Computing the Distribution of Material Removal Rates to Enable Efficient Customization of Coaxial Offset Shoulder Grinding

by

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Abstract

Mechanical Grinding is a complicated art packaged in a deceptively simple technique. The analysis presented here attempts to unravel some of the mystery by proposing a mathematical model to describe the interface between the grinding wheel and the workpiece in Coaxial Offset Shoulder Grinding. The goal is to better understand the geometry of this interface as a function of the alignment of the axes of rotation of the two wheels. By iterating the model with different initial conditions, an optimal configuration might be found which describes a situation providing for a minimized peak rate of wear across the grinding wheel. Examples using the model have shown a reduction of more than 2 orders of magnitude in the peak rate of wear, a situation which would drastically improve the process efficiency, by reducing the frequency of wheel dressing, and enable a higher effective material removal rate. The tangible benefit of the model would be its use as a simulation tool in industry to facilitate the task of optimizing a grinding process. Depending upon the process and the company, it is estimated that by using simulation, rather than prototyping, as a testbed, development costs can be reduced by more than $100,000 and leadtimes can be a couple of hours instead of several months. In addition to these up-front savings, the resulting process will most likely result in more efficient manufacture and higher quality.
1.0 Introduction

This thesis documents the analysis conducted to understand the effective geometry of the grinding wheel cutting face and the associated mathematical model developed to calculate the Material Removal Rate (MRR) as a function of location on this surface. The impetus for this effort was the discovery, from experience and experiment in industry with the Coaxial Offset Shoulder Grinding Process (See Figure 1), of two interesting phenomena. Using these discoveries, the peak rate of wear experienced by the grinding wheel can be reduced while at the same time enabling an increase in the overall Material Removal Rate capacity, both without changing the material properties or the rate of rotation of either the grinding wheel or the workpiece.

![Diagram of Coaxial Offset Shoulder Grinding]

**Figure 1: Coaxial Offset Shoulder Grinding**

The complete history of the experiments conducted in industry that contributed to the public knowledge of the two phenomena investigated in this thesis would be quite long and complicated. Considering the age (over 40 years old) of some
of the patents describing the use of these phenomena in grinding applications, it is clear that at least an awareness of them has been around for a long time. The investigation described herein was motivated not to simply continue this history, but instead to better understand recent experiments conducted at Landis Gardner \(^1\), a manufacturer of grinding equipment and accessories.

These two key phenomena upon which the model is based are, specifically, the introduction of a "skew angle" so that the axes of rotation of the grinding wheel and workpiece are no longer parallel, and the use of an "undercut" on the side of the grinding wheel next to the shoulder face of the workpiece (See Figure 2).

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\(^1\) The development of the mathematical model was requested by representatives of Landis Gardner in an effort to better understand their experimental findings and to possibly enable the development of better grinding machines and/or grinding processes. The Landis-Gardner representatives were interested in elevating the knowledge level of these phenomena from an awareness to a thorough understanding.
The "undercut" helps to prevent the side of the wheel from rubbing against the shoulder face of the workpiece. While the geometry of the traditional setup suggests that the contact should not happen, power requirements for the process indicate otherwise. As is later discussed, Thermal Expansion is involved. The "skew angle" significantly alters the geometry and kinematics of the contact area between the grinding wheel and the workpiece. The result is a significant reduction in the peak rate of wear experienced by the grinding wheel. Correspondingly, the mathematical model creates a geometric representation of the cutting surface based upon the several parameters affected by the changes. It is important to note that, while the nominal geometry of the grinding wheel changes, the net effect on the nominal geometry of the finished workpiece remains unchanged. Only the process itself is affected by the changes, not the output thereof.

While the results accumulated during the long history of industrial experiments in this area were only capable of providing qualitative information on the effects of their respective changes in the process parameters, they were quite beneficial. For example, the empirical data indicated that the "undercut" would result in a reduction in the grinding wheel power consumption and, consequently, the workpiece temperature. Everything else remaining the same, the corresponding decrease in the temperature gradient across the workpiece results in a better surface finish quality. Historical trials conducted with a machine layout modified with the "skew angle" showed a significant reduction in the peak rate of wear experienced by the grinding wheel. Significantly, while the findings from both of these experimental modifications were unable to quantify their respective benefits, they were still important enough to patent.

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2 Because of the age of the information to which I am referring, and the widespread awareness and application of it in the grinding industry, it is considered in the context of this thesis to be "common knowledge." The use of specific references might detract from the universality of the example.

3 Shaw, Milton C. Principles of Abrasive Processing pp. 261-313. Chapter 10, entitled "Surface Integrity," addresses several of the effects of grinding temperature on surface finish. The main focus of the chapter is to point out that it is very beneficial to keep the temperature as low as possible to enable higher quality control.

4 United States Patent #4115958, "Method of Cylindrical and Shoulder Grinding," protects just about every possible scenario resulting from these findings. No mention is made of any specific benefits, but the patent basically protects the use of these layout changes in any combination, thereby allowing the patent holder to experiment further and effectively customize a given process with trial and error.
Looking only at the investigations pursued in this thesis, the goal of the analysis leading up to and including the creation of the mathematical model was to bring to fruition the capability of generating instead a quantified measurement of the beneficial effects of the changes. A literature search revealed that this capability would offer a unique level of understanding of the system. It was hoped that, aided by the ability to calculate quickly and easily the optimal setup parameters, processes could now be customized to the specifics of the task at hand rather than only loosely adapted to the new conditions with the help of a vague understanding of cause/effect relationships. A thorough description of the equations in the model is provided in Section 3.2 since understanding the inner workings of an analytical tool is one of the better ways of learning how to best take advantage of the functions it offers. Section 3.3 contains graphs generated by the simulation tool for various “skew angle” and “direction of grinding wheel movement” parameters. Each iteration is briefly detailed and a discussion developed regarding the best combination.

A model is only applicable if its output is consistent with observations in the physical world. Because the mathematical model was motivated by and based upon physical tests, and the data from these tests was readily available, it was very easy to test the output of the model. The data from these physical tests have confirmed the validity of the trends described by the model.

2.0 Background

The technique of using one object which is abrasive, and relatively harder, to remove material from another object has been known and used for literally thousands of years. This simple technique, or art, is called Grinding. The ancient Egyptians relied upon it to shape the blocks they used in their pyramids and the Incas used it to build magnificent, mortar-less structures that still stand today. It probably will not come as a surprise, however, that modern industry needs a much more thorough understanding of the technology than these cultures ever had. Today we find that "the application of superabrasives and increasing demands for higher productivity and higher
quality require an appropriate selection of optimum set-up parameters." \(^6\)

Knowing what these optimal parameters are demands a more thorough understanding of the interface between the workpiece and the grinding wheel.

### 2.1 The Industrial Perspective

Industry often relies upon grinding to achieve high tolerances and/or difficult geometries. Because grinding wheels are typically made of materials that are very hard, the cutting surface can be controlled to extremely tight tolerances, even into the sub-micrometer range. \(^7\) This level of control, however, demands that the geometry of the grinding wheel cutting face does not change significantly. Wear will occur of course, but the rate and location of this wear, more than just its existence, are what is important.

Based upon the experience gained over time while using a process, the grinding wheel will be resurfaced, or "dressed," after a predetermined number of cutting cycles in order to reestablish a baseline. At this point, the machine again "knows" exactly where the cutting edge is in relation to the workpiece. Depending upon quality controls and the conditions experienced with the process, dressing might be scheduled every 100 cycles, for example, or every 1,000 cycles, etc. In extremely precise operations, the wheel might be dressed every cycle. It all depends upon what is required for the specifics of the process and product.

While dressing the grinding wheel is great for quality control, it has a major drawback. It is entirely unproductive. Dressing the grinding wheel uses machine time, significantly accelerates the wheel wear, and requires the use of an expensive diamond tool which has a limited lifecycle. Identifying the optimal parameters that will increase the number of cutting cycles between dressings is therefore of great importance for increasing productivity and reducing cost.

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\(^5\) Based upon the author's recollection of scientific explorations of these cultures as presented on Public Broadcasting System programming.

Many advances have been made to improve the wear life of grinding wheels, but it seems that little effort has been made to find the root cause behind the accelerated wear typical of certain areas of the grinding wheel. In some applications, a stress concentration due to the geometry at the interface may be the reason behind rapid wear of a portion of the cutting surface. In many other applications, however, it might instead be that the area of concern is required to remove a majority of the material from the workpiece. The analysis in this investigation concentrates upon mitigating the effects of this second scenario primarily by helping the users of a process to identify or verify that an MRR concentration is the cause of the accelerated wear. If the wheel geometry and/or the machine layout can be adjusted to reduce this peak wear rate without affecting the desired part geometry, then the number of cycles between dressings can be significantly increased. Process efficiency will benefit from a reduction in this inherent downtime.

2.1.1 Quality Control and Material Removal Rate

Industrial processes often involve a compromise. Meeting part specifications typically comes at the expense of productivity. The goal is therefore to meet the constraints while maximizing output. This same struggle exists in Mechanical Grinding where the specification involves surface finish quality and the struggle is to maximize the MRR so as to require the minimum processing time while also taking into consideration the downtime required for dressing the wheel.

The contributing factors to surface finish quality in grinding are numerous and highly coupled. The speed with which the grinding wheel surface traverses the workpiece is an example. Therefore, a change that improves the MRR but does not alter the speed of the grinding wheel surface would be desirable since

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8 Based upon the appearance, from the literature search, that the model presented in this thesis is unique.
9 As is later discussed in the next Section, the rate of material removal demanded of a grinding wheel, or a section thereof, determines how quickly wear will occur at the location being considered.
11 Shaw, Milton C. Principles of Abrasive Processing pp. 266-7. The “First order Interactions” in Table 10.2 on page 266 and in Table 10.3 on page 267 both demonstrate the heavy coupling associated with the “work speed” which is the speed (in feet per minute, f.p.m.) with which the surface of the grinding wheel traverses the workpiece.
it does not automatically affect the coupled contributions to surface quality. The simulation tool promotes changes that do not affect wheel speed.

Assuming that a Coaxial Offset Shoulder Grinding process has been incrementally improved over time, it is fair to assume that the ratio of the MRR (as determined by the infeed rate and workpiece grinding wheel surface speed) to the number of dressing cycles per, for example, 1,000,000 parts, has already been maximized. This considered, the process cannot be improved by simply increasing the infeed rate and spinning the wheel faster. These options have already been optimized. Instead, the kinematics of the interface between the grinding wheel and the workpiece might be altered to effect a beneficial change in the ratio by increasing the MRR capacity, by reducing the rate of dressing cycles, or both. The changes promoted by the simulation tool actually do both.

Historically, the most common approach to increasing the MRR had been to simply turn the grinding wheel faster. The primary determinant of the grinding wheel maximum RPM is the material from which the wheel is made. Correspondingly, significant advances have been made in grinding wheel materials properties. As a result, modern grinding wheels spin at speeds even two orders of magnitude faster than they did fifty years ago.

It is important to note, however, that grinding wheel RPM and actual MRR are not precisely correlated. Pushing a grinding wheel toward its maximum RPM only serves to significantly increase the rate of wear disproportionately to the increase in the amount of material being removed. Brittle fracture of the wheel under these extreme conditions occurs more readily. Consequently, most grinding wheels used in production environments typically run at about 85-90% of maximum RPM. In this way, overall productivity is kept high. The

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12 This is the case when considering the same workpiece material since changing the workpiece material affects the maximum desirable grinding wheel RPM. When grinding Titanium alloys, for example, the grinding wheel speed should be about one-third that used in conventional grinding applications. This specific example is cited in Shaw, Milton C. Principles of Abrasive Processing, page 326.
13 The dynamics affecting the wear of the grinding wheel are numerous and impressively complicated. Milton Shaw does a great job to detail most or all of the contributing effects. Refer specifically to pp. 54-81, 315-244, 403-9 in Shaw, Milton C. Principles of Abrasive Processing for explanations of the majority of these effects.
14 This has been my experience with grinding processes. The literature on the topic tends to support this estimate.
goal, therefore, is to arrive at a means of achieving a relatively higher MRR while still keeping wheel deterioration under control.

2.2 First Look at the Proposed Method
Reflecting upon the background just provided, the direction taken in this thesis seems almost obvious. Moving away from the "coaxial approach" of using parallel axes of rotation for the grinding wheel and workpiece (See Figure 3) geometrically enables an increase in the contact patch area and, in effect, a reduction in the peak rate of wear experienced by the grinding wheel. As was also discussed, if the contact patch area per unit time is increased, the MRR will similarly increase. Consequently, the total productivity for a grinding process can be improved significantly without the need for anything more exotic than a differently shaped grinding wheel and a realigned arbor.

![Coaxial Offset Shoulder Grinding](image1)

![Coaxial Face Grinding](image2)

**Figure 3: “Coaxial” Grinding Examples**

The real breakthrough in this new process is the quantifiable understanding of the geometric intricacies at the interface between the grinding wheel and the workpiece. By mathematically modeling this interaction, it is possible to compute the maximum MRR as a function of the modified imposed geometry.
The only special requirement is the departure from the “standard” design used for a grinding wheel in coaxial grinding. Instead of working with what is typically a symmetrical wheel, the new grinding wheels, mounted with an introduced angle between the arbor and workpiece, will have a specially contoured face that counteracts the effect of the introduced angle.

### 2.2.1 Coaxial Offset Shoulder Grinding

As was already detailed, the mathematical model developed in this thesis has been specially tailored for application to the Coaxial Offset Shoulder Grinding process (See Figure 4). This process is most often used to put the finishing touches on the critical surfaces of shoulder bearings. Industrial experience demonstrates that most of the wear during Coaxial Offset Shoulder Grinding occurs at the extreme outer edge of the grinding wheel (again, refer to Figure 4). Intuition might dismiss this phenomenon as simply consistent with the edge being the most fragile point on the wheel. Studying closely the kinematics of the situation reveals instead that this edge is actually required to do most of the material removal and is therefore subject to the most rapid wear. Even though a larger portion of the grinding wheel (Sections A & B in Figure 4) appears to be in contact with the workpiece, only the small portion that is at the corner edge (Section B in Figure 4), actually removes the depth of cut of the material. The remaining portion (Section A in Figure 4) in contact with the workpiece does very little if any cutting. Geometrically, the only cutting Section A should be required to do would be any material left behind as the corner edge wears from its original dimensions.
Coaxial Offset Shoulder Grinding, as is shown in the figure above in its simplest form, is typically used to finish-grind a precision surface onto the face of a workpiece. The grinding wheel can rotate in either direction relative to the rotation of the workpiece, depending upon the material properties and required tolerances of the process. The resulting finished shoulder might be used, for example, as a bearing surface. A typical application is at the connection between the connecting rod and the crankshaft. The connecting rod is held in place by the shoulders on either side so they must be smooth to reduce friction. In the case of a crankshaft, the grinding wheel would also finish the main bearing surface in addition to the shoulder. In the figure, this bearing surface would simply be an extension of Section B on the part beyond the depth of cut on the shoulder surface denoted by Section A.

Figure 4: Coaxial Offset Shoulder Grinding

Unfortunately, Thermal Expansion complicates the simple geometric model created to understand Coaxial Offset Shoulder Grinding. As heat is generated during the grinding process, thermal expansion of the workpiece brings the cut surface into contact with Section A of the grinding wheel. Assuming that the
corner edge of the grinding wheel has not worn substantially, the thermal
expansion usually generates only enough force to cause significant friction but
no material removal. The allowance in the model for an "undercut" has been
made to account for this expansion and to negate its detrimental effects. In
addition, the added space between the grinding wheel and the shoulder face of
the workpiece allows for better coolant access to this area.

3.0 Developing the Mathematical Model

Prior to the analysis made in this thesis, experiments conducted in industry
had revealed that the wear at the corner edge of the wheel in Coaxial Offset
Shoulder Grinding could be reduced by introducing an angle (the "skew angle")
between the axis of rotation of the arbor and that of the workpiece. The next
step, which is where this thesis begins, was to understand the kinematics
driving these experimental results. A mathematical model was chosen for this
task since it would enable the complex interaction to be broken down into its
constituent parts. These parts could, it was hoped, be individually understood
and modeled more easily than the whole. As an added bonus, a mathematical
model would also allow for the situation to be generalized and then optimized
for any given set of conditions.

As a first step in understanding the mathematics involved with modeling the
system, a cursory approach was taken to describe the simpler system of
"Coaxial Face Grinding" (See Figure 5). Coaxial Face Grinding is similar to
Coaxial Offset Shoulder Grinding in that the grinding wheel and workpiece are
rotating about parallel axes. The interface between the workpiece and the
wheel in the former, however, is much simpler and provided good insight into
mathematically modeling the MRR. Once this scenario was understood, the
technique was applied to Coaxial Offset Shoulder Grinding. Next, the concept
of an introduced angle between the axes of rotation of the workpiece and the
grinding wheel (See Figure 6) was included in the analysis, proving that wear to

15 For a thorough discussion of the effects of Thermal Expansion in a grinding process, consult Parts I & II of
"Contact Length in Grinding" by Qi, Rowe, and Mills. These reports, from pp. 67-85 of the "Proceedings of the
Institution of Mechanical Engineers. Part J": Journal of Engineering Tribology v21 n1 1997, describe the
lengthening of the geometric contact zone as a result of thermal expansion and material deformation.
the edge of the grinding wheel could be significantly reduced by increasing the effective cutting edge surface area. Finally, a provision was included in the model to allow for an "undercut" on the grinding wheel (See Figure 7) which eliminates the drag caused by Thermal Expansion. This final step completed the imitation of the physical model developed by Landis-Gardner.
"Newly cut" area created as workpiece rotates while grind wheel rotates and plunges to radial depth of cut

Grind wheel can rotate in either direction depending upon the surface finish desired and the material properties involved

Coaxial Face Grinding, shown in the figure above in its simplest form, is typically used to finish-grind a precision surface onto the outer edge of the workpiece. The grinding wheel can rotate in either direction relative to the rotation of the workpiece, depending upon material properties and the required tolerances of the process. The resulting finished edge might be used, for example, as a bearing surface. A typical application is the bearing locations on a shaft used in an automotive compressor. The depth of cut for this shaft application is about 150 microns.

Figure 5: Coaxial Face Grinding
The angle used in most applications would not be as large as is shown, but could be if needed. The take-away from this concept is the huge reduction in peak wear rate resulting from the introduction of even only a very small angle. The graphs in Section 3.3 demonstrate this fact.

**Figure 6: Acute Angle Added to Coaxial Offset Shoulder Grinding**
The figure above shows a further specialization of Coaxial Offset Shoulder Grinding. Here an "undercut" has been added to the portion of the wheel which otherwise would be directly next to the shoulder face of the workpiece. Experiment in industry has shown that the presence of this undercut significantly reduces the power required to drive the grinding wheel, suggesting that this area otherwise rubs against the shoulder face even though geometrically it should not. As is discussed, Thermal Expansion is involved. The model has been designed to accommodate this undercut in order to take advantage of the power savings while modeling accurately the MRR.

Figure 7: Undercut Added to Coaxial Offset Shoulder Grinding
3.1 Motivation Behind a Generalized Case

Of course, this modeling venture was not just an intellectual detour into the realm of mathematics without awareness of a broad industrial application. While a simpler model might have been developed to explain the results seen in the industrial experiments, the real payoff was in making a model that could be used to understand and optimize any process.

Applying the method of using an introduced angle in the Coaxial Offset Shoulder Grinding process basically increases the cutting area seen by the workpiece. Consequently, the processing time for a given operation can be reduced significantly and the number of grinding cycles between wheel dressing cycles can be increased since now the critical cutting face is not wearing nearly as quickly. The potential for an increase in the MRR, coupled with the reduction in required wheel maintenance, enables productivity improvement without the need for significant changes in either the machine or the tooling. Interestingly, however, the effect of these changes on the Overall Equipment Efficiency (OEE) for the process can be positive, negative, or nonexistent (See Section 4.1 for a thorough explanation of this apparent ambiguity). This uncertain impact on the OEE is very important to note. Depending upon the managerial philosophy at a plant, a process might be bound by the OEE measurement without a thorough understanding of the effects of proposed changes upon the overall productivity of the process.

The introduced angle does require some reconfiguration of the grinding equipment, which might be expensive. However, since the technique does not require the use of an entirely new technology, it is much easier and more cost effective to implement than another approach which might introduce an entirely new process.

3.2 Constructing the Mathematical Model

In this section, I develop an algorithm for computing material removal rate in thrust wall grinding as a function of key processing parameters. The parameters of the process are depicted in Figure 6 and are explained below:
Laures

\[ \theta \] -- The angle between the workpiece axis of rotation and the grinding wheel's axis of rotation. The two axes are assumed to lie in the same plane. In this model, the plane that contains both axes is defined to be the \( xy \) plane.

\[ \alpha \] -- The angle at which the grinding wheel feeds into the part (see Fig. 7)

\[ \omega \] -- The rate of rotation of the workpiece as it is driven by the workpiece spindle.

\( r_{\min} \) -- The smaller radius of the two cylindrical sections comprising the workpiece. This section of the workpiece undergoes cylindrical grinding.

\( r_{\max} \) -- The larger radius of the two cylindrical sections comprising the workpiece. The planar section of the workpiece on the face of the larger cylinder undergoes thrust wall grinding.

\( r_f \) -- The fillet radius at the corner between the cylindrical part of the workpiece and the thrust wall.

\( L \) -- The axial length of the smaller cylindrical section of the workpiece whose radius is \( r_{\min} \).

\( R(x) \) -- The radius of the grinding wheel as a function of axial position. This radius must be defined by the user at least one location. In this model, the user must define \( R(0) \), the radius at the origin of the \( xy \) coordinate system. This coordinate system origin is set at the left edge of the grinding wheel which is aligned with the left edge of the workpiece.

\( d \) -- The depth of cut as defined by the total amount of grinding wheel infeed per full revolution of the part.

Given the inputs described above, one may compute the value of \( x \) at the right face of the grinding wheel

\[ x_{\text{max}} := L \cos(\theta) + (r_{\max} - r_{\min}) \sin(\theta) \]

And given this parameter, one may define a function describing the shape of the grinding wheel. This is defined via a function of axial position \( R(x) \).
The grinding wheel is a surface of revolution constructed by revolving this curve \( R(x) \) about grinding wheel’s axis of symmetry (the \( x \)-axis). The final shape of the part will be the same curve revolved about the workpiece axis of symmetry (the \( xp \)-axis) (see Figure 6).

For the algorithm to work, one must also define the shape of the part before the grinding process began or the part’s shape after the last pass of the grinding wheel (whichever is appropriate in the given context). This is essential in computing MRR because the material that is to be removed is bounded between the surfaces defining the workpiece before and after grinding. I assume that the shape of the part before grinding is formed by displacing the grinding wheel profile a distance “\( d \)” parallel to the direction of infeed as defined by the parameter \( \alpha \). The shape from the point of view of the grinding wheel axis system is given by

\[
R_i(x) := \begin{cases} 
R_o - x \cdot \tan(90 - \deg - \theta) & \text{if } x < 0 \\ 
R_o + x \cdot \tan(\theta) & \text{if } 0 \leq x < |L - r_f| \cos(\theta) \\
[R_o + (L - r_f)(\sin(\theta)) - r_f \cdot \cos(\theta)] + \sqrt{r_f^2 - [x - (L - r_f) \cdot \cos(\theta) - r_f \cdot \sin(\theta)]^2} & \text{if } [L - r_f] \cdot \cos(\theta) \leq x < L \cos(\theta) + r_f \cdot \sin(\theta) \\
(R_o + L \cdot \sin(\theta)) - (x - L \cos(\theta)) \cdot (\tan(90 - \deg - \theta)) & \text{if } L \cos(\theta) + r_f \cdot \sin(\theta) \leq x < x_{\text{max}} \\
[[R_o + L \cdot \sin(\theta) - (x_{\text{max}} - L \cdot \cos(\theta)) \cdot \tan(90 - \deg - \theta) + (x - x_{\text{max}}) \cdot \tan(\theta)] & \text{if } x_{\text{max}} \leq x 
\end{cases}
\]

With the geometry of the grinding process described mathematically, it should now be possible to compute the material removal rate (MRR) experienced by the grinding wheel at any location. To understand the approach taken, it is useful to study Figure 8 which depicts a differential element on the surface of the grinding wheel. Let us assume that this surface element lies within the grinding zone and that the differential element lies within a section of the grinding wheel a distance \( x \) from the origin above the \( xy \) plane by an angle \( \phi \).
Figure 8: A differential element on the surface of the grinding wheel.

Due to the rotation of the workpiece and the infeed of the grinding wheel, material is flowing across the boundary of the differential element. The velocity of the flowing material with respect to the grinding wheel is

\[
\mathbf{v} = \omega \times \mathbf{r} + v_{feed}
\]

where \( r \) is the shortest vector from the workpiece axis to the differential element. This vector \( r \) can be described in terms of input parameters as

\[
\mathbf{r} = \begin{pmatrix}
\frac{R_o}{\tan(\theta)} + \frac{r_{min}}{\sin(\theta)} + x \\
\frac{R(x) \cdot \cos(\phi)}{\tan(\theta)} \\
R(x) \cdot \sin(\phi)
\end{pmatrix}
\]
Since the workpiece is at an angle $\theta$ to the grinding wheel, the vector describing the workpiece rotation is

$$\omega = \begin{pmatrix} \omega \cos(\theta) \\ \omega \sin(\theta) \\ 0 \end{pmatrix}$$

Similarly, the vector describing the infeed velocity can be described in terms of input variables

$$v_{\text{feed}} = \begin{pmatrix} \frac{\omega}{2\pi} \cdot d \sin(\alpha - \theta) \\ \frac{\omega}{2\pi} \cdot d \cos(\alpha - \theta) \\ 0 \end{pmatrix}$$

Now, the total flux of material across the element is given by the cross product of the velocity and the unit normal to the surface times the area of the differential element. The unit normal to the surface is

$$n = \begin{pmatrix} -\sin\left(\arctan\left(\frac{dR(x)}{dx}\right)\right) \\ \cos\left(\arctan\left(\frac{dR(x)}{dx}\right)\right) \cos(\phi) \\ \sin(\theta) \cdot \sin(\phi) \end{pmatrix}$$

The area of the differential element is simply the product of the length of its sides. The length of the side in the direction of the sweep about the grinding wheel axis is simply $R \phi$ (see Fig. 8). The length of the side in the axial direction is not simply $dx$ because the surface of the grinding wheel may be at an angle to the axis of symmetry of the grinding wheel – $dR/dx$ is not zero in general. So, the length of that side is the square root of the sum of $dR^2$ and $dx^2$. So, the flux through the differential element is

$$FLUX = n \cdot v(x) \left[ 1 + \left(\frac{dR(x)}{dx}\right)^2 \right]^{\frac{1}{2}}$$
In order to understand why certain sections of the grinding wheel (as defined by axial location) wear more quickly than others, we wish to compute the MRR as a function of axial location \( x \). This can be computed by taking slices of the grinding wheel defined by two planes perpendicular to the grinding wheel axis of symmetry. The planes are at axial position \( x \) and are separated by a small distance \( dx \) (see Figure 9).

![Figure 9: A differential “slice” of the grinding zone.](image)

In order to compute the total MRR for that slice, one only needs to integrate the flux within the grinding zone. As it is defined in Figure 8, the grinding zone
begins at an angle $\phi = 0$ where the final shape of the workpiece and the grinding wheel are tangent. Let us call the angle at the upper end of the grinding zone $\phi_{\text{max}}(x)$. This angle is in general a function of $x$ – as axial position changes, the width of the grinding zone may change. In general, the material removal rate as a function of axial position is therefore

$$MRR(x) = -\int_0^{\phi_{\text{max}}(x)} n \cdot v \cdot R(x) \left[ 1 + \left( \frac{d}{dx} R(x) \right)^2 \right]^{\frac{1}{2}} d\phi$$

For certain special cases of workpiece geometry it is possible to compute a closed form solution for $\phi_{\text{max}}(x)$. However, I wish to provide a solution method that can accommodate the general case that the grinding wheel geometry is defined by a function $R(x)$. In this case it is possible to compute $\phi_{\text{max}}(x)$ using a root finder

$$\phi_{\text{max}}(x) := \text{root}(\text{Diff}^{\phi}(x), \phi)$$

where

$$\text{Diff}^{\phi}(x) := \begin{bmatrix} x \\ R(x) \cdot \cos(\phi) \\ R(x) \cdot \sin(\phi) \end{bmatrix}$$

$$\text{ang} \leftarrow \arctan\left( \frac{p_1}{p_2} \right)$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\text{ang}) & -\sin(\text{ang}) \\ 0 & \sin(\text{ang}) & \cos(\text{ang}) \end{bmatrix} \cdot p$$

$$p_2 \leftarrow \text{Tinv}(p_2)$$

$$p_3 \leftarrow R_i(p_3) - p_3$$

This approach is best understood by considering Figure 10. Point $p$ is a point within the differential slice at an angle $\phi$ from the $xy$ plane about the grinding wheel axis of symmetry. If this point is at the top of the grinding zone, then it should lie on a surface of revolution formed by rotating the radius of the uncut part $R_i(x)$ about the workpiece axis of symmetry. This can be determined by the following procedure:
- Express point $p$ in terms of the workpiece coordinate system – the operator $T(\cdot)$ transforms the coordinates in the appropriate way.

$$T(p) := \begin{pmatrix}
\cos(\theta) & \sin(\theta) & 0 \\
-sin(\theta) & \cos(\theta) & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix} p \\ R_o \sin(\theta) \\ r_{min} + R_o \cos(\theta) \end{pmatrix} \begin{pmatrix} R_o \sin(\theta) \\ 0 \\ 1 \end{pmatrix}$$

- The angle of the point $p$ above the $xy$ plane about the workpiece coordinate system, "ang", can be computed using the arctangent operator.
- Rotate the point $p$ by -ang about the workpiece axis of symmetry so that it lies in the $xy$ plane. This gives the coordinates of the point $p_2$ expressed on the $xp$ $yp$ frame.
- Transform the point into the grinding wheel coordinate system using the inverse transform to yield the coordinates of $p_2$ expressed in the $xy$ frame. These coordinates are assigned the label $p_3$

$$T_{inv}(p) := \begin{pmatrix}
\cos(\theta) & -\sin(\theta) & 0 \\
\sin(\theta) & \cos(\theta) & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix} p \\ R_o \sin(\theta) \\ r_{min} + R_o \cos(\theta) \end{pmatrix} \begin{pmatrix} R_o \sin(\theta) \\ 0 \\ 1 \end{pmatrix}$$

- If the value of $\phi$ sent as an argument to the function Diff is at the top of the grinding zone, then the $y$ coordinate of point $p_3$ should be equal to the radius of the uncut part evaluated at the $x$ location of that point, $R_y(p_3)$ should equal $p_3_y$.
- A search using a root finder for a point where the function Diff is zero will yield the value of $\phi$ at the top of the grinding zone. This is the value needed as the upper limit of integration in the integral defining MRR($x$).
The algorithm described above will allow one to compute material removal rate (MRR) as a function of axial position. The approach will be effective for any geometry of the grinding wheel that can be described by a function of axial position. The approach is particularly effective in determining the MRR for thrust wall grinding including the complex three dimensional interactions between the grinding wheel and the part as shown in Figure 11. Some additional steps are required to accommodate undercuts (see Fig. 8) but those modifications lie beyond the scope of this thesis.

Figure 10: Solving for the limits of the grinding zone.
Figure 11: Interaction of the grinding wheel and workpiece in thrust wall grinding.

The next section explains how the tool for computing thrust wall grinding developed here can be used to define optimal parameters for the grinding process.

3.3 Using the Model to Find a Generic “Best Practice”

The following several pages are a brief description of the simulation tool. The description begins with a picture of the input portion where the various variables are defined (quantified by the user) for use in the mathematical model. The next page contains a figure to aid in describing these input variables. The several pages that follow then use graphic outputs from the model to demonstrate a theoretical “Best Practice Search” for a Coaxial Offset Shoulder Grinding process when varying two inputs, the “skew angle” between the axes of rotation of the grinding wheel and the workpiece, and the “direction of travel of the grinding wheel.” Three strategies are assessed to determine a “best practice.”
\[ r_{\text{min}} := 2.5625 \text{in} \quad r_{\text{max}} := 3.625 \text{in} \quad R := 200 \text{mm} \quad \text{feed} := \frac{.12}{\text{in}} \quad \omega := \frac{800}{\text{rev}} \quad \theta := 1 \text{deg} \]

\[ r_f := 2.5 \text{mm} \]

\[ \alpha := 90 \text{deg} \]

Feed angle -- zero is feed toward axis of the workpiece, 90 is feed along axis of the workpiece, \( \alpha \) is feed orthogonal to grinding wheel axis

\[ d := \frac{\text{feed}}{\frac{\omega}{2\pi}} \quad d = \text{mm} \]

Depth of cut (i.e. total motion of the grinding wheel in the feed direction)

\[ L := r_f \]

Length of the cylindrical portion of the workpiece that is to be ground. In this sheet, it is set to be just long enough include the whole fillet

This graphic is a copy of the actual "input" portion of the simulation tool. Using the variables defined with the help of the system representation shown on the next page, the user enters the desired values for these variables and runs the simulation to generate a profile (shown on the subsequent pages with sample values of the variables.). Based upon this profile, and the constraints of the real-world system, the user can determine, relatively quickly, the optimal setup parameters for the system. Rather than physically testing each set of parameters, the tool can be used to model each scenario in only a few minutes. The model is rather complex, however, so a fast computer is definitely recommended!
The graphic above depicts the type of grinding system addressed by the mathematical model and provides a reference to delineate the variables used in the model for describing the system. The "acute angle" in this representation is quite large, on the order of 30°. In industry, the applied angle is typically much smaller, on the order of 1-5°. It has been made larger in this case to demonstrate more easily the effects upon the system resulting from the skewed axes of rotation. The model is capable, however, of calculating larger angles, although less efficiently. The graphs soon to follow in this section will demonstrate this. In particular, one of the two graphs loses resolution to the point that the effect is then best seen with the remaining graph. This will be discussed further and will be more obvious in the upcoming examples.
The remaining pages in this section contain graphs generated by the simulation tool. The key variables used during the generation of these plots are the "skew angle between the axes of rotation of the grinding wheel and the workpiece," denoted by Theta, and "the direction of travel of the grinding wheel relative to the coordinate place perpendicular to the axis of rotation of the workpiece," denoted by Alpha.

The setup represented here demands that the majority of the material removal be done by a relatively small portion of the grinding wheel. The graph at top shows that only 0.005" of the wheel is actually removing material. The rest is not being used. The graph at the right depicts the demand on the grinding wheel as a function of location on the wheel. The perpendicular distance between the red solid line and the blue dashed line indicates the amount of material being removed by the wheel at that point. The gap is relatively wide in this instance.

Theta = 1 degree, Alpha = 90 degrees
By increasing the skew angle between the axes of rotation by only 4 more degrees, the demand loading on the grinding wheel is significantly altered. Before, the peak Material Removal Rate was $1.6 \times 10^{-3}$. Using these new parameters here, however, that peak rate is reduced by nearly an order of magnitude. This reduction translates into a reduction in the peak wear rate experienced by the wheel as well, improving process efficiency as has been discussed.

Theta = 5 degrees. Alpha = 90 degrees
When theta is large, 25 degrees or more, the simulation tool has difficulty generating the second plot that graphically demonstrates the Material Removal Rate along the wheel topography. The other simpler plot that is still generated, however, shows very clearly that the benefits increase as the skew angle increases, although at a deteriorating rate. In this case, with an additional 20 degrees in the skew angle, the peak Material Removal Rate has been decreased by another half order of magnitude, creating a similar effect upon the peak wear rate experienced by the wheel. Notice also how much more of the wheel is being used, with nearly three times as much of the wheel now contributing to the MRR.

Theta = 25 degrees, Alpha = 90 degrees
As Theta increases, the peak MRR continues to fall and the amount of the grinding wheel surface involved with the process of removing material similarly grows. At this point, however, the relative rate of return is very slow compared to that achieved with a similar increase in Theta when Theta was small. If a process can allow for a large Theta, however, it is beneficial to use these parameters since peak MRR is reduced from where it would be with a smaller Theta.

Theta = 45 degrees, Alpha = 90 degrees
Now we are operating with Alpha at 0 degrees. The grinding wheel is now travelling directly perpendicular to the axis of rotation of the grinding wheel. Not surprisingly, most of the material removal is done by the edge of the wheel exposed during this direction of movement. Theta is small, so there is some distribution of the load, but not very much. However, compared to the other examples where Alpha was 90 degrees, the peak MRR is much lower than even the best rate attained with the other approach.

Theta = 1 degree. Alpha = 0 degrees
Interestingly, the same effect that helped the MRR in the other direction of travel (Alpha) caused by increasing the Theta is actually causing the opposite effect here. Instead of reducing the peak material removal rate by exposing more of the wheel to the workpiece, it appears that there is a slight concentration effect happening. The peak material removal rate is actually increasing slowly.

Theta = 5 degree, Alpha = 0 degrees
This approach with Alpha at 0 degrees is turning out to be a worsening condition as the Theta is increased. While this might seem like bad news, it is actually good information since it shows that the peak material removal rate can be lower in this process than even with a high Theta in the other while keeping the overall process layout quite similar to that of Coaxial Offset Shoulder Grinding. The best result when Alpha is 0 degrees happens when Theta is closest to 0 degrees also.

Again in this case, as Theta gets larger, the tool is unable to generate the graphical plot of MRR.

Theta = 25 degree, Alpha = 0 degrees
The trend is continuing, proving that the model is consistent in its analysis of a situation. The trend with these parameters is to lose effectiveness in terms of the reduction in the peak MRR. This is exactly what is happening and, again, at a declining rate as Theta increases.

Theta = 45 degree, Alpha = 0 degrees
An interesting approach involves using a varying angle of Alpha. In this situation, Alpha varies with Theta so that the grinding wheel now moves directly along its axis of rotation. In effect, both the edge and the side of the wheel are now exposed to the workpiece. The results, as we will see as Theta and Alpha increase, are rather consistent. An Alpha of 90 degrees showed a decrease in peak MRR as Theta increased while the 0-degree Alpha showed an increase in the peak MRR. Combining these effects by allowing Alpha to vary with Theta does a pretty good job of holding the value steady.

\[
\text{Theta} = 1 \text{ degree, Alpha} = 1 \text{ degrees}
\]
The peak MRR is increasing slowly with increasing Theta/Alpha. The amount of grinding wheel exposed to the workpiece, however, is growing which is positive, even if the peak MRR is not decreasing. At least the workload is being distributed a bit more.

Theta = 5 degree, Alpha = 5 degrees
Again, now having a larger value of Theta, the graphical MRR plot is not generated. And, while the peak MRR has increased a bit again, the portion of the wheel required to assist with removing material from the workpiece has also grown substantially, which is helpful in increasing wheel wear life.

\[ \Theta = 25 \text{ degree}, \alpha = 25 \text{ degrees} \]
This final iteration of the combined value of Alpha and Theta has resulted in no surprises. The peak MRR is highest for this approach and the amount of grinding wheel exposed to material removal from the workpiece is also at its highest point.

From the analysis presented here, it would appear that having a small Theta and an Alpha of 0 degrees is the best approach to reducing the peak MRR while not affecting significantly the layout of the Coaxial Offset Shoulder Grinding Process.

Theta = 45 degree, Alpha = 45 degrees
4.0 Benefits Analysis

The use of the simulation tool will affect various elements of the process and the Grinding Industry. Not all of these effects will be positive. For example, the metrics used at a facility to monitor a process might not necessarily capture the system impact of the use of the tool. Management might actually consider it to be detrimental. Section 4.1 looks at the Overall Equipment Efficiency (OEE) metric in particular to address this issue. On a broader level, the simulation tool will affect the industry by enabling more efficient customization of Coaxial Offset Shoulder Grinding. Section 4.2 presents some estimates of this impact.

Beside these industry-specific benefits, it is important to reemphasize that the real, direct process-specific benefit of the use of the simulation tool is the ability to more rapidly and routinely customize a Coaxial Offset Shoulder Grinding process so that the peak rate of wear experienced by the grinding wheel is minimized. Section 4.2 presents an estimate of the benefit of enabling quicker customization. The ability to *routinely* customize a process, however, should not be overlooked. Rather than relying upon intuition to direct this process, the tool operates according to specific geometric rules designed into the mathematical model. It will always operate the same, regardless of the user.

Reducing the peak rate of wear of the grinding wheel directly impacts both the efficiency and the quality of the process. The "dressed" contour of the grinding wheel is not changing as rapidly now since the wear is occurring more slowly. Consequently, the wheel does not need to be dressed as often to restore the contour to its original dimensions. If the wheel were dressed just as often, on the other hand, then at the very least the standard deviation of the dimensions of the parts would be smaller than with the old process.

The manner in which the approach incorporating a "skew angle" effects a reduced peak wear rate is through the distribution of the material removal responsibility along a larger cross-sectional area of grinding wheel (this is shown especially well in the graphs in Section 3.3). Because of this fact, it may be possible in some instances to increase the overall MRR by taking advantage
of the increase in the MRR capacity enabled by the availability of more space per unit time in which to store chips or fines. This is, however, an application-specific benefit since there are many coupled parameters in the grinding process and taking advantage of one might very well compromise another. In this case, speeding up the grinding wheel or increasing the infeed rate, both of which would take advantage of the increased surface area for MRR, might each adversely affect the surface finish quality. Returning to the original goal of the thesis, and one which does nothing to complicate matters, the most important benefit is the reduction of the peak rate of wear since it enables fewer dressing cycles for a given quantity of finished parts produced by the machine. The next section explores some of the benefits of reducing the dressing requirements.

4.1 Impact on Overall Equipment Efficiency (OEE) Metric

The Overall Equipment Effectiveness, also called the Overall Equipment Efficiency, is a measure used in industry to track the usefulness of an established "process." Typically, the "process" being measured is an individual machine. However, at times, the measurement is applied to a cluster of machines or even to an entire processing line involving several machines and/or several sub-processes. In the example presented in this section, the OEE is developed for a single machine. This is the typical practice, and it makes for a better example since it is much easier to follow the accounting.

By design, the OEE measurement is a very effective monitoring tool. It is not intended for making comparisons between processes. It ensures that the original "specifications" of a process are being met over the passage of time. In other words, if a piece of equipment, when it is first installed, is capable of running at an OEE of 75%, then every effort should be made to keep that machine running at an OEE of 75%.

Significantly, as will be shown here, the OEE is not well-suited to making comparisons among dissimilar processes. In effect, doing so would be the same as comparing apples to oranges, even if the difference involves only a small improvement to the original process. Unfortunately, the OEE is often used in
this manner. This can lead to false assessments of the true effectiveness of a process change.

Let us consider the example of a simple grinding machine. It is used for 60 minutes per hour, 8 hours per day, 5 days per week. In a given "work week," it has 2400 minutes of available time: $5 \text{ days} \times \frac{8 \text{ hours}}{\text{day}} \times \frac{60 \text{ minutes}}{\text{hour}} = 2400 \text{ minutes}$.

The machine cycle time is 1 minute and it can process only 1 part per cycle. If it were able to produce parts non-stop for an entire workweek, it would produce 2400 parts. Of course, a grinding machine probably cannot be used for an entire week without some "in-process maintenance." For the purpose of this example, we will specify that the machine, in order to keep within tolerance, must dress (resurfaced) the grinding wheel every 10 parts. The dressing operation takes 10 minutes. In effect, for every 10 minutes of productive time (10 parts times 1 minute per part), the machine must undergo 10 minutes of unproductive time for wheel dressing. It is easy to see that the machine is now only able to make 1200 parts during a work week since the total time per part, for processing plus dressing, is now two minutes (1 minute to process the part plus 1 minute of amortized dressing time). Consequently, the machine OEE is 50% (1200 parts produced/2400 parts from cycle time).

At this point in the discussion, it is necessary to introduce another term, "Productivity." While the OEE measures how well a given process adheres to its original guidelines or specifications, the measure of process productivity is an absolute measurement that can be used to effectively measure process improvements. If a machine, our grinding machine for example, can produce 1200 parts in an ideal (assuming no unplanned downtime) work week, then its baseline weekly productivity is 1200 parts. Any changes made to the process will affect productivity relative to this established reference point of 1200 parts per week.
Changes in the processing time per part and the amortized unproductive dressing time affect the "productivity" of a grinding machine, but in a different manner than they affect the OEE. Reducing one or both will increase productivity. On the other hand, while reducing one or the other will increase the OEE, reducing both will have an undetermined effect. The methods by which these changes can be effected are numerous. Therefore, before continuing, it is important to establish first those techniques that are relevant to changes effected by the introduced angle advocated in this thesis investigation.

Processing time can be reduced either by using a different grinding wheel that can remove material more quickly, or by increasing in one way or another the total cutting surface area exposed, per unit time, to the workpiece. Since the investigation presented here does not require the use of a different grinding wheel material, only the "surface area per unit time" increase is significant.

The negative effect of the time used to dress the wheel can be mitigated by reducing the time required per dressing cycle, or by increasing, without an adverse effect on quality, the number of parts that can be processed between dressing cycles. It is fair to assume that the dressing cycle time is already at a minimum for a given grinding wheel material. A different material could affect this cycle time in either the positive or negative directions but this investigation does not consider the use of a different material anyway so it is not relevant to the discussion. The important element, therefore, becomes finding a way to increase the number of parts processed between successive dressing operations.

Significantly, this thesis investigation effects changes in the process that enable both of these benefits simultaneously. Through the introduction of an angle between the axes of rotation of the grinding wheel and the work piece, the cross-sectional area, and therefore the effective surface area per unit time, of

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16 This does not include the amortized time per part for replacing the wheel at the end of its service life. For the purpose of this example, it is not important to complicate the accounting with this factor since it is assumed to be insignificant compared to the 1-minute-per-part dressing time.
the cutting face is increased. By essentially exposing more of the grinding wheel, per unit time, to the workpiece, this change has the same effect as increasing the grinding wheel RPM, but without the detrimental effects previously discussed in Section 1.2.17. The introduced angle also changes the geometry of the interface. This new geometry has the effect of distributing the wear experienced by the cutting surface over a larger area, thereby reducing the peak rate of wear on the wheel and enabling an increase in the number of parts that can be processed between wheel dressing cycles.

A conservative example of the improvements caused by the introduced angle can be used to understand the varying effects upon the OEE and compare each result with the effect upon the productivity measurement. Consider first that the angle introduced between the axes of rotation of the grinding wheel and the work piece effectively doubles the cutting surface cross-sectional area and halves the peak rate of wear experienced anywhere on the cutting surface. Then, the cycle time would be halved (since the MRR would effectively be doubled with twice the cutting surface area per unit time at the same wheel RPM) and the time between dressing cycles doubled (since the rate at which the out-of-tolerance condition will develop is now halved).18 The processing time per part would therefore be only 30 seconds. The total dressing time of 10 minutes, now distributed among 20 parts instead of just 10, would result in an amortized penalty of only 30 seconds per part instead of 1 minute. Considering 2400 minutes per workweek of available time, the maximum number of parts without dressing the wheel would be 4800. Taking into account both the processing and dressing times, the actual number of parts produced would be 2400. Again, the OEE for the process is 50% (2400/4800).

Even with the significant changes in the process just discussed, from the standpoint of the OEE, no improvements were made. For this reason, it is easy

17 It is fair to assume that a grinding wheel is going to be used at an optimal RPM where MRR versus wheel degradation is idealized with respect to the effect upon productivity. Cycle time will be as low as possible without increasing too much the amortized unproductive wheel dressing and wheel replacement times.
18 These cause/effect relationships are not entirely accurate, but are sufficient for use in this example.
to see why the productivity measurement is so important. While the OEE was unaffected, productivity increased 100% (from 1200 to 2400 parts per week).

When only one factor is improved, the OEE measurement changes, but not in a consistent manner. If, for example, only the number of parts produced between dressing cycles were doubled, the OEE would improve. The maximum number of parts that could be produced in a workweek would still be 2400, but the total cycle time, including amortized dressing time, would be 1-½ minutes. The machine would now produce 1600 parts per week. The OEE would increase from 50% to 67% (from 1200/2400 to 1600/2400 parts) and the productivity would increase by 33% (from 1200 to 1600 total parts per week).

The results are somewhat different, however, if the cycle time is reduced from 1 minute per part to 30 seconds per part while the amortized dressing time remains constant at 1 minute per part. Now, in a 2400-minute workweek, the machine could produce 4800 parts if no dressing time were needed. Considering the total cycle time of 1 ½ minutes, the output from the machine is again 1600 parts per week. The productivity again increased by 33% (from 1200 to 1600 parts per week), but the OEE actually decreased from 50% to 33% (from 1200/2400 parts to 1600/4800 parts). Obviously, the OEE is not a good measurement when considering process improvements.

This long discussion is an attempt to mitigate misunderstandings in industry. Depending upon the management philosophy at a plant, the OEE might be the only measurement in use. In this case, an improvement such as the one suggested here might be concluded to have a negative effect, depending upon how the changes in the equipment affect the cycle time and the number of cycles possible in between dressing cycles. If relatively more improvement were gained in the cycle time, by an increase in the effective MRR, than is made to reduce the amortized dressing time, the improvement would have an overall negative effect upon the OEE. The measure of productivity is the proper method to assess the true effect of these changes.
4.2 Financial Impact on Grinding Industry

An analogy\textsuperscript{19} to the Injection Molding Industry, where software tools are used to assist in the design process, is presented here in order to attempt an estimate of the economic impact expected from the use of the simulation tool in the Grinding Industry.

4.2.1 Injection Molding Industry Background

Software tools which aid in the design of the molds used in Injection Molding vary significantly in price and function. Roughly speaking, these tools are divided into three categories: low-, middle-, and high-end\textsuperscript{20}. The low-end products\textsuperscript{21} cost around $2,900 and are considered "entry level." Their purpose is to assist a Project Engineer with managing the players in the mold-making arena: mold maker; designer; plastics supplier; etc. Tools at this level of sophistication typically have about 15 outputs, or variables, that they manipulate in the simulation.

The middle-end mold-making software tools\textsuperscript{22} are priced around $4,900. These tools target the Design Engineer who has already designed the mold using solid modeling. These software can be used to facilitate either product or mold design by validating the design for manufacturing. The simulation is particularly convenient to use since it is easily integrated with the modeling software to avoid costly and time-consuming formatting between platforms. Tools in the middle-end category manipulate anywhere from 20 to 40 variables in their output.

\textsuperscript{19} The analogy is not intended to present facts as much as it is to suggest the potential for financial returns resulting from the introduction of the tool to the market.

\textsuperscript{20} The information regarding this segregation of modeling tools, as well as the information regarding specific examples in each category, was obtained during a phone conversation with James Span, a product specialist at American Precision Products (APP). More information about the company and/or the various products and their functions and costs, can be found at http://www.actech.com/

\textsuperscript{21} For example, "C-Mold" from C-Mold, a division of American Precision Products (APP). The price and function data were provided in a phone conversation with Jim Span from APP.

\textsuperscript{22} For example, "3D Quikfill" from C-Mold, a division of American Precision Products (APP). The price and function data were provided in a phone conversation with Jim Span from APP.
Laures

The high-end molding software tools are priced anywhere between $25,000 and $90,000. They are designed for use by Engineering Analysts from any discipline and support analyses from within the entire field of mold-making. These comprehensive software packages also enable the user to configure the software to their specific needs, adding or deleting modules as necessary. Because they are so heavily customized depending upon the application, the exact level of sophistication is not known. These very comprehensive tools are capable of handling, however, more than 100 variables in their simulation.

4.2.2 Grinding Wheel Market Background

Market data shows that the Ferrous and Superalloy Grinding Wheel Market has total value of $1.4 Billion. Of the total Grinding Wheel Market, $363 Million worth of product is made entirely from Cubic Boron Nitride (CBN) and is sold for use in applications requiring CBN grinding wheels. The data is very scattered and incomplete. Therefore, knowledge of the exact usage of these CBN wheels probably does not exist. A rough estimate places just under 30%, or about $100 Million worth, of CBN wheels being used in Coaxial Offset Shoulder Grinding.

4.2.3 Estimated Impact of the Simulation Tool on the CBN Market

As is evident from the graphics and discussion in Section 3.3, the efficient application of various techniques to the Coaxial Offset Shoulder Grinding process can result in more than a one-hundred-fold reduction in the peak rate of wear experienced by the grinding wheel. The corresponding increase in process efficiency resulting from fewer dressing cycles and from the potential to increase the MRR will be more than 50%. This estimate is, in fact, probably too conservative but allows for many if not most of the applications to restrict the introduced angle to only a few degrees in order to keep the new process similar to the old. Regardless, substantial overall improvement can be expected.

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23 For example, "C-Mold Advanced Solutions" from C-Mold, a division of American Precision Products (APP). The price and function data were provided in a phone conversation with Jim Span from APP.

24 The information, provided by Brian Nailor, a marketing manager with GE Superabrasives, was contained in a presentation entitled "Borazon CBN Market Analysis and Opportunities 1998/1999." [Borazon is a trademark of General Electric Company, U.S.A]

The question of a quantified estimate of the impact of the simulation tool upon the industry still remains unanswered. While it is impossible to predict exactly what the savings will be, a total savings of at least 20% for the Coaxial Offset Shoulder Grinding industry as a whole is reasonable. These savings are not so much created by the application of the techniques to improve process efficiency as they are the result of facilitating the task of doing so. The tool will save upwards of six months of development time and more than $100,000 in prototyping costs over the trial-and-error method currently used. These savings coupled with the process improvements that might otherwise have not been implemented because of the high cost of developing them lends one to estimate roughly $20Million in savings on $100Million in annual output.

5.0 Conclusion

This thesis is an investigation into the development of a simulation tool for use in the field of Mechanical Grinding. The tool enables the user to graphically represent the rate of material removal from the workpiece, as a function of location on the grinding wheel, for the Coaxial Offset Shoulder Grinding process. The ability to quantify this information is critical in the effort to reduce the peak rate of wear experienced by the grinding wheel, a notorious weakness for this particular process. Conquering this problem imparts significant positive ramifications on the overall cost efficiency of the process.

New methods for shoulder grinding have recently been developed based upon empirical knowledge accumulated in the grinding industry. These new techniques are in widespread use in industry but currently require time-consuming prototyping work to determine the best process parameters. The new analysis tool allows engineers to quickly simulate the effects of the techniques and optimize process parameters to maximize tool life and minimize cycle time.

The analysis in this thesis uses tools from several disciplines to ensure that the development of the simulation tool was conducted with a holistic view of its
impact upon the Grinding Industry. In particular, systems-thinking tools from Systems Architecture were applied to guide the process of determining the effects of the new tool on systems at various levels: machine, factory, enterprise, industry. Concepts from Operations Management were employed at the machine level, investigating the effect the tool would have upon process efficiency metrics, in particular the Overall Equipment Efficiency (OEE). Managerial Accounting principles were applied at all levels to verify the viability of the tool from a financial standpoint. Elements of Manufacturing Strategy were applied at the factory and enterprise levels to assess the benefits of adding flexibility and speed to the grinding process by enabling rapid customization. Systems Engineering was similarly considered in the analysis to identify elements of the tool or its effects that might play a counterproductive role.

The application of these various tools, concepts, and analyses during the investigation in this thesis served to verify the efficacy and efficiency of the simulation tool. In summary, the use of the tool was found to benefit the system at all levels. In fact, no contradictory elements were found, other than the up-front overhead associated with implementing the use of the tool.

The analysis in this thesis estimates that the new computational technique can reduce development leadtimes by upwards of six months and associated development costs by more than $100,000, depending upon the company and the specifics of the application involved. A comparison to software used in the Injection Molding Industry suggests that the potential impact of this tool on the Grinding Industry could be as high as $20Million per year, assuming a 20% improvement in the Coaxial Offset Shouldering Grinding process specifically and an overall 5% improvement for the CBN industry, although individual results will be substantially better.