ratio is the material removal rate divided by the wheel wear rate, it is one way to represent the efficiency of the grinding wheel. Here, it is evident that for a given power that is needed by the machine, the Seeded-Gel wheel grinds the D3 steel much more efficiently. Because of this, the D3 steel is commonly processed using a Seeded-Gel grain instead of the 38A grain. Since our experiments only altered the grain type in the grinding wheel, this difference in performance can be linked to the interaction between the steel and the specific grain type.

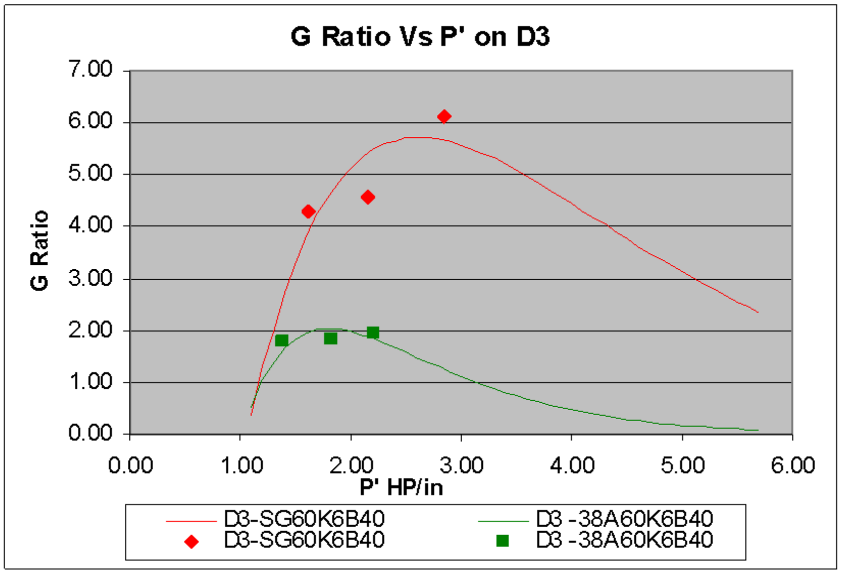


Figure 29: G-Ratio vs. Power - D3 steel

In Figure 30 and Figure 31, the performance of the 4340 steel against the two grinding wheels can be seen. In Figure 30, the differences in power with a specific MRR is given. The SG wheel has higher unit power and G-Ratio values for a given MRR than the 38A wheel. As a result, 4340 steel causes much less wheel wear when being processed with SG wheel, while simultaneously requiring more power to do so.

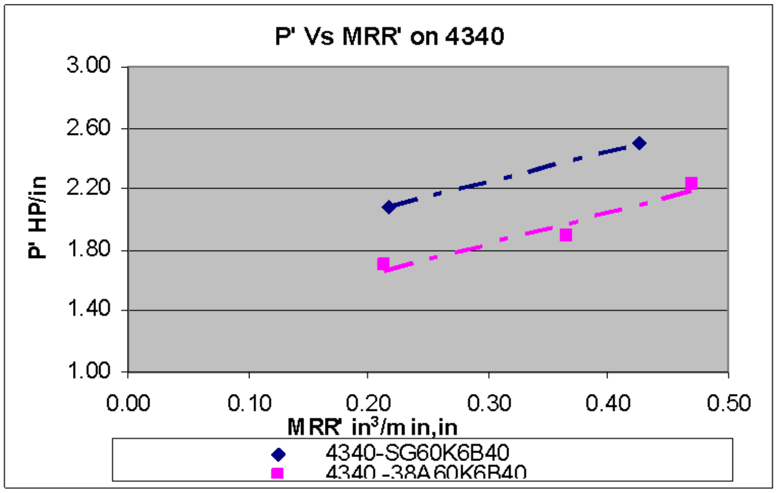


Figure 30: Power vs. MRR - 4340 Steel

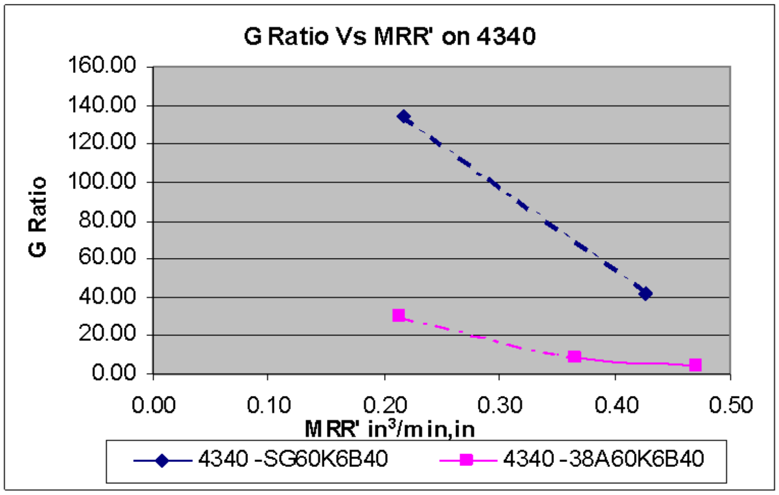


Figure 31: G-Ratio vs. MRR - 4340 Steel

Below, in Figure 32 and Figure 33, the grinding performance of 304 S Steel can be seen with the two different grinding wheels. In these specific tests, the power required for the Seeded-Gel wheel is significantly higher than the 38A wheel. Even while doing so, however, the WWR does not differ between the two wheels for a given MRR. Therefore, although the SG wheel requires less power to operate, the wheel wear for both wheels are roughly the same.

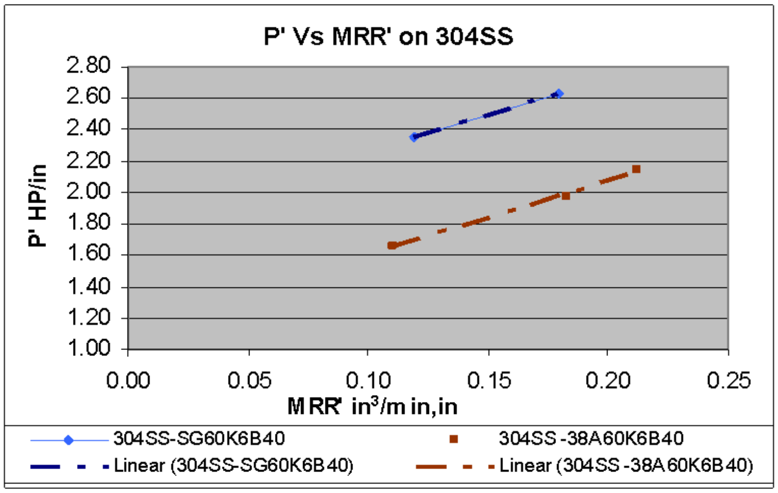


Figure 32: Power vs. MRR - 304 SS

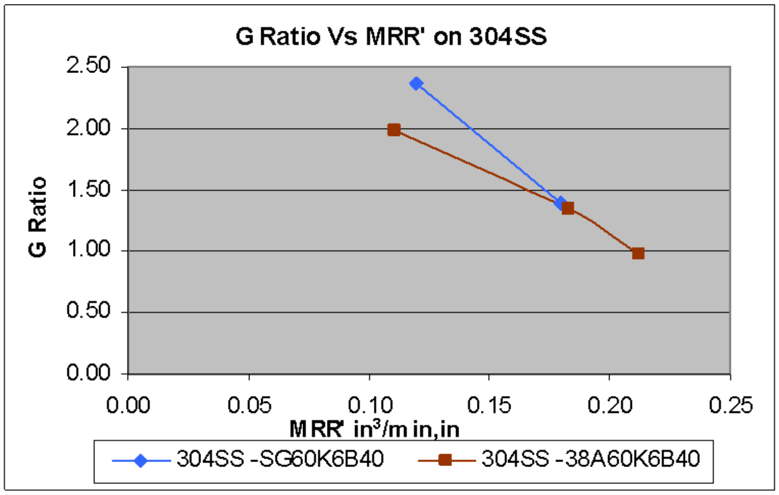


Figure 33: G-Ratio vs. MRR - 304 SS

5.5. Efficiency of the Different Steels

Now that analysis has been conducted upon the material properties responsible for the grinding performance in the penetration part of the test, it is important to determine how the steels perform overall. In Figure 34 and Figure 35, plots of G-Ratio vs. Power are displayed. In the first graph, it is clearly visible that 4340 steel when being processed with the 36A wheel has a much higher G-Ratio value than the 304 and D3 steels. Like it was said before, the 4340 steel grinds more efficiently with the Seeded-Gel wheel. As a result, the G-Ratio values of 4340 being ground with SG grain is much more efficient than the 38A wheel and therefore has a much higher G-Ratio value. At the bottom of the graph are the curves representing the other two steels, a blown up view of which is displayed in Figure 35. In this figure, it is evident that both 304 and D3 steel are close in efficiency while being processed with the 38A wheel, while D3 is much more efficient when being processed with the Seeded-gel wheel.

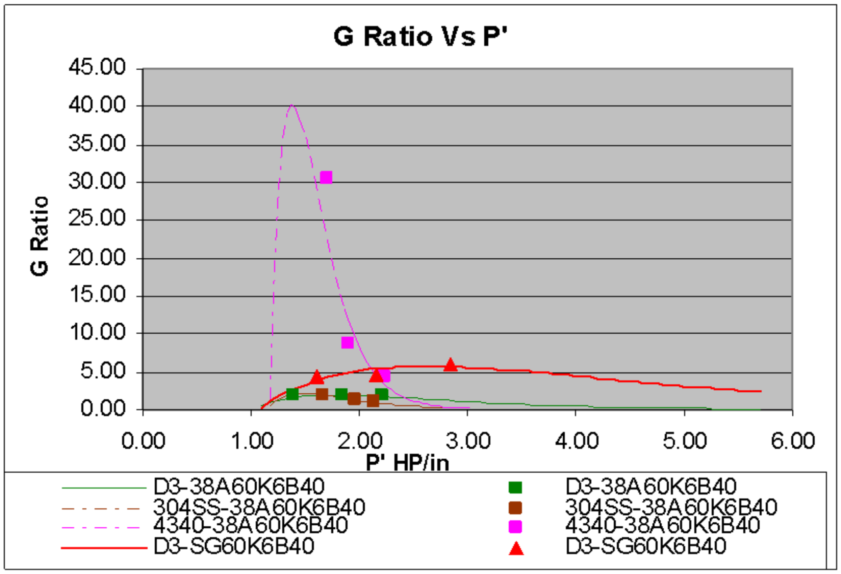


Figure 34: G-Ratio vs. Power – All Steels

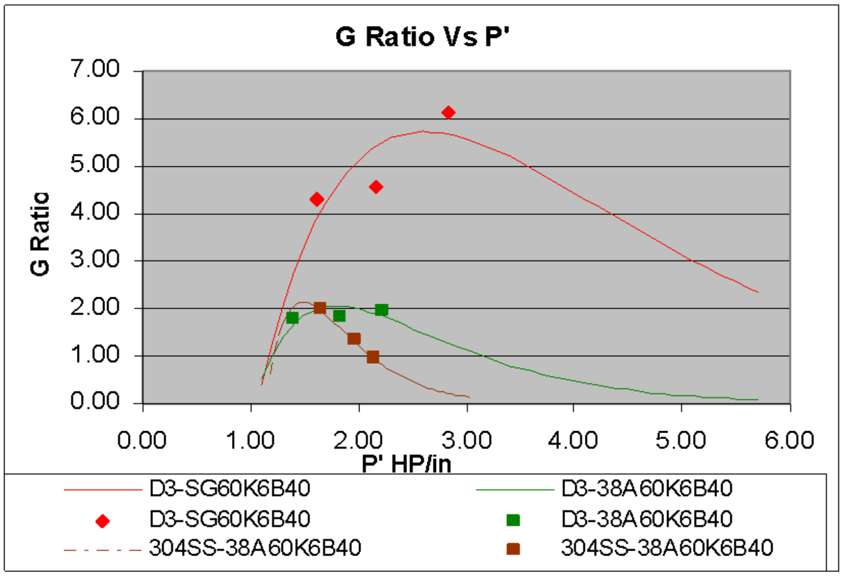


Figure 35: G-Ratio vs. Power - D3 + 304 Steels

In the figure below, a graph comparing the material removal rates to the unit power can be seen. This graph includes the data gathered from the three different steels being processed with both grinding wheel choices. From there, it is evident that for a given MRR value, the 304 steel always requires the most power to run the grinding wheel. The amount of power required to grind D3 steel is independent of the grinding wheel choice. Finally, 4340 steel when being processed with the 38A wheel requires the least amount of power out of the three per MRR, while it requires roughly as much power as the D3 steel when being processed with the SG wheel.

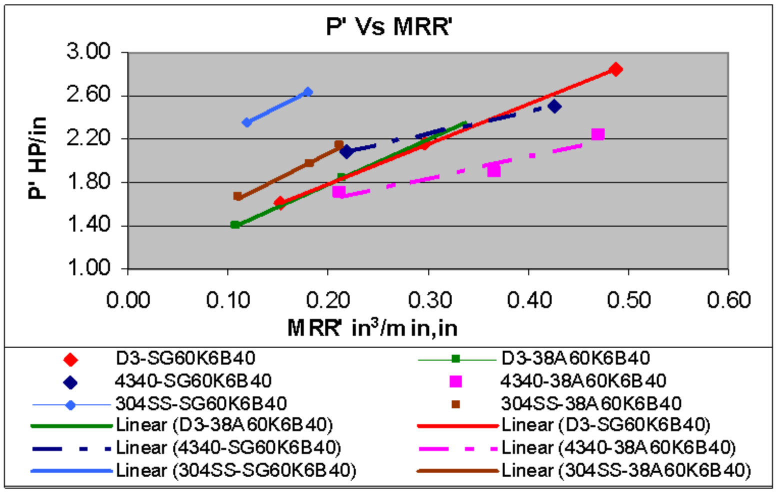


Figure 36: MRR vs. Power - All Steels

In Figure 37 and Figure 38, Coe's plots for the different steels can be seen. As seen below, it is easily understood that the 4340 steel is the most efficient out of the three because it has a low SGE value which means that it requires little power to remove a certain amount of material from the steel. At the same time, it also causes very little wheel wear to occur during the grinding process. It is important to note that even though the SGE values for 4340 when being processed with both grinding wheels are similar, the SG wheel causes much less wheel wear to occur.

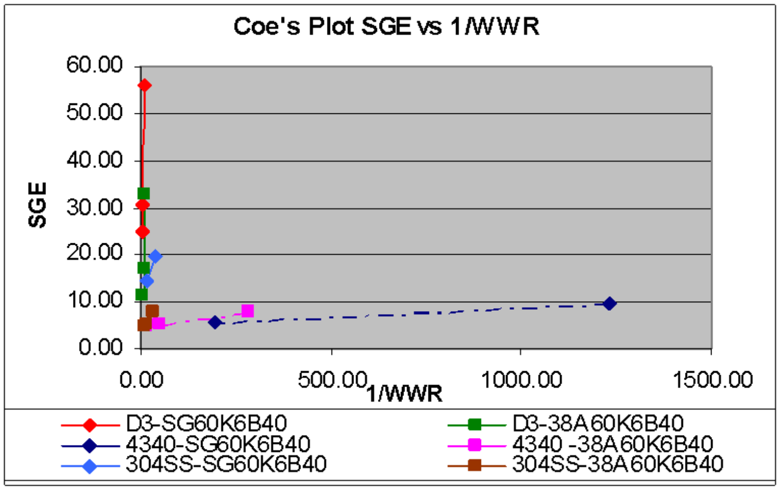


Figure 37: SGE vs. 1/WWR - All Steels

Below, in Figure 38, the results of the SGE vs. 1/WWR plot are shown with the D3 and 304 stainless steels only. From this graph, it is clear that the 304 has much less wheel wear occurring than the D3 steel under similar testing conditions. It is also visible that the power over MRR for D3 is significantly higher than the other two steels.

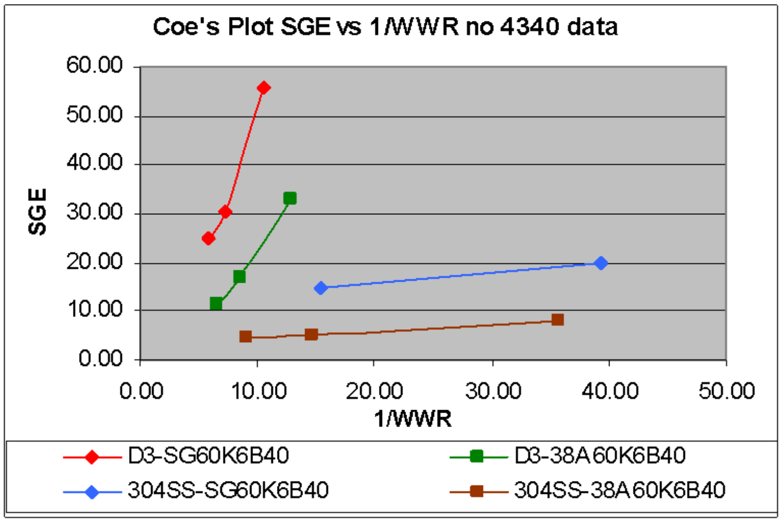


Figure 38: SGE vs. 1/WWR - D3 + 304 SS Only

6. Conclusions

There is not one singular property that is responsible for grinding performance of the different steels. On the contrary, many different steel properties in conjunction with the elements and microstructure included in the steels all add together to determine a particular steels ease in grinding.

Many of these correlations were based upon the R^2 values found between different test outputs and material properties. Since the testing was limited to only a handful of data points for each steel, the R^2 analysis is based upon three data points. Even though this level of statistical relevance will not produce exact results, it will be enough to enable an analysis of the test results.

After conducting analysis on the DOE that was run, it was evident that different material properties affected the different parts of the grinding process. For the penetration aspect of the grinding process, it appears that the hardness and ultimate tensile strength have an appropriate correlation. Since the threshold power is a good indicator in determining how hard it was to conduct initial penetration, this term was utilized in the analysis. After looking at R^2 values, it appeared that hardness and ultimate tensile strength could have an effect on threshold power. When the steels are analyzed, while also keeping in mind what grinding wheel steels are ground most effectively with, it was apparent that hardness and UTS could have an effect on the level of threshold power required. As the hardness and UTS of the steels increases, the threshold power decreases. Therefore, as the material gets softer, it requires more power to grind away the first bit of material because the steel will plastically deform. With these three steels, the hardness and UTS can be linked to the carbon content. Often, carbon is added to steels to allow it to be heat treated. Such is the case in the D3 steel. As a result, the hardness and the UTS of the D3 is significantly higher than the other two steels. In addition, when comparing the % of carbon in all of the steels, a strong linear correlation is reached which is displayed by the high R^2 value between power and carbon.

Another grinding output that the hardness and UTS appear to affect is the surface finish of the steel after the grinding occurs. As these two properties in the steels increase, so to does the quality of the surface finish. In other words, as the hardness and ultimate tensile strength of the material increase, the surface finish height decreases. This means that the average difference between the peaks and valleys of the steel being sampled also decreases. This correlation is supported by the high R^2 value between Power, Hardness and UTS to surface finish.

It is important to note that in this case, having only three steels to test prohibits the ability to focus in on one specific property which affects a certain aspect of the grinding process. With these strong R^2 values occurring, it is difficult to predict what exact material property affects grind performance when numerous properties are linked together, as is shown in Figure 39. As can be seen, hardness has nearly a perfect correlation to UTS for these three steels, and as a result, one can't determine which property determines the grinding performance.

R^2 Values for Material Properties

	Elasticity	Hardness	UTS	Ductility	Toughness
Elasticity	1	0.8224133	0.772892	0.983764034	0.945017062
Hardness	0.8224133	1	0.996194	0.715346659	0.961185285
UTS	0.7728921	0.99619352	1	0.658132196	0.93388591
Ductility	0.98376403	0.71534666	0.658132	1	0.99636336
Toughenss	0.94501706	0.96118528	0.933886	0.99636336	1

Figure 39: R^2 Values for Material Properties

The next part of the grinding cycle, which most of the analysis was based upon, is the shearing aspect of the grinding process. Graphs comparing the results of this part can be seen in Figure 34 through Figure 38. After looking at these figures, it was evident that 304 was the most difficult steel to grind, while 4340 was by far the easiest. Since no material property affects MRR or WWR directly, as shown by the low R^2 values, it was evident that different interactions were occurring in this aspect of the grinding process. After analysis, it appeared that a combination of the five terms above ultimately determined how effectively the steels would grind.

Ductility, or % elongation at break, and fracture toughness appear to have a large part in the grinding effectiveness of the different steels. As the steels become more ductile, they are more apt to plastically deform which results in a higher power threshold. In addition, it also causes the power required by the grinding wheel to increase. With a high % elongation at break and high fracture toughness, the steels tend to produce long chips because of the materials resistance to fracturing. As a result, the chips tend to get in the way of the grinding and adhere to the wheel itself. This action adds added friction to the wheel which raises the power needed to grind the work piece. Thus, these two material properties have a large effect on the overall grinding performance of the steels.

Even though ductility and fracture toughness affect the overall performance of the steels, these properties can be linked to additional ones. Toughness, for example, can be correlated to hardness and ultimate tensile strength. These terms are inversely related to each other, so as the fracture toughness of the steels increase, the hardness and UTS values for the steels drop.

The approach taken by this project was successful in finding relationships between grinding test outputs and material properties. With additional time and availability of testing, these correlations could be developed further and more statistical relevance could be added to the findings. Saint Gobain is very interested in finding concrete ways of determining what wheel specifications are needed to most effectively and efficiently conduct grinding operations on specific steels used in industry. This project aimed at assisting them in that pursuit, and has made significant progress in the right direction towards understanding the properties which most strongly effect grinding performance.

7. Recommendations

Based on the conclusions that were reached, it appears that some recommendations for future projects are in order. The first suggestion is that in order to gain a better statistical relevance, more data points are needed. This can be accomplished in one of two ways; either repeating the tests that were already run a number of times, or to increase the types of steels used. Increasing the amount of test runs would allow for statistical averages that would ultimately result in a better R^2 value. The same end goal would be accomplished by using more steels, however this might also allow for better pinpointing of the specific properties responsible for grinding performance. The current study lacks steels with a wide range of properties, which could contribute to a lack in confidence of the statistical relevance of the data.

Another aspect of the study that would be improved with further research would be the effect of the materials internal grain structure and composition. A more in depth look at the size of the internal grains of the metal, and the conditions of the grain boundaries could possibly help in understanding why grinding performance reacts in certain ways to different metals being ground. The size of the grains in the wheel, compared to the size of the internal grains of the metal may also be part of the overall relationship between work-piece metal, grinding wheel choice, and resulting grinding performance. Microstructure is definitely an aspect of the material that will affect grinding conditions and should be investigated fully in order to completely develop known relationships between steel, grinding wheel, and grinding performance.

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Appendix A: Steel Properties Table

Type of Steel	Aluminum	Carbon	Chromium	Copper	Manganese	Molybdenum	Nickel	Niobium	Phosphorus	Silicon	Sulfur	Titanium
304		0.06	18.03	0.29	1.54	0.27	8.43		0.023	0.45	0.018	
4340 quenced 800C, 540C temper, 25mm round	0.032	0.395	0.84	0.16	0.74	0.24	1.71	0.002	0.012	0.26	0.0016	0.001
4340 quenced 800C, 425C temper, 25mm round	0.032	0.395	0.84	0.16	0.74	0.24	1.71	0.002	0.012	0.26	0.0016	0.001
D3 high carbon, high chromium, cold worked tool steel		2.2	11.54		0.32	1.18			0.025	0.51	0.012	

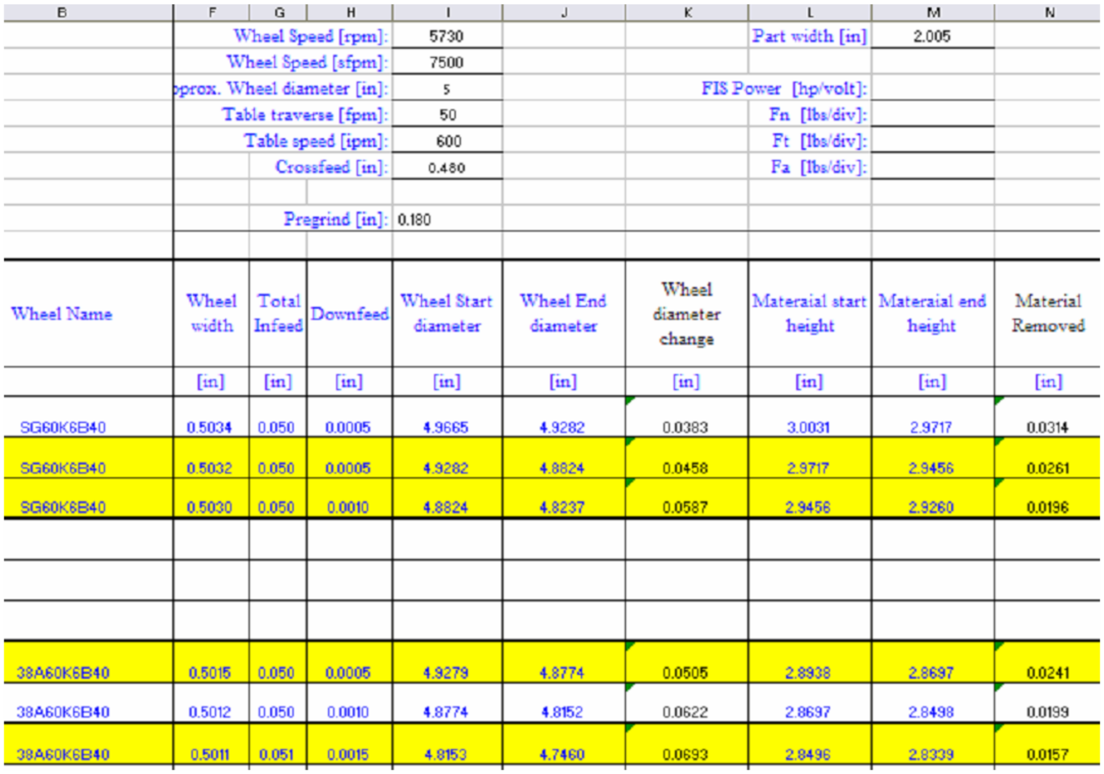
Type of Steel	Vanadium	Density (lb / cu. in.)	Specific Heat (Btu/lb/Deg F - [32-212 Deg F])	Melting Point (F)
304		0.289	0.12	2600
4340 quenced 800C, 540C temper, 25mm round	0.003	0.284	0.114	2675
4340 quenced 800C, 425C temper, 25mm round	0.003	0.284	0.114	2675
D3 high carbon, high chromium, cold worked tool steel	0.55	0.281	0.114	2650

Type of Steel	Electrical Resistivity (micro-ohm/cm @ 68 F)	Thermal Conductivity	Mean Coeff. Of Thermal Expansion
304	72	112 BTU-in/hr-ft^2-F	9.9 microin/in-F
4340 quenced 800C, 540C temper, 25mm round	24.8	242.64-346.68	7
4340 quenced 800C, 425C temper, 25mm round	24.8	242.64-346.68	7
D3 high carbon, high chromium, cold worked tool steel	67	203-220	7

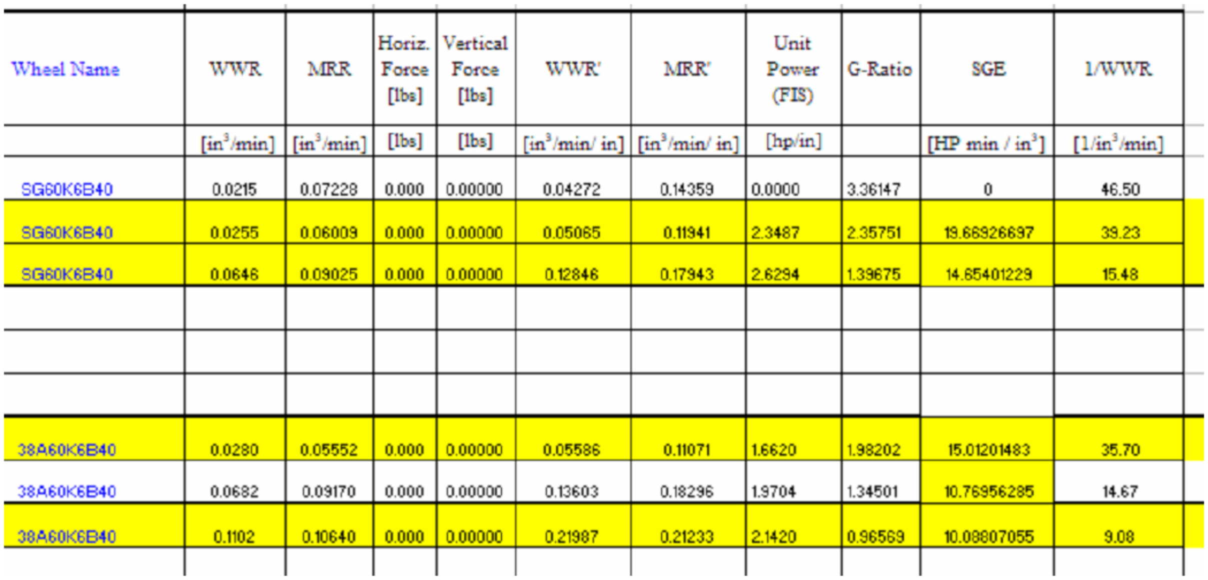
Type of Steel	Mod. Of Elasticity (Tension) ksi	Hardness Vickers (HV)	Tensile Strength (ksi)	Yield Strength ksi
304	27500-29400	170-210	73.97-89.92	29.73-45
4340 quenced 800C, 540C temper, 25mm round	29730-30890	325-400	153-188	140-173
4340 quenced 800C, 425C temper, 25mm round	29730-30890	385-475	192-235	178.4-217.6
D3 high carbon, high chromium, cold worked tool steel	29730-31330	580-640	304-363	270.4-332

Type of Steel	Elongation at Break	fracture toughnessksi.in^.5	shear modulus 10^6 psi	mod. Of rupture ksi
304	30-57%	108.3-207.5	11	29.73-44.96
4340 quenced 800C, 540C temper, 25mm round	10-16%	33.67-58.24	11.46-12.04	140-172.6
4340 quenced 800C, 425C temper, 25mm round	8-12%	71.89-82.81	11.46-12.04	178.4-217.6
D3 high carbon, high chromium, cold worked tool steel	14%	16.65-19.57	11.46-12.18	270-332

Appendix B: Grinding Test Data for 304 Steel

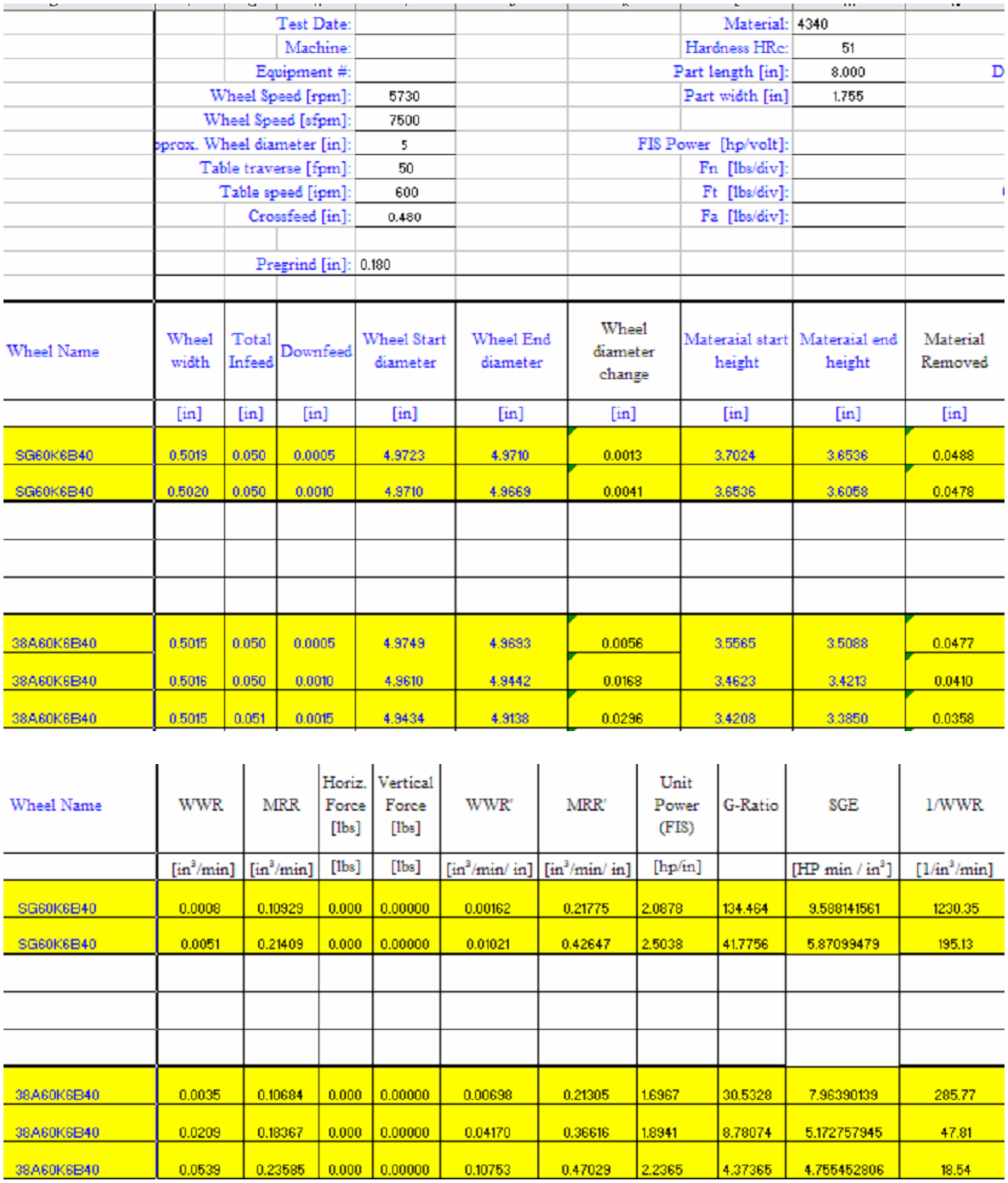


B	F	G	H	I	J	K	L	M	N
	Wheel Speed [rpm]:			5730			Part width [in]	2.005	
	Wheel Speed [sfpm]:			7500					
	pprox. Wheel diameter [in]:			5			FIS Power [hp/volt]:		
	Table traverse [fpm]:			50			Fn [lbs/div]:		
	Table speed [ipm]:			600			Ft [lbs/div]:		
		Crossfeed [in]:		0.480			Fa [lbs/div]:		
		Pregrind [in]:		0.180					
Wheel Name	Wheel width	Total Infeed	Downfeed	Wheel Start diameter	Wheel End diameter	Wheel diameter change	Materaial start height	Materaial end height	Material Removed
	[in]	[in]	[in]	[in]	[in]	[in]	[in]	[in]	[in]
SG60K6B40	0.5034	0.050	0.0005	4.9665	4.9282	0.0383	3.0031	2.9717	0.0314
SG60K6B40	0.5032	0.050	0.0005	4.9282	4.8824	0.0458	2.9717	2.9456	0.0261
SG60K6B40	0.5030	0.050	0.0010	4.8824	4.8237	0.0587	2.9456	2.9260	0.0196
38A60K6B40	0.5015	0.050	0.0005	4.9279	4.8774	0.0505	2.8938	2.8697	0.0241
38A60K6B40	0.5012	0.050	0.0010	4.8774	4.8152	0.0622	2.8697	2.8498	0.0199
38A60K6B40	0.5011	0.051	0.0015	4.8153	4.7460	0.0693	2.8496	2.8339	0.0157



Wheel Name	WWR	MRR	Horiz. Force [lbs]	Vertical Force [lbs]	WWR'	MRR'	Unit Power (FIS)	G-Ratio	SGE	1/WWR
	[in^3/min]	[in^3/min]	[lbs]	[lbs]	[in^3/min/ in]	[in^3/min/ in]	[hp/in]		[HP min / in^3]	[1/in^3/min]
SG60K6B40	0.0215	0.07228	0.000	0.00000	0.04272	0.14359	0.0000	3.36147	0	46.50
SG60K6B40	0.0255	0.06009	0.000	0.00000	0.05065	0.11941	2.3487	2.35751	19.66926697	39.23
SG60K6B40	0.0646	0.09025	0.000	0.00000	0.12846	0.17943	2.6294	1.39675	14.65401229	15.48
38A60K6B40	0.0280	0.05552	0.000	0.00000	0.05586	0.11071	1.6620	1.98202	15.01201483	35.70
38A60K6B40	0.0682	0.09170	0.000	0.00000	0.13603	0.18296	1.9704	1.34501	10.76956285	14.67
38A60K6B40	0.1102	0.10640	0.000	0.00000	0.21987	0.21233	2.1420	0.96569	10.08807055	9.08

Appendix C: Grinding Test Data for 4340 Steel



Test Date:		Material:	4340	
Machine:		Hardness HRc:	51	
Equipment #:		Part length [in]:	8.000	D
Wheel Speed [rpm]:	5730	Part width [in]	1.755	
Wheel Speed [sfpm]:	7500			
pprox. Wheel diameter [in]:	5	FIS Power [hp/volt]:		
Table traverse [fpm]:	50	Fn [lbs/div]:		
Table speed [ipm]:	600	Ft [lbs/div]:		
Crossfeed [in]:	0.480	Fa [lbs/div]:		
Pregrind [in]:	0.180			

Wheel Name	Wheel width	Total Infeed	Downfeed	Wheel Start diameter	Wheel End diameter	Wheel diameter change	Materaial start height	Materaial end height	Material Removed
	[in]	[in]	[in]	[in]	[in]	[in]	[in]	[in]	[in]
SG60K6B40	0.5019	0.050	0.0005	4.9723	4.9710	0.0013	3.7024	3.6536	0.0488
SG60K6B40	0.5020	0.050	0.0010	4.9710	4.9669	0.0041	3.6536	3.6058	0.0478
38A60K6B40	0.5015	0.050	0.0005	4.9749	4.9693	0.0056	3.5565	3.5088	0.0477
38A60K6B40	0.5016	0.050	0.0010	4.9610	4.9442	0.0168	3.4623	3.4213	0.0410
38A60K6B40	0.5015	0.051	0.0015	4.9434	4.9138	0.0296	3.4208	3.3850	0.0358

Wheel Name	WWR	MRR	Horiz. Force [lbs]	Vertical Force [lbs]	WWR'	MRR'	Unit Power (FIS)	G-Ratio	SGE	1/WWR
	[in^3/min]	[in^3/min]	[lbs]	[lbs]	[in^3/min/ in]	[in^3/min/ in]	[hp/in]		[HP min / in^3]	[1/in^3/min]
SG60K6B40	0.0008	0.10929	0.000	0.00000	0.00162	0.21775	2.0878	134.464	9.588141561	1230.35
SG60K6B40	0.0051	0.21409	0.000	0.00000	0.01021	0.42647	2.5038	41.7756	5.87099479	195.13
38A60K6B40	0.0035	0.10684	0.000	0.00000	0.00698	0.21305	1.6967	30.5328	7.96390139	285.77
38A60K6B40	0.0209	0.18367	0.000	0.00000	0.04170	0.36616	1.8941	8.78074	5.172757945	47.81
38A60K6B40	0.0539	0.23585	0.000	0.00000	0.10753	0.47029	2.2365	4.37365	4.755452806	18.54

Appendix D: Grinding Test Data for D3 Steel

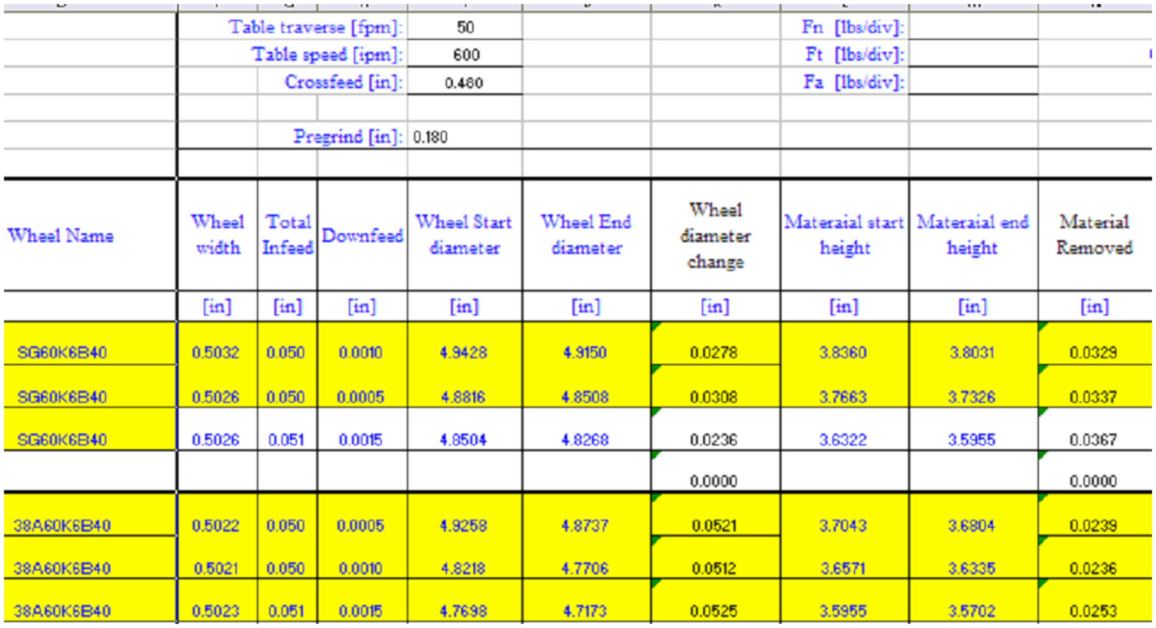


Table traverse [fpm]: 50

Table speed [ipm]: 600

Crossfeed [in]: 0.480

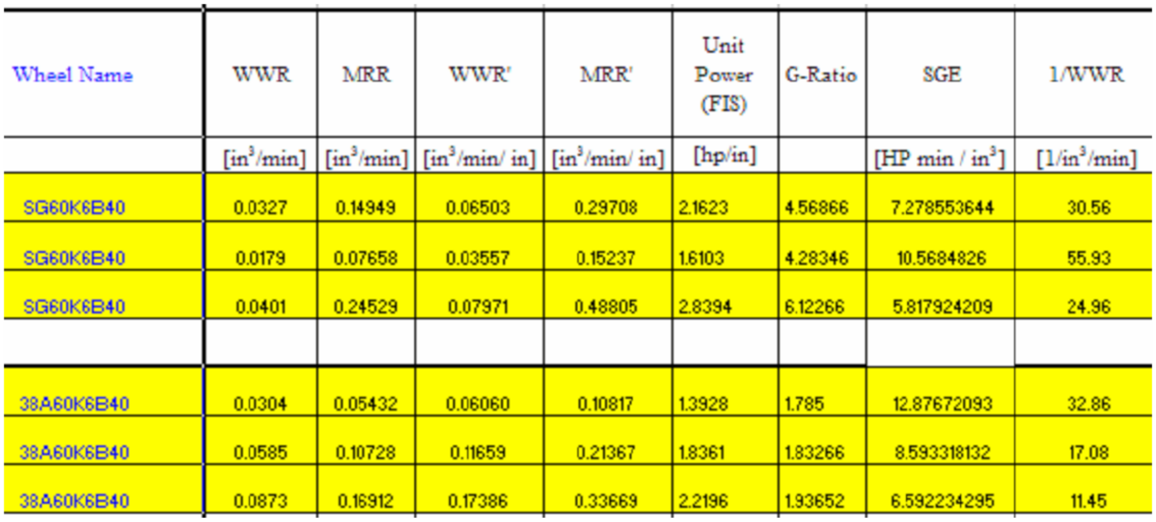
Pregrind [in]: 0.180

Fn [lbs/div]:

Ft [lbs/div]:

Fa [lbs/div]:

Wheel Name	Wheel width	Total Infeed	Downfeed	Wheel Start diameter	Wheel End diameter	Wheel diameter change	Materaial start height	Materaial end height	Material Removed
	[in]	[in]	[in]	[in]	[in]	[in]	[in]	[in]	[in]
SG60K6B40	0.5032	0.050	0.0010	4.9428	4.9150	0.0278	3.8360	3.8031	0.0329
SG60K6B40	0.5026	0.050	0.0005	4.8816	4.8508	0.0308	3.7663	3.7326	0.0337
SG60K6B40	0.5026	0.051	0.0015	4.8504	4.8268	0.0236	3.6322	3.5955	0.0367
						0.0000			0.0000
38A60K6B40	0.5022	0.050	0.0005	4.9258	4.8737	0.0521	3.7043	3.6804	0.0239
38A60K6B40	0.5021	0.050	0.0010	4.8218	4.7706	0.0512	3.6571	3.6335	0.0236
38A60K6B40	0.5023	0.051	0.0015	4.7698	4.7173	0.0525	3.5955	3.5702	0.0253



Wheel Name	WWR	MRR	WWR'	MRR'	Unit Power (FIS)	G-Ratio	SGE	1/WWR
	[in^3/min]	[in^3/min]	[in^3/min/ in]	[in^3/min/ in]	[hp/in]		[HP min / in^3]	[1/in^3/min]
SG60K6B40	0.0327	0.14949	0.06503	0.29708	2.1623	4.56866	7.278553644	30.56
SG60K6B40	0.0179	0.07658	0.03557	0.15237	1.6103	4.28346	10.5684826	55.93
SG60K6B40	0.0401	0.24529	0.07971	0.48805	2.8394	6.12266	5.817924209	24.96
38A60K6B40	0.0304	0.05432	0.06060	0.10817	1.3928	1.785	12.87672093	32.86
38A60K6B40	0.0585	0.10728	0.11659	0.21367	1.8361	1.83266	8.593318132	17.08
38A60K6B40	0.0873	0.16912	0.17386	0.33669	2.2196	1.93652	6.592234295	11.45

Appendix E- Steel Making Process

The first step in today's production of steel is the mining of iron ore. The types and methods of mining this ore varies greatly by region due to their natural resources. For the United States and Canada taconite, a flint like rock, is the primary source for mining iron ore. Australia on the other hand mines from many other sources including magnetite, pisolite, and band iron formation ores. As the demand for iron ore and technology increases many new sources have also developed. However most of these sources require some sort of refinement as their next step in the production of steel.

This refinement is called beneficiation and also varies depending on the source it was mined from. For inferior sources the mined material is crushed and then passed over a bath of solution which separates the valuable hematite from the other mineral fragments. More pure sources such as magnetite is refined by crushing it and then easily moved with large magnets because of its magnetic properties. With the iron ore refined by one method or another it is now time to change it into metallic iron.

Changing iron ore to iron is done through the process of smelting. Iron ore is made up of molecules of iron and oxygen atoms bonded together. To remove the oxygen, the iron and oxygen bond has to be broken. This is done by introducing carbon which has a stronger bond with oxygen then iron. This is all done in smelting by coating the iron ore with coke, a porous material high in carbon, and then blasted in a furnace. The resultant is molten pig iron.

Steelmaking is the next step in producing steel. In this phase the excess carbon that was created in making pig iron is removed along with other impurities. Depending on the type of steel other alloying elements will also be added in this process. The steelmaking process has changed over the years. The first method of mass producing steel was named after its inventor Bessemer. In his process molten iron is poured into a Bessemer converter in which oxidation takes place by blowing air up through channels in the bottom of the vessel. The Bessemer process was improved with the development of Siemens regenerative furnace that allowed higher temperature to be reached and a more efficient use of fuel. When the regenerative furnace was used for steel making the process was called the Open Hearth Steelmaking. This method was used in steelmaking plants until the LD process replaced it. The main improvement in this process was the replacement of air with pure oxygen in the oxidation. This is the process that is most commonly used today.