Signature Analysis of OD Grinding Processes with Applications in Monitoring and Diagnosis

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Signature Analysis of OD Grinding Processes with Applications in Monitoring and Diagnosis

By
Wei Tian

A Thesis
Submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
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By

Wei Tian
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APPROVED:

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Abstract

Grinding operations can be analyzed through monitoring and analysis of the spindle power during the process. Due to the complexity of the process, the analysis on grinding processing signal still heavily relies on personal experience of the engineer instead of having a standard structured method. Therefore, subjectivity and inconsistency is introduced into the analysis procedure. In this thesis, a general method is established to characterize signal, utilize the characterization result to predict the real time condition of grinding wheels and the impact on the process performance measures, and provide suggestions in modification of process parameters to improve the grinding operation. This method is initiated from signal acquisition and conducted based on characterizing the signal and organizing expert knowledge. When the standard procedure to analyze the grinding process through power signal is established, the correlation between input and output can be understood, which can later be utilized for diagnostic applications. During the diagnosis, the real-time grinding wheel status is estimated and the output of the process is predicted. Then, suggestions on modifying the input parameters to address given output issue are generated. Therefore, a signal analysis and knowledge based monitoring and diagnosing system is developed to help enhance the current grinding process planning. This system is realized with a software tool developed with specifically designed algorithms under Matlab environment, upgrading from manual signal processing to an automated characterization procedure and providing process evaluation and improvement suggestions, which will improve the objectivity, consistency and accuracy in the analysis of grinding processes.
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1 Introduction

In this chapter, an overview of the analysis of grinding processes is provided that includes the difficulties in the analysis and the method of Signature Analysis. Then, the problem is defined and the objectives of this thesis are specified. Finally, the organization is provided.

1.1. Overview

This thesis presents a method to analyze grinding processes, utilizing the method of Signature Analysis, incorporating techniques of signal processing, characterization and knowledge-base construction.

The analysis of grinding processes is complicated because grinding material removing process is full of complexity. There is no theoretical model that can be used to explain the mechanisms of grinding process completely or reveal the correlation between process parameters and the outcome. The state of the art in industrial applications heavily relies on personal understanding of grinding and there is no standard procedure to follow, which creates subjectivity in the analysis.

Under this circumstance, this thesis proposes and implements an approach of utilizing the method of Signature Analysis to help study the grinding process, trying to unravel it through the signal. The first step is to characterize the grinding process by establishing a standard pattern of it, which can be used later to correlate the process parameters and the result.
In order to realize this method, the following difficulties need to be overcome. Firstly, there is no existing algorithm to perform this characterization because prevailing study are more inclined to focus one grinding cycle or even one fixed feed rate. Then, even if the process is characterized, there still no existing method to present the characterization result so that it can be correlated with the process parameters and outcome of the process.

Hence, there proposes a method to characterize and diagnose outside diameter (OD) plunge grinding process based on heuristic knowledge, and implement this method with a software tool.

1.2. Thesis Objectives

The effort of this thesis can be classified in three categories. One is to characterize grinding processes. The other is to apply the characterization result to perform diagnosis of the process.

The objectives of this thesis are:

1. To understand the OD plunge grinding process, identifying the process parameters, performance measures and characteristics of it;
2. To propose a method to characterize the process effectively;
3. To propose a method diagnose the process based on the characterization result;
4. To develop a software tool to realize and automate the characterization and diagnosis tasks.
1.3. Thesis Organization

Chapter 2 provides an introduction to the background related to this thesis, including grinding processes, the method of Signature Analysis, and analysis techniques incorporated in the characterization.

Chapter 3 elaborates the utilization of the Signature Analysis method, including the characterization process and the construction of knowledge base.

Chapter 4 demonstrates the implementation of the methodology mentioned the Chapter 3, including the algorithm for characterization and the functions of the software.

Chapter 5 concludes the thesis, the current achievements and limitations are summarized, and possible future studies and applications are discussed.
2 Background

This chapter provides an introduction to the background information related to this thesis, including the fundamental knowledge related to grinding processes, existing analysis effort, an approach of Signature Analysis to conduct the analysis, and techniques incorporated to realize this method.

2.1 Grinding Processes

This section provides an introduction to grinding processes. First, an overview of grinding process is presented, explaining the definition, importance, and decomposition the processes. Second, grinding wheel is introduced and wheel related problems in the process are elicited, followed by a not – wheel – related problem in grinding process, chatter. Then, an introduction to OD plunge grinding based cycle design is provided, delivering an outlook that how the grinding processes are organized and can be analyzed. In the end, the author reviews effort in industrial applications and research work regarding to the analysis of grinding processes.

2.1.1 Overview of Grinding Operations

Grinding is a material removing process that uses multiple abrasive particles to perform material removal and surface generation [41]. Usually, it is considered as the final process of a component that requiring smooth surfaces and high tolerance requirement. Currently, it accounts for 20% ~ 25% of the total expenditure on material
removing operations [31]. There are several types of grinding operations, flat surface grinding, cylindrical grinding, and other special grinding processes, like centerless grinding, electrolytic grinding etc. [39]. An surface of outside diameter can be obtained from cylindrical grinding processes that can be further traverse grinding and plunge grinding by means of the direction of feeding motions. Figure 2-1 provides an example of outside diameter grinding process [34]. As shown, the workpiece is fixed and can only rotate against a given axis. Both grinding wheel and work piece are spinning at high speed. Also, the grinding wheel is feeding along either the axial or radial direction of work – piece and interferes against the work – piece.

Figure 2-1 An example of OD grinding

Generally speaking, any grinding process can be decomposed into an intrinsic input vs. output model, as shown in Figure 2-2.
Figure 2-2 A decomposition of grinding processes

The Input Parameters include four folds, process parameters, consumable tools, machine tool and the work – piece. Machine tool determines system rigidity. Work – piece brings run – out and size errors, hardness variations, etc.. Consumable tools, including abrasive products, coolant and other tools used in the process, also introduce some process variables. The specification and dressing condition of abrasive products of them affects the grinding process greatly. Process parameters include wheel speed, workspeed, grinding cycle design, dressing parameters and inspection method, etc. [25, 42].

The outcome of the grinding process is usually the ground part. Since the function of grinding process is to remove designated amount of material and to generate a designated surface, the performance of the process can be evaluated from two aspects, the geometric accuracy and surface quality. Besides that, the economic aspect cannot be neglected either.
The process can be measured through the term of technical output, which includes but not limited to the relative motion of wheel and workpiece, temperature, force, power, vibration, etc..

The dashed line that connects the Input Parameters and the Output indicates there these two blocks are correlated. However, the relationship stays unclear and needs to be studied [24]. As mentioned that grinding is a complex process, there may not be straightforward correlation between input and output existed, especially there is still no theoretical model available. Therefore, it is a practical method to study the technical output, seeking for patterns that link the input and output.

2.1.2 Grinding Wheel and Related Problems

Grinding wheel, as the abrasive product utilized in OD plunge grinding processes is an important factor of the process and its behavior has great influence to the performance measure.

2.1.2.1 Grinding wheel

Grinding wheel is the type of abrasive products utilized in OD plunge grinding processes. Compared to the cutting tools in other machining processes like turning, the grinding wheel is much more complicated, the complication of which introduces excessive uncertainty and intricacy to the process. Furthermore, the difference in the cutting tools result in great difference in the specific energy in chip formation [33], which indicates different mechanisms in the process.
Conventional grinding wheels, compared to those which utilize super – abrasive grains like diamond or CBN, are bonded which consist of abrasive grains, bonding and pores. The Figure 2-3 is a picture of typical shape and appearance of grinding wheels, provided by Saint – Gobain Abrasives [38].

![Grinding Wheels](image)

Figure 2-3 A picture of grinding wheels

Those grains are randomly distributed in a grinding wheel, they have a great variety in sizes, shapes and orientations and they form multiple micro cutting edges to remove material from workpiece. Besides grains, bonding materials and pores also account for interactions during the process.

The grains interact with workpiece surface during the process and account for a great majority of the energy consumption of the material removing in three modes, sliding (rubbing), plowing and cutting, as other machining processes. The interaction mode is determined by the wheel sharpness [39], indentation of grain into the workpiece [18] and the material properties of the workpiece.

The mode of sliding means the grain passes along the workpiece surface and does not penetrate, thus no material is removed; plowing means the grain passes along the
workpiece surface and causes lateral material piled up but without forming any chip [12]; cutting means the grain passes along the workpiece surface and chip is formed.

Even though sliding and plowing do not contribute to material removal, they account for energy consumption and wear of grinding wheel by encouraging the attritious wear flat on the periphery, resulting in excessive friction against the workpiece and wheel wear.

2.1.2.2 Wheel wear

Once the grain is worn flat, it loses sharpness and needs more force and energy to interact with the workpiece. When the force exceeds the retention force from bond, the grain on the surface will fall out and the grains which were located beneath the surface with sharp cutting edges will then emerges and replaces the old cutting edges. This phenomenon is called self – sharpening.

Attritious wear and grain dulling usually occur at the same time, where the sharp cutting edges of the grain particles are being worn out gradually due to interactions with the workpiece. Compared to the fact of grain dulling and self – sharpening, wheel wear is a culmination of numerous individual events as mentioned. This amount of wear can be quantified with the term of “grinding ratio” (G-ratio), defined as the volume of material removed per unit volume of wheel wear, represented as $G\text{ – ratio} = \frac{V_w}{V_s}$, where $V_w$ indicates volume of removed material and $V_s$ equals to amount of wheel wear [31]. Since the rate of wheel wear can be quantified, it can be controlled. In grinding processes, this type of problem can be solved by compensating the feed of the grinding wheel. However, the wear rate of grinding wheel is strongly related with economic aspect of the process, considering the cost of grinding wheel and changeover time.
Besides wheel wear, there are other two types of common problems in grinding processes that are related to grinding wheel, loading and glazing.

### 2.1.2.3 Loading

Wheel loading can be defined as accumulation of grinding chips at the inter-grain space [12], as shown in Figure 2-4 [26]. The origin of this issue comes from the strong tendency of adhesion during the chip formation process where workpiece material deforms.

![Figure 2-4 A sketch of wheel loading](image-url)

The occurrence of loading is contributed from two aspects, from the geometric side, the size and volume of the chip vs. inter-grain space [12]; from the material property side, the affinity between grain and workpiece material, and the ductility of workpiece material also contribute to the occurrence of loading.

When loading occurs, the clogged chip also interacts against workpiece. Meanwhile, the real indentation depth for each grain is actually reduced. It is a barrier towards higher material removal rate. Under this circumstance, if the machine is still remaining the setting before the loading occurs, a great force and high temperature is

```
generated, which result in a greater deflection and surface roughness is greatly worsened. Furthermore, severe loading results in excessive force, temperature and power, which may jeopardize geometric precision, cause surface damage and reduce wheel life.

2.1.2.4 Glazing

Glazing, or named as worn flat, is a phenomenon during grinding operation that tips of active grains are worn flat and therefore forms a smooth surface on the grinding wheel. The occurrence of glazing leads to elevated force in both tangential and normal directions, and the specific energy increases and thermal damage may occur [12]. However, the smooth grinding wheel surface introduces more proportion of sliding and plowing, which have positive influence on the surface roughness for the ground part.

2.1.3 Chatter

Chatter is another undesirable phenomenon in grinding processes that manifests as near harmonic vibration in large amplitudes. It causes damage to geometric accuracy and surface finish, which is a critical problem for precision processing. Also, the presence of chatter brings productivity constraints since chatter usually attenuates or disappears when feed rate decreases. Furthermore, the damage caused by chatter may not be detected by equipment but only visual observation [13]. Therefore, the detection of chatter becomes a top that needs to be studied.

Chatter can be classified into forced chatter and self – excited chatter. Forced chatter mostly results from unbalanced grinding wheel. Self – excited chatter refers to
vibrations that results from response of grinding system to transient stimulation. The presence of chattering is related to grinding system stiffness and may originates from different reasons [19,25].

The near harmonic vibration feature that chatter originates with provides a solution to detect the presence of chatter through measurement of certain in – process variables, like force, acceleration and acoustic emissions (AE).

2.1.4 OD Plunge Grinding

This thesis adopts the outside diameter plunge grinding process (shown in Figure 2-5) as an example to study the process and validate the proposed method trying to unravel the correlation between the input and output. This operation processes the outside diameter surface of the work – piece. The term “plunge” indicates that the grinding wheel is fed against the work – piece only in the radial direction.

Figure 2-5 A sketch of OD plunge grinding process
During the process, the work – piece rotates against the grinding wheel, which usually rotates at a much higher rate. At the beginning, the grinding wheel approaches the work – piece at a relatively high speed right before they come to contact. Then, the feed rate usually reduces to a designated level and the material removing process begins as the wheel and work – piece come to contact. The wheel stops feeding when the final dimension is met, then grinding wheel lingers at that position for a given amount of time before it begins to return the original point. Till then the processing to one workpiece is completed. The period, that is from the moment that the grinding wheel starts to approach the work – piece to the moment that the grinding returns to its original position, is named as a grinding cycle as shown in Figure 2 – 6.

![A Grinding Cycle (Roughing → Spark - Out)](image)

Figure 2-6 A sketch of a typical OD plunge grinding cycle

Usually, a grinding cycle consists of several stages, including roughing, finishing, and spark – out by means of different feed rates, as shown in Figure 2 – 6, which consist
of two stages, a roughing stage followed by a spark out stage. The duration and feed rates of each stage constitute the mostly of the design of a grinding cycle.

There are three prevailing types of grinding cycles by the number of sequential stages incorporated in a cycle, two stages defined as roughing and spark out stage; three stages defined as roughing, finishing and spark out stage; four stages defined as roughing, spark – out, finishing, final spark – out.

Roughing is the stage that has the highest feed rate once the wheel comes into contact with the work – piece and usually performs as the first stage in a grinding cycle. It aims to remove as much material as possible to obtain productivity requirement. However, the high feed rate also comes with high deflection and vibration, leading to precision and surface quality issues. Therefore, roughing is usually followed by other stage prior to the retraction of grinding wheel. Finishing is a stage of reduced feed rate to reduce deflection. The last stage in a grinding cycle right before the wheel retraction is usually spark – out, when wheel stops feeding against the work – piece and maintains contact only because of the existence of deflection occurred in the previous stages.

2.2 Related Research on Grinding Signal Analysis

The author reviews existing effort in analyzing grinding processes with two approaches, efforts in industrial applications and academic research from literature review.

The grinding process can be measured by different types of technical outputs, like force, temperature, Acoustic Emission (AE), power, etc.. Force and temperature have
been widely used to measure grinding processes because their strong correlation with interactions between the grinding wheel and workpiece, as they are considered as the technical output of grinding processes [31]. Recently, AE measurement has become more and more popular in research community [2]. When the grinding wheel engages with the workpiece and force is generated, elastic waves is generated and can be captured by the AE sensor. Power is not as widely used in academic research as the other measures because the system to measure power usually has larger inertia than force or AE and may not represent transient feature accurately. Also, the power is affected by more factors than force signal. However, measurement of power is much easier, compared with force, temperature and AE. For this reason, the power based measurement and analysis is adopted in this thesis.

When the grinding power signal is acquired, the analysis of grinding processes can be conducted, following a procedure provided in Figure 2-7. This analysis method is adopted by a grinding wheel manufacturer.

![Diagram](#)

**Figure 2-7 Concurrent analysis procedure**
Currently, the analysis still relies on human beings. There are a few approaches for people to interpret the measurement. Based on interviewing several experts in this area, their analysis method and procedure is integrated in the following three paragraphs. In most cases, it is quite rare for application engineers to scrutinize the signal completely but browsing the whole measurement and observing the overall shape, seeing if there is any obvious pattern, like changing trend and rate. For example, based on the observation that the power curve is shifting upwards gradually from cycle to cycle, the engineer may conclude there is a great possibility that loading occurs in the process.

More specific analysis requires more effort and techniques. The grinding process needs to be analyzed by cycle to get a specific view. Therefore, engineers need to identify grinding cycles from whole measurements. Then, since each grinding cycle consists of multiple stages, the person needs to identify the stages. Based on the identification of cycles and stages, engineers can then calculate some points of interest. For example, customer complains that bad surface finish on some parts. Based on the observation, the engineer noticed that after a few cycles, it takes considerably longer time for power to decay so that it cannot reach the steady region as the spark – out stage ends. In this situation, engineers may suspect the occurrence of wheel loading or glazing, and suggest the customer either to dress the wheel or increase the duration of spark – out stage.

Once the grinding cycles and stages can be identified, the power consumption at given material removal rate can be fetched, and plotted on a figure of Power vs. Material Removal Rate (MRR), with which the status of grinding wheel can be predicted more accurately. However, it is very rare for engineers to conduct this type calculation and plot because it is too complicated to calculate the values and generate plot.
Although more than one person may contribute in the analysis, the conclusion still heavily relies on the personal knowledge and based on the observation of measurement data without standard procedure, here comes following two problems that need to be solved. One is that a common methodology or criteria that can be utilized to identify of grinding stages still needs to be developed to make sure engineers so that the signal can be characterized into a standard format automatically. With the implementation of this characterization tool, different people can conduct analysis based on the same characterization result to reduce the subjectivity. This implementation of this standard pattern identification tool can encourage quantitative analysis over qualitative analysis. The other problem is how to generate the conclusions in a standard manner to reduce subjectivity in the analysis. Even though the standard format of processed signal is available, how it can be utilized in the diagnosis of grinding process needs to be studied.

The problems mentioned above can be completely solved if correlation between the input parameters, output parameters, and the technical outputs are well understood. Current researches regarding towards this direction have been conducted in a different approaches, including fundamental analytical, kinematic and FEA analysis, molecular dynamics modeling (MD), constitutive modeling, artificial neural network, and ruled based modeling method [5].

The first three approaches are more oriented on study of physical mechanisms behind the phenomena of the process, they share a microscopic view and are trying to solve the problem from the root by unravel the mechanisms of the process [7, 17, 18, 19, 41, 43]. So far, those approaches still cannot provide an overview of the process and serve as a practical tool provide instructions and suggestions in process control.
Prevailing researches are highly oriented on a single cycle with fixed feed rate, which means only one stage is incorporated in a grinding cycle, as shown in Figure 2-8 [29].

Figure 2-8 Grinding Force Signal

In order to address the two problems mentioned in industrial applications, characterization of grinding signal and performing diagnosis based on the processed signal, an advisory system needs to be developed. The advisory system can be classified by the types of model, the prevailing types include the constitutive model, artificial neural network model, and rule based fuzzy logic model [5].

“GrindSim” is a typical constitutive model based advisory system, developed for simulation and optimization of cylindrical grinding processes. It begins with the input parameters that are required in configuring a grinding process, like G ratio, wheel hardness, system stiffness, initial wheel status and other processing parameters. Besides that, a few coefficients need to be calibrated. By running this model, the software can simulate the process and generate prediction on both technical output and outcome of grinding processes, incorporating items like forces, power, deflection, wheel wear,
thermal effect, surface roughness, part shape, etc. [15, 31]. One of the advantages of this type of system is since the model is built on constitutive or empirical model with physical meaning related to grinding process, even the calculation may deviate from the expected result due to improper calibration, the possibility for the system to generate an absurd result is low, and the accuracy can then be fixed through further calibration.

Therefore, with this software, once a set of processing configuration is provided, the group of measures can be generated through the simulation. Ideally, with the simulation result, the user can get the result of the geometric accuracy, surface quality as well as the economic issue and judge whether the input parameters are acceptable. With trial and error, the grinding process can be optimized.

However, there are some disadvantages in this model. One of the greatest problems is the existence of the series of coefficients that require calibration with experiment. Each time the configuration changes, calibration process needs to be performed to obtain the result that matches experiment data. Another disadvantage is that the system cannot be utilized in monitoring or diagnosis purposes.

Another type of advisory system is developed based on ANN [37]. Similarly to the previous approach, it takes process parameters as input and predicts the output. However, unlike the constitutive model based system, the correlation between the input and output are almost completely not clear and the reliability of the prediction heavily rely on four grinding process irrelevant parameters, judicious selection of representative signals, suitable signal preprocessing and feature selection, proper preparation of the representative data base for training, and proper selection of the ANN topology. In order
to obtain promising prediction result, ANN model requires a great amount and continuous adaptive training operations, which may not be a good solution for industrial applications when a straight–forward correlation is requested and limited resource to perform continuous adaptive training.

The last type is the rule based system. This kind of system is constructed based on heuristic knowledge, delegating high volume low level decision making work load to computers so that humans can be released for low volume high level decision making by integrating expert knowledge to construct a knowledge base. The knowledge is formulated in a standard format and can be retrieved through specific algorithm, like fuzzy logic [8, 26].

The accuracy of result of this model relies on two factors, the collection and formulating of human knowledge, the retrieval and decision making process simulation. This type of system could be a major solution to provide assistance in future because it resembles the process of human reasoning, especially when processing difficult problems are required. However, currently, there is still no existing solution that is able to analyze a specific grinding process accurately and reliably. Also, like the other two solutions, once fuzzy logic is adopted, a great amount of data for calibration is still required.

However, in order to characterize the grinding power signal, identifying the cycles and multiple stages within each cycle, those methods, approaches, and tools mentioned above are basically not applicable. Existing academic researches mostly focused on seeking an explanation or solution to a specific process, rather than delivering a method or procedure that can be utilized in assisting the analysis in industry. To realize
this approach, the method of Signature Analysis is adopted, as illustrated in the following section.

2.3 Signature Analysis

The method of Signature Analysis is a method that can be utilized to monitor, diagnose and optimize a specific system based on the characterization of measurement. It begins with interpreting the information extracted from measurable signals to establish a clear pattern, which is called the “signature”. Then, the signature, as a characterized signal with clear pattern, is correlated to a specific problem or feature of a system. Thus, this problem or feature can be analyzed through the analysis of this signal [3, 40].

2.3.1 Signature Analysis

The term “Signature”, is basically from signal, the difference between a signature and a signal is illustrated in the Table 2-1. Compared to signals by normal means, signature contains more information can help in analyze a system, like shown in the table below.

<table>
<thead>
<tr>
<th>SIGNATURE</th>
<th>SIGNAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Something (as a tune, style, or logo) that serves to identify; also a characteristic mark</td>
<td>General means that transmit and convey certain information</td>
</tr>
<tr>
<td>With specific signal pattern</td>
<td>With identified pattern or no pattern</td>
</tr>
<tr>
<td>With capability to characterize a system</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-1 Signature VS Signal
Generally, utilizing signature to characterization follows a standard procedure shown as follows.

![Diagram](Image)

Figure 2-9 General work procedure for Signature Analysis

The procedure begins with acquiring the data from the system that is measured. The signal then needs to be processed and interpreted, expecting to obtain patterns in order to characterize the system. Thus, a signature is established. Followed by the establishment of the signature, the task becomes correlating the signature with the characteristics of the systems, including the input factors and the output measurement. This stage can be named as system recognition. With the help of the signature and the recognized system pattern, the system can then be manipulated and optimized.

An example of utilizing this method in the investigation of grinding process under simulative environment of grinding burn is presented [29]. This case begins with analyzing the characteristics of the problem of interest, grinding burn. By analyzing the mechanism of grinding burn, it is identified that burn is a temperature related issue. The phenomenon is artificially simulated with pulse laser to raise the temperature and the process is measured with Acoustic Emission sensor so that a set of signal is obtained.
Besides this set of measurement, another two sets of measurement are conducted, a grinding process with the occurrence of grinding burn, and another grinding process with the same operation parameters without the occurrence of burn.

![Signature Identification of Grinding Burn](image_url)

Figure 2-10 Signature Identification of Grinding Burn

By comparing the three sets of signals, the characteristics of grinding burn are identified and proved. Thus, once this signal pattern occurs in the process, the grinding burn can be concluded. This case demonstrates how signature is identified, and how it can be utilized in diagnosis of grinding process.

The method of Signature Analysis provides an approach to identify and solve the problem of a manufacturing system based on the characterization on the measurement (signal) by establishing certain correlation between the signature and system feature. Hence the correlation can be utilized to diagnose and optimize the system.

### 2.3.2 Signal Processing Related Techniques

In order to identify the signal pattern to conduct the method of Signature Analysis, there are some techniques available in signal processing.
2.3.2.1 Noise Reduction

The original data is collected in the time domain with different frequency components. The signature pattern may only be identified from in a portion of the whole frequency. Thus, digital filters can be developed to remove certain proportion of frequency component. The frequency selective filters can be classified into lowpass, highpass, bandpass and bandstop filters [35].

Identification of grinding process in a generic method proposed in this thesis is based on analysis on the scale of grinding cycles, seeking for method to separate the stages in each cycle. Hence, a lowpass filter, removing the high frequency component from the signal and preserving the profile, needs to be developed. Matlab provides a great amount of assistance in studying the characteristics of filters and simplifies the design of filters.

2.3.2.2 Signal Representation

The original data is collected in time domain. Assuming certain characteristics of the process is related to corresponding feature in the signal, and the feature may present in different domains, the signal should be properly represented to facilitate the feature capturing. Basically, there are four ways to represent the signal, as shown in Figure 2-11, time domain, frequency domain, Short Time Fourier Transform (STFT) and wavelet domain.
It is well known that Fourier Transform is an applicable and popular method for converting a time-domain signal into its frequency domain. However, Fourier Transform does not provide any resolution on time-axis, so that the transient feature of the grinding process cannot be well addressed.

Fourier Transform can be defined as that any integrable function $h(t)$ can be represented in a frequency domain as follows, $H(\omega) = \int_{-\infty}^{\infty} h(t)e^{-j\omega t} dt$, where $h(t)$ is the original signal in time domain, $\omega$ is frequency, and $H(\omega)$ is the result of Fourier. In order to facilitate signal analysis, Discrete Fourier Transform (DFT) is developed to implement the Fourier Transform of discrete signal and Fast Fourier Transform (FFT) is an improved algorithm developed to compute the DFT [4].

With a time–frequency analysis method, unlike Fourier Transform to present global frequency feature of the whole length of data record, the location in time and frequency feature of a transient phenomenon can be illuminated on a time–frequency
domain. STFT (Short Time Fourier Transform) and WT (Wavelet Transform) are two widely used time – frequency methods in the area of signal processing [16].

Unlike conventional Fourier Transform, the Short Time Fourier Transform (STFT) is able to provide the local frequency feature on time axis. By introducing window function that moves along the time axis to the original time series, the local frequency feature at a moment can be indicated by the location of the window function. The width of the window affects the representation, wide window (poor resolution on time) results in good resolution on frequency, and narrow window (good resolution on time) results in poor resolution on frequency, which complies with the Heisenberg Uncertainty Principle.

Wavelet Transform is able to represent the signal on a time – frequency plane with dynamically adjusted resolution of time and frequency addressing the Heisenberg Uncertainty Principle. Practically, it represents as narrow window for high frequency component and wide window for low frequency component [1, 11].

### 2.4 Summary

Since the grinding is known for its complexity and various approaches have been proposed, trying to solve problems in the process. Prevailing researches on the grinding signal are heavily oriented on single cycle and single stage problem with force or AE signals with, rather than at the level of grinding cycles with multiple stages. There are three types of prevailing advisory systems, constitutive model, ANN and rule based fuzzy
logic models. However, the accuracy and requirement for large amount of calibration work limits their applications in industry.

A method based on Signature Analysis, mainly based on the analysis of power signal and establishing the knowledge base from integrating human knowledge, is proposed and implemented in this thesis.
3 Signature Analysis of OD Grinding Processes

This chapter presents how the principles of signature analysis are applied in the diagnosis of OD plunge grinding processes. It incorporates the characterization with of the signal and the knowledge base construction to correlate the signature with the features of the system. The characterization is conducted based on the study of current signal processing procedure to resemble the human reasoning procedure. The knowledge base construction is derived from a simplified rule based advisory system model.

3.1 Methodology

Similarly to the generic procedure of Signature Analysis method shown in Figure 2–9, this application of signature analysis on OD plunge grinding processes follows a procedure from signal acquisition through characterization to establish the correlation between the characterization result and the system characteristics, shown in Figure 3-1.

Figure 3-1 The Procedure for Signature Analysis of Grinding Operations
Above all, it starts with the acquisition of grinding signal, followed by the characterization of the signal that reveals the process. This system begins with pre-acquired measurement signal. Thus, the result needs to be represented and visualized in a proper way to allow proper perception. Furthermore, this result can be utilized to predict the outcome of the process and provide suggestions on how to adjust input parameters to avoid problems.

Characterization of the grinding process is a complicated work and is full of difficulties. Firstly, the signal, spindle power signal, from grinding operation comes with a background noise. Secondly, the formats and patterns of the signal show a great variety that also brings difficulties to the software tool for automatic processing.

Once the characterization is conducted and pattern are extracted and represented, they can be used to correlate the system characteristics. Considering the complexity of grinding process, and there are hardly any straight-forward correlation between the process input and outcome, a technical output, grinding wheel status is utilized to link the input and the outcome, which can be estimated by characterization result. It also affects the outcome directly and can be modified by adjusting input parameters.

With this correlation established, with the given signal, inquiring the knowledge base, related suggestions regarding to the signature can be fetched and the system can thus be monitored and diagnosed.

To realize, the work can be basically separated into two major modules, one is called “Signal Processing”, which processes the signal and extracts the signature from it, and then presents the signature in proper methods. The other module is named as
“Knowledge Base”, since establishing correlation between the characterization result and the grinding wheel status, and thus predicting the outcome of the process and generating suggestions are completed in this module, as shown in Figure 3-2.

![Figure 3-2 Overall framework](image)

The module of Signal Processing starts from the definition of grinding cycle power signal to obtain a pattern so that the signature can be acquired, and incorporating techniques of data definition, noise reduction, spectrum analysis, automatic time domain calculation and visualization to extract the pattern from the measurement data.

The module of Knowledge Base is constructed based on a simplified rule based knowledge base system. The correlation between the input and output are formulated in a straight – forward manner without incorporating Fuzzy Logic. Also, instead of making decision, it provides the user with the information, like a checklist, that is required in decision making. With these two modifications, the complication of the construction of
the rule based knowledge based system is greatly reduced and can be more practical for the industrial applications. This module begins with comparing characterization result with the theoretical pattern of given wheel issue to estimate the condition of the grinding wheel. While the wheel condition estimation can be used to predict the output measurement of the process, and the input factors are related to both the grinding wheel issues and the output aspect.

3.2 Signature Processing Module

This section includes the definition and representation of the signature.

3.2.1 Signature Definition

Since the purpose of this being presented module is to identify the signature from the signal, it is necessary to establish the format of signature before conducting the development.

Usually, a measurement data consist of multiple grinding cycles with background noise. Above all, a noise reduction needs to be conducted. The following defining and characterization operations are conducted on filtered data. First, the cycle has to be identified since the signature is defined on the level of cycle. For each cycle, the stages needs to be identified by defining the starting and ending point, and transition from dynamic to steady region in each stage needs to be identified, as shown in the Figure 3-3. Based on this separation result, there defined a series characteristic values that is related to the feature of the system, especially some of them incorporate features to predict grinding wheel status.
As shown in Figure 3-3, a grinding cycle with two stages are represented, the blue dots represents starting and ending point of stages. For sequential processing like this, the two stages are defined by the three points, the blue dot in the middle is shared by roughing stages and spark – out stage, as the ending point and starting point respectively. The red dots represent the transition inside each stage.

![A Grinding Cycle (Roughing → Spark - Out)](image)

Figure 3-3 Grinding Cycle Definition

Once those points for each stages and sub – stages are defined in a cycle, some values of interest can be calculated.

For other types of grinding cycles that consist of different number of stages, a similar definition can be conducted. However, for the cycle with four stages, the spark – out that follows roughing can be neglected since it does not contribute to the output or grinding wheel status clearly. Therefore, based on a grinding cycle with three stages, once points to define the stages and sub – stage are obtained, the values that contribute to
the outcome or grinding wheel status can be calculated, as defined in Figure 3-4 and Table 3-1.

Figure 3-4 A Typical Grinding Cycle with Three Stages

<table>
<thead>
<tr>
<th>SLOPE &amp; NUMBERS</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Roughing Feed</td>
<td>12 Rough Duration</td>
</tr>
<tr>
<td>2 Rough Power Increase</td>
<td>13 Sub1</td>
</tr>
<tr>
<td>3 Rough Power Plateau Slope</td>
<td>14 Sub2</td>
</tr>
<tr>
<td>4 Rough Power Plateau Value (Mean)</td>
<td>15 Finish Duration</td>
</tr>
<tr>
<td>5 Finish Feed</td>
<td>16 Sub1</td>
</tr>
<tr>
<td>6 Finish Power Decay</td>
<td>17 Sub2</td>
</tr>
<tr>
<td>7 S/O Decay</td>
<td>18 S / O Duration</td>
</tr>
<tr>
<td>8 Threshold Power</td>
<td>19 Sub1</td>
</tr>
<tr>
<td>9 Material Variation</td>
<td>20 Sub2</td>
</tr>
<tr>
<td>10 Max Power</td>
<td>21 Cycle Time</td>
</tr>
<tr>
<td>11 Max Power / Machine Capability</td>
<td>22 Time Constant of S / O</td>
</tr>
</tbody>
</table>

Table 3-1 Standard Datasheet Items
The values mentioned Table 3-1 can serve as a basis of the numerical signature of the grinding cycle. There are also graphical form of the signature, which can be derived from Table 3-1.

### 3.2.2 Signature Representation

The signature can be represented numerically and graphically.

#### 3.2.2.1 Numerical Representation

The numerical representation of signature, the format of which shown in Table 3-2, is based on the standard datasheet items. The first column incorporates all the items mentioned in Table 3-1 and the each consequent column stands for the values calculated from a grinding cycle. To the right of the values for each cycle, there are statistical measures, including mean value and standard deviation for each item. The last column is the changing trend indicator, the changing trend of each item over cycles are calculated by percentage, indicating percentage of increase or decrease over the cycles.
### Table 3-2 Numerical Representation of Signature

<table>
<thead>
<tr>
<th>Item</th>
<th>Cycle 1</th>
<th>Cycle ...</th>
<th>Mean</th>
<th>Deviation</th>
<th>Trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough Feed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough Power Slope</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough Steady Slope</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough Steady Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finish Feed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threshold Power (Pth)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fin sub1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fin sub2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/O Duration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/O sub1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/O sub2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2.2.2 **Graphical Representation**

There are two ways for graphical representation, Power vs. MRR and Power Superimpose.

Power vs. MRR demonstrates the correlation between mean power consumption at given material removal rate (represented by feed rate) of a grinding cycle, it is plotted based on the mean power consumption at steady region and feed rate for each stage. Shown in Figure 3 – 5, the Power vs. MRR line for each cycle can be described by two measures, the offset, and slope. Compared to the base line, the change of these two variables can help predict the grinding wheel status, the details of this part of will be introduced in Knowledge Base Module.
On the Power Superimpose plot, power curve for designated grinding cycles are superimposed. Therefore, an intuitive view of changes among the cycles plotted is obtained.

Figure 3-6 An example of Power Superimpose
3.3 Signature Extraction Techniques

Once the signature is well defined, an algorithm needs to be developed so that the signature can be automatically identified from incoming signal of grinding process in the time domain. The signature extraction can be broken down in four parts, noise reduction, cycle identification, stage identification, and sub–stage transition identification.

3.3.1 Noise Reduction

The signal acquired from prevailing virtual instrument digital acquisition system is discrete in time domain, usually consist of multiple cycles. However, this acquired signal cannot be processed directly because it contains large amount of high–frequency component, and sometimes it is very difficult to identify the profile of the grinding cycle. So that a low pass filter needs to be developed to remove the high–frequency noise and the low–frequency profile can be viewed, as shown in Figure 3-7. The red line represents the original measurement and the blue line is the filtered result. It is clear that the profile is more easily to identify with the filtered signal.
Matlab greatly simplifies the development of filter by providing various types of filter functions [45].

### 3.3.2 Cycle Identification

The cycle identification can be completed with two approaches, with and without the presence of feed channel.

When feed signal is provided, it can be used to separate grinding cycle easily and accurately. The feed signal indicates the displacement of the grinding wheel. The original position of grinding wheel is considered as the zero point. After each cycle, the grinding wheel returns to the original position. The cycles can be separated by identifying the points where the grinding wheel leaves and returns to zero. The starting point of a given grinding cycle is defined as the medium point between when the wheel returns to the zero point from the previous cycle and when the wheel leaves zero point in the given cycle.
When feed signal is not provided, there is no evidence to support the movement of grinding wheel. Therefore, the grinding cycle can only be estimated through the estimation of the power signal. It is assumed that when a grinding cycle is completed, the power consumption will return to the original level before the processing. Several horizontal reference lines with equal offset from the minimum value to the maximum value of the process is drafted. This process groups the power signal into several levels. The section below one of the low reference lines are generally considered as the control points to fetch cycle separation points. If there are two consequent points, and power at the first point is decreasing and is increasing at the second point. The medium point before these two points mentioned above are considered as the cycle separation points, shown in Figure 3-8.

![Cycle separation point](image)

Figure 3-8 Cycle Separation with Power Signal

By completing this cycle separation process, the grinding cycle from the signal can be identified and grinding signal can now be stored and analyzed in cycles.
3.3.3 Stage Identification

Once the cycles are identified, stages in each grinding cycle need to be identified. This operation can also be classified in two approaches, with and without presence of feed channel.

If feed is available, the stage definition points can be generated based on the change of slope in feed signal. First, by locating the point where grinding wheel indents into the workpiece most, the ending of spark – out stage can be identified. Understanding the fact that there is no infeed during spark – out stage, the starting of spark – out stage can be fetched by locating the point in feed signal where the slope turns towards zero. On the other end, the start of feed is defined as the point where feed leaves the zero point, followed by the point when the wheel comes into contact with workpiece, considered as the starting point of roughing stage. Since the number of total stages is given from configuration file, if there are only two stages in the cycle, the stage defining points are completed by locating the feed starting point, roughing stage starting point, spark – out stage starting point and the spark – out stage ending point. Otherwise, there are additional stage defining point before the roughing stage starting point and the spark – out stage starting point. Those additional points can be identified through the “High Point Function” that identifies the turn point from a series.

In the case where feed signal is not available, the type of grinding cycle is limited in the type of two stages in a cycle, roughing $\rightarrow$ spark – out. Similarly to the cycle separation without feed signal, the power leveling function is utilized. The point where the power signal leaves the threshold level is defined as the roughing stage starting point. The point where the power signal decreases from the top level is considered as the spark
out stage starting point. The point where the power signal returns to threshold stage is considered as the spark – out ending point.

By realizing this custom designed procedure, the stages in each grinding cycle can be captured.

### 3.3.4 Sub-stage Transition Identification

In order to calculate the predefined datasheet, the transition from dynamic to steady region in each stage needs to be identified. It can be realized through the “High Point Function”. This function is developed to calculate the sub-stage transition point, and is also used in identifying turning point in the stage identification process.

The assumption is that each stage consists of two regions, the dynamic and the steady, either of which can be approximated as a straight line in the signal. Thus, by connecting the starting and ending point, a reference line is obtained. The three lines form a triangle, as shown in Figure 3-9.

![Figure 3-9 Demonstration of “High Point Function”](image-url)
The turning point in the signal is then approximated by the vertex to the segment formed by the reference line. By calculating the distance from each discrete point in the signal to the reference line, the point with the farthest distance from the reference line is returned. This point, in the signal, is considered as the sub-stage transition point.

In order to utilize this High Point Function, the starting and ending point of analysis zone needs to be specified in prior from either the slope change point in feed data or the power leveling function. Theoretically, the success capture of the transition point is determined by the local curvature of the transition area. Suppose the data consists of two perfect lines, as shown in Figure 3-10. As long as the reference line crosses both of the regions, a triangle can be formed with the transition point as one of the three vertexes. Therefore, the distance from the red lines to the blue reference lines reaches maximum at this vertex, no matter how the analysis zone is defined.

Figure 3-10 Demonstration of High Point Function with Infinite Local Curvature
When the transition is not a perfect single vertex but a transition zone, nor the two regions as perfect straight lines, different definition of analysis zone affects the identification of the transition point. However, when the transition takes time, the definition of transition time is also quite vague. The accuracy and robustness of this function is quite promising when the array is not as defined and even when noise is present. There is no clear mathematic derivation of this case but the capability of this function is illustrated with an example shown as follow.

As shown in Figure 3-11, any point from 450 to 625 is acceptable as the transition point. By altering the reference line, the returning result from High Point Function is presented.

![Figure 3-11Robustness Validation of High Point Function](image-url)
Figure 3-11 shows a simulation signal of the dynamic and steady sub–stages with a gradual transition and white noise. As shown in the figure, any point ranging from 425 to 650 in the horizontal axis is considered as the reasonable.

The robustness of the program is studied by altering the reference lines by range and slope and then verifying the identified transition result for each reference line is shown in Table 3-3.

<table>
<thead>
<tr>
<th>Reference Line No.</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>495</td>
</tr>
<tr>
<td>2</td>
<td>495</td>
</tr>
<tr>
<td>3</td>
<td>495</td>
</tr>
<tr>
<td>4</td>
<td>495</td>
</tr>
<tr>
<td>5</td>
<td>495</td>
</tr>
<tr>
<td>6</td>
<td>495</td>
</tr>
<tr>
<td>7</td>
<td>495</td>
</tr>
<tr>
<td>8</td>
<td>542</td>
</tr>
<tr>
<td>9</td>
<td>542</td>
</tr>
</tbody>
</table>

Table 3-3 Robustness Validation Result of High Point Function

As shown in the Table 3-3, all of the results fall into the range of 450~625. And 495 becomes the most popular result. When the reference lines are defined as the starting boundary is very close to the transition area, the calculation result shifts towards right a little but still in the acceptable range. And standard deviation of this set of result is 20.725. Given process capability defined as $C_{pk} = Tolerance / (3 \times Stand Deviation)$, with a threshold at 1.33 as acceptance. The $C_{pk}$ for this process is 3.617, which is far beyond the expectation. Therefore, this program is considered robustness to process this kind of data.
Then, the sub – stage transition point is identified and the calculation of datasheet can be conducted.

3.4 Knowledge Base Module

When the characterization result has been delivered in the format of a standard data sheet, another problem arouses as how this result can be utilized to analyze the grinding process.

3.4.1 Framework of Knowledge Base

Considering the complexity of the grinding process, a great variety of input factors and uncertainty in the process itself, it is not realistic to establish the correlation between the input and output factors directly. However, based on the study of grinding signals, it is noticed that a strong correlation exists between the real time condition of grinding wheel and the signals. Meanwhile, the wheel condition determines the technical output of this process, including geometric dimension and integrity of the ground surface.
3.4.2 Wheel Condition Analysis

Loading, glazing and wheel worn are the most popular wheel problems during grinding process. Currently, the correlation between the signal pattern and the wheel conditions of loading, glazing and wheel over–worn have been proved.

3.4.2.1 Loading

On the power curve, it can be noticed that the loaded signal represents higher power at all material removing stages, excluding the threshold power. And the transition from dynamic to stable periods care is becomes longer than usual. In a single grinding cycle, the stable sections of roughing or finishing reveals a trend of power increase may indicate the wheel loading. Signal in multiple cycles make the judgment of loading much easier and more obvious, power is increasing, time – constant is increasing. On the
standard sheet can be described as follows, the loading pattern in single cycle and multiple cycles are shown.

<table>
<thead>
<tr>
<th>ID</th>
<th>Item</th>
<th>Single Cycle</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rough Feed</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Rough Pwr Slope</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Rough Steady Slope</td>
<td>&gt;0</td>
<td>Increase</td>
</tr>
<tr>
<td>4</td>
<td>Rough Steady Pwr</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>5</td>
<td>Finish Feed</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>6</td>
<td>Pth</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>7</td>
<td>Finish Steady Pwr</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>8</td>
<td>Finish Pwr Slope</td>
<td>&gt;0</td>
<td>Increase</td>
</tr>
<tr>
<td>9</td>
<td>S/O Pwr Slope</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>10</td>
<td>Max Pwr</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>11</td>
<td>Ratio</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>12</td>
<td>Rough Duration</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>13</td>
<td>Rgh_sub1</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>14</td>
<td>Rgh_sub2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>15</td>
<td>Finish Duration</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>16</td>
<td>Fin_sub1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>17</td>
<td>Fin_sub2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>18</td>
<td>S/O Duration</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>19</td>
<td>S/O_sub1</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>20</td>
<td>S/O_sub2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>21</td>
<td>Cycle Time</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>22</td>
<td>Time Constant</td>
<td>N/A</td>
<td>Increase</td>
</tr>
</tbody>
</table>

Table 3-4 Pattern of Loading

Based on this datasheet, Power VS Material Removal Rate (MRR) can be drafted that can indicate the wheel condition more clearly. In the figure below shows the standard pattern of Power VS MRR plot when loading occurs. MRR is correspondent to feed rate while the vertical axis indicates the steady power (mean power) at the given feed rate.
For the case of loading, the power will be elevated, especially at higher MRR. However, at lower MRR the difference between the loaded wheel and a normal does not reveal too much difference. And the threshold power does not elevate, either.

3.4.2.2 Glazing

The prediction of glazing follows the same format and basis as that of situation of glazing, from the value pattern from the datasheet and more clearly from Power VS MRR plot. The pattern of glazing are very close to that of loading, because both loading and glazing result in an elevated level of force, and thus power, which result in an elevated temperature and deflection. Therefore, the steady power increases; dynamic duration and time constant also increase.

<table>
<thead>
<tr>
<th>ID</th>
<th>Item</th>
<th>Single Cycle</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rough Feed</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Rough Pwr Slope</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Rough Steady Slope</td>
<td>&gt;0</td>
<td>Increase</td>
</tr>
<tr>
<td>4</td>
<td>Rough Steady Pwr</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>5</td>
<td>Finish Feed</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>6</td>
<td>Pth</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Value</td>
<td>Change</td>
</tr>
<tr>
<td>---</td>
<td>---------------------------</td>
<td>--------</td>
<td>---------</td>
</tr>
<tr>
<td>7</td>
<td>Finish Steady Pwr</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>8</td>
<td>Finish Pwr Slope</td>
<td>&gt;0</td>
<td>Increase</td>
</tr>
<tr>
<td>9</td>
<td>S/O Pwr Slope</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>10</td>
<td>Max Pwr Slope</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>11</td>
<td>Ratio</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>12</td>
<td>Rough Duration</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>13</td>
<td>Rgh_sub1</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>14</td>
<td>Rgh_sub2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>15</td>
<td>Finish Duration</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>16</td>
<td>Fin_sub1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>17</td>
<td>Fin_sub2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>18</td>
<td>S/O Duration</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>19</td>
<td>S/O_sub1</td>
<td>N/A</td>
<td>Increase</td>
</tr>
<tr>
<td>20</td>
<td>S/O_sub2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>21</td>
<td>Cycle Time</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>22</td>
<td>Time Constant</td>
<td>N/A</td>
<td>Increase</td>
</tr>
</tbody>
</table>

**Table 3-5 Pattern of Glazing**

Even though glazing has identical pattern on the standard datasheet, it can be differentiated through Power VS MRR plot. As in the Power VS MRR plot, the wear flat on the tip of grains result in more friction during the material removing. Glazing also results in an increase on the Power VS MRR plot. However, the case of glazing does not result in as great difference as in the case of loading but resembles more like a steady offset from the threshold power.
Wheel is worn throughout the grinding operation. That is why that feed is the adjusted to compensate it. However, if wheel is worn out faster than expected, it is called “Over – worn”. An overworn wheel leads to over – sized final product in most situations.

<table>
<thead>
<tr>
<th>ID</th>
<th>Item</th>
<th>Single Cycle</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rough Feed</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>2</td>
<td>Rough Pwr Slope</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Rough Steady Slope</td>
<td>&lt;0</td>
<td>Decrease</td>
</tr>
<tr>
<td>4</td>
<td>Rough Steady Pwr</td>
<td>N/A</td>
<td>Decrease</td>
</tr>
<tr>
<td>5</td>
<td>Finish Feed</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>6</td>
<td>Pth</td>
<td>N/A</td>
<td>Decrease</td>
</tr>
<tr>
<td>7</td>
<td>Finish Steady Pwr</td>
<td>N/A</td>
<td>Decrease</td>
</tr>
<tr>
<td>8</td>
<td>Finish Pwr Slope</td>
<td>&lt;0</td>
<td>Decrease</td>
</tr>
<tr>
<td>9</td>
<td>S/O Pwr Slope</td>
<td>N/A</td>
<td>Decrease</td>
</tr>
<tr>
<td>10</td>
<td>Max Pwr</td>
<td>N/A</td>
<td>Decrease</td>
</tr>
<tr>
<td>11</td>
<td>Ratio</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>Rough Duration</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>13</td>
<td>Rgh_sub1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>14</td>
<td>Rgh_sub2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>15</td>
<td>Finish Duration</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>16</td>
<td>Fin_sub1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>17</td>
<td>Fin_sub2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>18</td>
<td>S/O Duration</td>
<td>N/A</td>
<td>Stable</td>
</tr>
<tr>
<td>19</td>
<td>S/O_sub1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 3-6 Pattern of Over – worn

<table>
<thead>
<tr>
<th></th>
<th>S/O_sub2</th>
<th>N/A</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Cycle Time</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>22</td>
<td>Time Constant</td>
<td>N/A</td>
<td>Increase</td>
</tr>
</tbody>
</table>

Figure 3-15 Standard Power VS MRR plot for Over - worn

In the case of wheel over – worn, the power curve usually shift downwards that indicates an overall decrease of energy consumption, this pattern is also agreed by what is shown in the table and the Power VS MRR plot.

3.4.3 Output Prediction

As mentioned, there is direct correlation between wheel condition and grinding output. In this case, grinding output is defined by terms of surface roughness, geometric accuracy, and cost.

3.4.3.1 Loading

Based on study of the grinding process, wheel loading is believed to lead to excessive heat and force, and accordingly excessive deflection, power and temperature.
Therefore, it may bring negative affluence on the accuracy, surface roughness, and cost. More specifically, size holding on the final product is jeopardized due to excessive deflection; roundness may be jeopardized due to reduced system stiffness; surface quality may deteriorate; the possibility for burn to occur is increased. On the cost and productivity wise, excessive grinding wheel wear is expected and the material removal capability of the wheel is limited to a reduced level.

In order to avoid loading, the following suggestions can be made,

- Dress the wheel or reduce the dressing interval;
- Select wheel with increased porosity;
- Increase the washing or flushing effect of the coolant;
- Reduce feed rate.

3.4.3.2 Glazing

Glazing may bring certain affluence on accuracy, surface quality and cost. For the accuracy, the size holding on the part is jeopardized. By terms of cost, the excessive wheel wear occurs due to increased tendency of grain pullout. However, the effect on surface quality is hard to justify. On one hand, glazing increased the possibility for burn to occur; while on the other hand, it may be able to improve the surface roughness level for elevated proportion of sliding interaction. In order to avoid glazing, the following action can be taken,

- Dress the wheel or reduce the dressing interval;
- Reduce feed rate;
- Select wheel with harder grain;
Select wheel with stronger self-sharpening tendency (soft bond).

3.4.3.3 Over-worn

Wheel over-worn may affect the accuracy and cost. In detail, dimension on final product may deviate to a specific direction if the feed is not compensated properly. In the case of over-worn, the wheel life expectancy is reduced. The following actions can be taken to avoid wheel over-worn,

- Adjust feed compensation;
- Select grinding wheel with stronger bond;
- Reduce feed rate.

3.5 Suggestions Checklist

The input adjustment is categorized by terms of corresponding output measures, including geometric accuracy, surface quality, and cost related aspects. The content for each aspect is shown as follows, which is included in the knowledge base.

Geometric Accuracy

- Dress wheel or reduce skip dressing interval;
- Adjust dressing parameters;
- Check coolant performance;
- Design slower process (reduce feed rate);
- Check wheel worn rate;
- Check grain or bond specification (Consider wheel upgrade);
• Check process control.

**Surface Quality**

• Dress wheel or reduce skip dressing interval;
• Adjust dressing parameters;
• Check coolant performance;
• Check wheel worn rate;
• Check grain or bond specification (Consider wheel upgrade).

**Cost**

• Adjust dressing parameters;
• Check coolant performance;
• Optimize process arrangement;
• Change wheel specification (bond / grain / porosity) to allow fast process and low wheel wear;
• Avoid loading or burn or chattering;
• Adjust feed rate for better productivity, lower wheel wear rate and less change over requirement.
3.6 Summary of Knowledge Base Construction

The construction of this knowledge base is illustrated in this section. This knowledge base is constructed based on integrating of heuristic knowledge, most of which from expert knowledge and literature. Content wise, the grinding wheel condition is adopted to abridge the performance measures and process input parameters, thus monitoring and diagnosis can be realized. The grinding wheel condition here includes three issues, loading, glazing and over-worn. Once the signal is characterized, by comparing the datasheet with the knowledge base, the grinding wheel condition can be identified. Then the performance measurement is predicted and the suggestions on modify process parameters are generated. Therefore, with this knowledge base, the monitoring and diagnosis of the process has become possible.
4 Implementation

As the method that how the OD plunge grinding process can be analyzed with the method of Signature Analysis, this chapter introduces the implementation of the method. As mentioned, the analysis begins with signal characterization and can provide suggestions to the grinding process. These functions can be implemented through the development of the software tool. This chapter provides an introduction to the framework, operation flow chart and interfaces of this software tool.

4.1 Framework

Corresponding to the structure of this analysis work, the software also consists of two modules, the Signal Processing and Checklist. The framework of operations can be illustrated in the figure below by terms of input, characterization and output. The Signal Processing module covers operations from the Input towards the datasheet and special plot functions in the Output box. While the wheel condition analysis and checklist from the Output box are incorporated in the Checklist module.
In the “Input” box, there are items classified into two groups, mandatory input and optional input. As mentioned before, this software processes grinding power signal. Thus, the power signal is required to perform subsequent process with. The configuration file, also listed in the mandatory input, is a file that user generates in this software to help the software computer understand the signal.

In the “Input” box, there is also a group of input items marked as optional, including the feed signal, “Pick Control Points” and “Cycle Information”. Those items can enhance the performance and extend the capability of the signal processing module.

Different inputs are corresponding to different signal processing options in the middle box, named as “Signal Processing”.

On the right hand side of this figure shows the box of “Output”. The most straightforward output item is the datasheet extracted from the signal. Besides that, the software
offers two special plot functions, Power vs Material Removal Rate and the Superimpose of power by cycle. By comparing the calculation result with the built-in pattern, an understanding of the grinding process can be obtained and suggestions can be generated.

4.2 Capability and Limitations

The software implements the algorithm described in Chapter 3. As specified, the process requires the signal to comply with certain requirements. In the case that feed data is available, three types of grinding cycle can be characterized. While in the case that feed is not available, only the type of grinding cycle consists of roughing and spark – out is acceptable.

There are some requirements towards the feed, when available, to assure correct characterization process.

- Wrongfully mounted direction is tolerable. The program requires the direction that the grinding wheel approaches the workpiece as the positive direction; vice as the negative direction. However, if the sensor is mounted otherwise, it will not be otherwise. This situation is commonly seen and addressed by this software by simply introducing a coefficient to adjust the data to obtain the right direction.

- Offset is tolerable. It is acceptable that the “floor”, which refers to the original position of the grinding wheel, is not represented by zero in the data since the program provide a calibration function to offset the floor to the zero point. However, the offset parameter needs to be carefully designated, under – offsetting does not render the original position with zero point; while on the other side, over - offsetting
leads incorrect cycle starting time. In the case that feed still remains on the zero floor after the engagement between the wheel and work piece, error may occur.

- Drifting is not tolerable. The coefficient and calibration function can help adjust the feed data effectively only if no clear drifting is present. The grinding wheel should return to the same position after every cycle and thus the feed data should share the same floor. Otherwise, not only the cycle separation may not be correct, the validity calculation result related to feed data becomes voided.

- Noise level on the feed data should be limited. It is assumed that the vibration commonly presented in the power signal rather than the feed signal. To assure correct characterization, the profile of feed data should be identifiable and there should not be any local fluctuation, a result which is hard to achieve with filters. The high frequency noise is not tolerable on the feed data since the characterization is based on the profile of the data and high frequency noise is the greatest barrier to present the profile from being identified.

For the data without feed data, the type of grinding cycle for characterization is limited to roughing \(\rightarrow\) spark – out. Similarly, some requirements apply, described as follows.

- Drifting is not tolerable. As the case where feed data is applicable, drifting is not tolerable. The presence of drifting leads to not only the inaccurate cycle separation result but also incorrect calculation result.

- The profile should comply with the roughing \(\rightarrow\) spark – out type. In this type of grinding cycle, power remains still until the wheel engages with the workpiece, where a spike on power data is formed, followed by the roughing state, which consists of a
bank of increasing and a plateau. After which, there is a spark – out stage.

Unexpected profile may lead to incorrect characterization result or even provoke exceptional error in the program.
4.3 Operation Flow Chart

To elaborate the operation and functions of this software, the following flow chart is provided.

Figure 4-2 System Flow Chart of the Software Tool
4.4 Interfaces

The software tool is implemented with two modules and multiple subsidiary graphical interactive interfaces.

4.4.1 Starting Interface

Once the software is executed, the starting interface is generated, shown in Figure 4-3. This interface includes three executable buttons and an image that indicates the fundamental information of this program.

![Starting Interface](image)

Figure 4-3 Starting Interface

The image includes the information of title, developer and version information. In this figure in particular, it displays the “Signature Analysis for OD Plunge Grinding
Operations” as the title and indicates the developer as CAM Lab at WPI with “0.85 Beta” as the version number.

The three buttons at the bottom, “Signal Processing”, “Checklist” and “Exit”, provide access to three functions from this page. “Signal Processing” and “Checklist” button trigger two main modules of this program that process the grinding signal and help analyze the grinding process respectively. Clicking on the “Exit” button will close the whole software.

4.4.2 Signal Processing Module

This module incorporates the import, processing, visualization, characterization and output of signal. It consists of multiple interfaces, including the main interface, where most of the operations are accessed and viewed, and two types of special plot functions.

4.4.2.1 Main Interface of Signal Processing Module

By clicking the “Signal Processing” button from the starting page, the signal processing module can be initiated, as shown in Figure 4 – 4.
Figure 4-4 Signal Processing Module Initial Status

Legend:

1. Menu and Toolbar Group
2. Signal Handling Group
3. Plot Selection
4. Plot Window
5. Characterization Option 1: Primary Characterization Group
6. Characterization Option 3: Semi-auto Characterization Group
7. Characterization Option 2: Auto Characterization
8. Special Plot Group
9. Datasheet Display and Export Group

Legend Explanation:

1. Menu and Toolbar Group
Three items are included in the menu, File, Config (Abbreviation for Configuration) and Help.

File: Load signal file, reset the program, and exit

Config: Configuration related operations, run configuration interface, load configuration file, view configuration file

2. Signal Handling Group

Four buttons related to handling of signal import are grouped together, including load signal file, run configuration interface, load configuration file and spectrum analysis interface.

3. Plot Selection

This is a pop–up menu for plot selection. User is able to select the initial, previewed, filtered and characterized signal as well as the spectrum display.

4. Plot Window

Signal is plotted in this window corresponding to selection of item 3.

5. Characterization Option 1 : Primary Characterization Group

This option requires user to know some of the specifications of the grinding process and the signal, including sampling period and duration of each stage. After setting the cycle information, the software characterizes the grinding signal based on the user input cycle information.

6. Characterization Option 3 : Semi–auto Characterization Group

In this option, the user does not need to know the information about the grinding process and signal beforehand. However, user needs to select the control points from
a sample cycle to define the grinding process. Characterization is performed based on user defined result.

7. Characterization Option 2: Auto Characterization

In this option, user does not need to perform any extra input work but rely on the software to perform the characterization automatically.

8. Special Plot Group

In this group, two plot functions are provided, the Power vs. MRR and Power Superimpose by cycle.

9. Datasheet Display and Export Group

Once the characterization is performed, the result datasheet will be displayed in this part and can be exported to an excel file.

4.4.2.2 Special Plot Function Interface

The two types of special plot interfaces, the Power vs. MRR and Power Superimpose functions are presented in this section.

The Power vs. MRR plot interface consists of two plot windows. The upper window is for preview of the power data in any specific cycle. Once the curve is confirmed as the interest cycle, the Power vs. MRR is plotted in the lower plot window and color coded to facilitate the comparison. The plot for each cycle can also be exported to Excel format through the “Data Output” button located below the “Value Summary” panel that facilitates further analysis.
The interface of Power Superimpose share a great amount of similarity that involves designation of interest cycle, interface design style, functions, etc..

Figure 4-5 Special Plot Interface - Power vs. MRR

Figure 4-6 Special Plot Interface - Power Superimpose
4.4.3 Checklist Module

This module implements the proposed idea of utilizing grinding wheel status as a gateway to study the correlation between input and output of the grinding process. This module incorporates a built-in knowledge base.

4.4.3.1 Main Interface of Checklist Module

The main interface of this module is initiated once the button “Checklist” on the starting interface is clicked. The initial interface of the Checklist Module is shown in the following figure.

![Checklist Main Interface](image)

Figure 4-7 Checklist Main Interface

Legend:

1. Title
2. Wheel Condition Estimation Group
3. Output Prediction
4. Suggestions
Introduction to Interface:

1. Title: title as displayed as “Checklist”.

2. Wheel Condition Estimation Group

   Grinding wheel related functions are arranged, including a pop-up menu to select the grinding wheel status; an “Explanation” button to provide text instruction for each status; and a “Wheel Condition Analysis” button to activate wheel condition estimator.

3. Output Prediction

   Impact of the grinding wheel issue on output can be displayed by clicking on each of the three radio buttons in this group.

4. Suggestions

   Suggestion corresponding to accuracy, surface quality or economic output can be generated by selection the radio button in this group.

5. Exit Button: Execution of this button aborts this interface.

6. Version Information

7. Content Display Window

   Once the condition of grinding wheel is identified, clicking on the corresponding radio button on the left side will display the content in this window to present the content from the knowledge base. Thus, estimated output and suggestions are provided.

4.4.3.2 Wheel Condition Estimation Interface

The wheel condition estimation interface can be accessed from the main interface of the Checklist Module, shown in Figure 4-8.
Figure 4-8 Wheel Condition Analyzer Starting Interface

Legend:

1. Title
2. Wheel Condition Selection Menu
3. Explanation
4. Datasheet Display
5. Power vs MRR Plot Windows

Introduction to Interface:

1. Title: title as displayed as “Checklist”.
2. Wheel Condition Selection Menu
3. Explanation button: Provide text instruction for the corresponding issue selected.
4. Datasheet Display:
   The datasheet uses the same pre-defined values as defined earlier. However, content in this table can be classified into two groups, the theoretical pattern and
measurement. For each grinding wheel issue mentioned above, there is a corresponding pattern represented with the pre-defined datasheet. To the right of the theoretical pattern, there is characterization result. By comparing the theoretical pattern with the real measurement result, grinding wheel status can be estimated.

5. Power vs MRR Plot Window

As compared to the datasheet, the Power vs. MRR plot also incorporates a comparison between theoretical pattern and the real measurement. The upper window represents the theoretical pattern of given wheel status while the lower window provides a plot function for the characterized signal.

The estimation of wheel condition can be drawn from two facts, matching the characterization result from measurement data with the pattern of corresponding wheel issue, and the pattern of Power vs. MRR plot, both of the facts are provided in this plot.

As mentioned, the datasheet can be classified into the theoretical pattern and measurement result. To be more specific, as shown in the following figure, the theoretical pattern includes pattern in one cycle and the possible changing trend of each item. In the classification of measurement, the mean value and changing trends among cycles of each item are included.

![Figure 4-9 Datasheet Classification](image)
The following figure presents an example of the datasheet with theoretical pattern on the left columns and measurement result on the right.

![An Example of Datasheet with Theoretical Pattern and Measurement](image)

Figure 4-10 An Example of Datasheet with Theoretical Pattern and Measurement

The interface also provides a function to plot Power vs. MRR for two cycles, the cycle number can be specified through this interface and plotted on the lower right corner, while the theoretical pattern is presented on the upper right corner. Based on the comparison between the two plots, combined with the comparison between measurement and theoretical pattern, the estimation of grinding wheel condition can be drawn.
5 Conclusion and Future Work

This chapter provides a summary of this thesis, including the current achievements and future work.

5.1 Current Achievements

Currently, a standard method to process grinding power has been established and a software tool is developed to implement this thought, including techniques of noise reduction, spectrum analysis, visualization and characterization. The characterization significantly reduces the work load of engineers and realizes the plot of power vs. MRR. Also, this characterization result reduces subjectivity in the analysis procedure and provides engineer with a common foundation for discussion.

Additionally, with the characterization result, the software can provide assistance in estimating grinding wheel status by inquiring its built – in knowledge base. Then, the output is predicted and suggestions are generated for given wheel issue for reference.

About the wavelet study, it is noticed that wavelet can be utilized to reduce noise, to process the grinding signal effectively, and identify chatter on power signal, referring to Appendix A.
5.2 Future Work

The existing knowledge only incorporates a limited amount of knowledge and is far from being comprehensive. Further studies on the mechanisms of grinding processes and more experience with the characterization process may be able to provide more guidelines in the knowledge base.

Also, the existing software tool is an off-line analysis tool. In order to diagnose the operation in a better manner, it is better to develop an on-line characterization system so that this software tool may have more access to the grinding process, expecting more interference and capability towards the grinding operation.
References


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Appendix A: An Application of Wavelet Analysis to Grinding Process
Appendix B: Software Tutorial