A Dissertation

entitled

Theoretical-Experimental Study of Fluid Delivery and Heat Management in Grinding

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Doctor of Philosophy Degree in Engineering

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August 2015
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Grinding is a machining method by using abrasive grain acting on the workpiece surface, especially important in the precision machining field. High energy is generated by removing material per unit volume during the process. Almost all the energy is converted into heat and concentrated in the grinding zone by cutting and rubbing, causing the grinding zone temperature rise sharply, and form great temperature gradient in the vicinity of ground workpiece surface. If the grinding temperature is above a certain threshold, it can cause surface thermal damage, such as burns, material oxidation, surface residual stress and crack, etc., thus affecting the service life and work performance of the workpiece. At the same time it can also affect the service life of the grinding wheel. The main functions of fluids is cooling, lubrication, cleaning, chip removing and antirust. To eliminate the influence of heat generation in grinding, the grinding fluid are used in this complex process. The cooling and lubricating capability of grinding fluid plays a decisive role.

This project builds comprehensive theoretical models centered on the fluid and heat transfer in grinding and a semi-empirical force model based on the analysis of specific grinding energy. In these models, the grinding parameters are taking into account.
These models are validated experimentally using experimental data. Using the improved prediction capabilities, new and significant knowledge will be gained about the grinding process, thus leading to superior manufacturing decision making.
For my family and my best friends
Acknowledgements

First of all, my sincere gratitude goes first and foremost to Dr. Marinescu, my advisor, for his constant encouragement and guidance. He has walked me through all the stages of designing these experiments, solving the problems and writing of this dissertation. Without his instructive advice and illuminating suggestion, this dissertation could not have reached its present form.

I should give my hearty thanks to Dr. Cioc. For his invaluable help and patient instructions on Computational Fluid Dynamic (CFD) and heat transfer field.

I would like to thank Dr. Afjeh, Dr. Sheng and Dr. Lipscomb for being committee member. Thanks for giving me useful suggestions on my dissertation.

I also would like to deeply thank to Mr. Todd Gearig. For his grateful help for manufacturing the workpiece and manipulation of the machine in the experiment.

A special acknowledgement to Dr. Weismiller of Master Chemical Corporation for providing the grinding fluid.
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Chapter 1

Instruction

1.1 Grinding Applications

With the development of science and technology, the industry has higher requirements of surface quality and performance of all kinds of industrial products. Grinding, as a kind of precision machining method, must constantly make improvement to the theory. Grinding fluid and temperature fields, which are important parts of the theory of grinding, play an important role on the workpiece surface quality. Especially the research of cooling and lubrication mechanism of the grinding fluid in the grinding contact zone will help improve the fluid and temperature fields’ theory.

There is a relative motion between grinding wheel and workpiece in the grinding process. The abrasive grains, which are distributed on the peripheral surface of the grinding wheel, cutting on the workpiece produces the grinding surface. There are three stages of the grinding process. First is the sliding stage, the workpiece only has elastic deformation, the abrasive grains’ blade have no cutting actions. Second is the ploughing stage, when the normal stress is more than the workpiece yield stress, the cutting edges are pressed into the plastic body. The deformed metal is pushed to the side and ahead of the abrasive grains by the plastic deformation, eventually leading to surface uplift. The
third one is the chip formation stage. In the sliding and ploughing stages, no chips are produced by the abrasive grains. Therefore, there is a critical grinding depth to cut the metal and produce chips. When the abrasive grains’ cutting thickness is lower than the critical grinding depth, the abrasive grains’ blade slides on the surface instead of cutting. Critical grinding depth is related to the grinding wheel speed, workpiece feed rate, abrasive grains’ blade etc.

1.2 Grinding Fluid Applications

Due to the grinding fluid application, a third kind of boundary condition, surface heat transfer, is added to the grinding temperature field. Grinding fluid takes away a large amount of heat energy, which decreases the grinding temperature in the contact area. On the other hand, grinding fluid has cleaning, lubrication functions on grinding wheel, which decrease the grinding force, producing lower heat energy and decreasing the grinding temperature.

1.2.1 Grinding Fluid Functions

The application of grinding fluid in the grinding process is very critical for the surface quality of the workpiece and the life span of the grinding wheel. The multiple functions of grinding fluid can be grouped in four main categories: cooling, lubrication, flushing away of swarf and dislodged wheel grits. The grinding fluid must provide direct cooling to the grinding contact zone, absorbing and transporting the heat generated during grinding process. Grinding fluid is applied to the grinding zone to limit the heat generation. The lubricating effect of grinding fluid is used to reduce friction between the
abrasive grain and the workpiece, as well as between the bond and the workpiece. Grinding fluid plays an important role in the manufacture industry. Correct application normally results in enhanced process stability, better workpiece quality and increased tool life.

1.2.2 Grinding Fluid Types

Grinding fluid is commercially available with different property profiles to meet the requirements of specific machining tasks. It can be divided into two main kinds: water-based grinding fluid and oil-based grinding fluid.

1.2.2.1 Water-based Grinding Fluid

Water-based grinding fluid is mixed with water. Usually the concentration is 10%. With plenty of water to dilute, it overcomes the problems of oil based fluid, such as flammability and cleanability. But water-based grinding fluid can make the machine and workpiece rust easily. It has three main types: synthetic, semi-synthetic and emulsion. Synthetic is mainly for the application which needs better cooling performance. Semi-synthetic is multi-purposes, broadly application, good stability and longer life. Emulsion is a traditional type, lower cost, with lower stability, lower lifetime, and difficult to maintain.

1.2.2.2 Oil-based Grinding Fluid

Oil-based grinding fluid has a good lubrication function, but the cooling capability is worse than water-based grinding fluid. It is usually applied on a low cutting
speed. It can lengthen the service life of the tools and improve the surface quality of the workpiece. But in the high speed and heavy cutting processes, it can deteriorate the sanitation with the unpleasant odor, and also cause fire.

1.3 Previous Studies of Fluid Flow in Grinding

In the grinding area, air and fluid compose a very complicated flow field. In the practice, only a few of the fluids can go inside the contact area between the workpiece and grinding wheel. How to improve the useful flow rate of the grinding fluid is a difficult process. In other words, let more grinding fluid go through the contact area as far as possible, increase the percentage of the grinding fluid with real cooling and lubrication function. To achieve this goal, we need to build a model of the fluid flow field.

Guo and Malkin [1] used mass conservation function and momentum conservation function to build a mathematic model considering the effect of grinding wheel porosity. In this theory, they calculated the permeate depth of grinding fluid in the wheel and pointed out that the porous wheel has the function of pumping the grinding fluid into the grinding area. Chang [2] considered the effect of porosity, built a model of creep-feed grinding with conservation function. He pointed out that the dynamic pressure increases with the increase of the amount of grinding fluid application. Lin and Satoshi [3] used Reynolds and Laplace equations to build a fluid flow equation and got the analytical solution of the computational dynamic fluid pressure. Zhang and Akiyama [4] measured the depth of permeate in the experiment and had a relationship between the permeate depth and the maximum grinding temperature. Through the above theoretical and experimental analysis, we conclude that the grinding fluid initially enters into the porous
wheel and moves with the grinding wheel, getting through the grinding contact area. When the grinding wheel leaves the contact area, the fluid gets out of the porous area and no longer moves with the grinding wheel. Schumack [5] derived a surface grinding flow equation based on the steady, incompressible Navier-Stokes equation with the effect of inertia. They proposed that the lubrication theory is only useful for the low Reynolds flow. Mihić [6, 7] built a model of the grinding contact area and its vicinity with complex fluid and solid physical properties, used to analyze in detail the abrasive contact region. The grinding contact area between the grinding wheel and workpiece surface is modeled as a porous zone, corresponding to the abrasive contact. Computational fluid dynamics (CFD) is used to study the fluid flow in grinding.

1.4 Previous Studies of Grinding Temperature

Almost all the work of the grinding is converted into heat energy. The energy transfers on the grinding wheel, workpiece and chips. Because usually the depth of cut in grinding is shallow, the heat energy is accumulated in the surface layer instead of transferring into workpiece interior, then it comes into being high temperature. The heat energy has great influence on the workpiece surface quality and usability. Especially when the temperature exceeds a certain threshold, it causes the surface thermal damage (surface oxidation, burn, residual stress and crack). It decreases the wear and fatigue resistance ability of the workpiece, thus leading reduction in the reliability and service life of the workpiece. In addition, the accumulated temperature can affect the dimensional and shape accuracy in the grinding periods. On the other hand, the grinding heat generated in the contact area between workpiece and grinding wheel not only affect the
workpiece, but also affect the service life of the grinding wheel. Therefore, the research of the distribution of the temperature on the workpiece is to study the grinding mechanism and improve the ground workpiece surface integrality. To decrease the temperature in the contact area, the grinding fluid application is the most used method. When the fluids enter inside the grinding contact area, the temperature field has an additional third kind of boundary condition: the heat transfer between workpiece surface and the grinding fluid. Grinding fluid takes away most of the generated heat energy, which decreases the temperature on the temperature field.

1.4.1 Analytical Studies

Grinding heat energy is from the consumption of grinding power. Most of the heat energy is taken away by the workpiece, grinding fluid, grinding wheel and chips. A special attention should be focused on heat energy on workpiece, which is the main reason for the grinding temperature increasing and thermal damage. As a result, previous researchers had lots of study on grinding heat transfer in the grinding area.

In 1942, J. C. Jaeger [8] first proposed the theory of a moving heat source. For the grinding process, the moving heat source model is a good theoretical basis. Based on the shear plane moving heat source theory, Outwater and Shaw [9] established the heat source model of heat transfer in the workpiece. At the same time, the model was validated by the experiments with a thermocouple temperature measurement method. Hahn [10] proposed a theory that the grinding heat energy is produced by the abrasive grain wear flat. Indeed, heat generation can be accurately described by the force of abrasive grain wear flat and ignore the force of shear flat. In 1970, Ruisseaux and Zerkle
improved Jaeger’s model, the cooling effect of coolant on the grinding surface is superimposed on the thermal model. In this model, assume that part of the heat energy generated by the abrasive grain contact area can be taken away by the grinding fluid. If the fluid transmission speed is fast enough, the heat energy has not enough time to go deep inside the workpiece and is taken away by grinding fluid, the grinding temperature will not be very high. Howes [12] found when the grinding zone temperature exceeds grinding fluid boiling temperature, grinding fluid boiling film seriously reduces the cooling efficiency. He concluded that the role of the grinding fluid is its effective lubrication performance which reduces the grinding force and temperature. Malkin [13] carried a detailed elaboration on the grinding heat theory of metal material, the shear energy in the chip deformation energy is approximately equal to the melting energy per unit volume of the workpiece; almost all the ploughing and sliding energy is in the form of heat energy into the workpiece, only 55% of the chip deformation energy into the workpiece. Shafto [14] proposed that in creep feed grinding, the fluid convection cooling is a key factor in the grinding process, and sometimes, the heat energy taken away by the fluid convection cooling is more than sum of the others. But he also pointed that when the fluid is boiling, the taken away energy is reduced.

1.4.2 Previous Grinding Temperature Measurements

It is extremely important for obtaining the distribution of temperature in the grinding zone to analysis the mechanism of the grinding thermal damage. The temperature measurement is the precondition for comprehending the mechanism of thermal damage and improvement of the surface quality. So far, there are already many
kinds of methods for measuring the grinding temperature. Thermocouples and optical technique are the two main methods for measuring the grinding temperature.

1.4.2.1 Thermocouples Measurement

There are several methods of setting up a thermocouple within a workpiece to measure the temperature in the grinding contact zone. There are three main kinds: Conventional double-pole thermocouples, grindable double-pole thermocouples and single-pole thermocouple.

The usual configuration of the double-pole thermocouple is shown in Figure 1-1 [15]. This technique is to insert the thermocouple blow the workpiece. The thermocouple has a standard calibration and usually provides a good temperature signal. However, this thermocouple measures temperature below the workpiece surface, this is a potential source of inaccuracy.

The grindable double-pole thermocouple as shown in Figure 1-2 can be machined at the workpiece surface [16]. Two sheet metal and mica film is placed overlapping. The insulation of the mica sheet makes metal and workpiece not conductive. When grinding, the heat can melt the metal and workpiece together to be a circuit. According to the thermal current intensity of contact surface, the grinding temperature can be obtained. Compared with double-pole thermocouple, the technique’s advantage is grindable. But increasing the number of layers involved in the double-pole arrangement increases the size of the assembly. Also the mica is fragile; it is not easy to keep it insulated.

The single-pole thermocouple is shown in Figure 1-3 [17]. Compared to double-pole thermocouple, this technique is easier to assemble. With the heat generated during
the process, the thermocouple and workpiece melt together to be a circuit. The principle is similar to grindable double-pole thermocouples. But the temperature that we get is the temperature of the ground thermocouple, not exact temperature of the ground workpiece surface. Also in wet grinding, the fluids can disturb the measurement, making a short circuit under the junction area. If the insulation is broken, it will be hard to get the temperature signal.

Figure 1-1: Double-pole Thermocouple [15]

Figure 1-2: Grindable Double-pole Thermocouple [16]
1.4.2.2 Optical Measurement

Figure 1-4 shows the optical technique grinding temperature measurement [18, 19]. A thermo-camera can record the thermal distribution on the side of the workpiece. The specialty of this device is that the whole grinding process can be obtained directly from the image of temperature distribution. The defect is that the thermal distribution image is on the side of the workpiece which cannot give the accurate temperature distribution inside the grinding contact zone.

1.4.3 Computer Based Simulation of Grinding Temperature Field

The computer simulation is a technical method which is based on mathematical or physical models according to a certain grinding condition [20-23]. Through the simulation, without actual experiment involved, the simulation results can be used to infer, estimate, and evaluate the performance of the grinding system according to some
certain grinding conditions, analyzing the effect of different grinding conditions on the temperature field. At the same time, the initial simulation is based on the experiment results.

Computer simulation has the following significant effects for the research of grinding temperature field:

(a) By the computer simulation of various grinding processes, it can get a simulated result close to the experiment one which is time consuming.

(b) Compare the experiment results with the computer simulation, and then to explore the rationality of the theory, to determine the relationship between the various influence factors in the grinding process.

(c) Forecast all sorts of problems that may occur during the grinding process, and put forward to corresponding solutions.
Suto [24] proposed an empirical simulation model of grinding process and had good results corresponding to the experiments. But the size of the abrasive grains were not involved in this model. Steffens [25] had a concept of digital simulation of grinding movement, simulating one abrasive grain movement. But the cutting of the abrasive grain did not involve sliding and ploughing, and the material removal rate is constant. Chiu [26] had a comprehensive study of the grinding process, proposed a model with the time function. But this model ignored the effect of the grinding wheel and abrasive grains size. Malkin [27] had research of energy conversion, the change of the grinding force, grinding area temperature, precision grinding and surface quality by using the computer simulation technology, and had a lot of valuable conclusions.

1.5 Previous Research of Grinding Energy Partition

In grinding heat simulation, how much heat is produced during the process and how much percentage of the generated heat is conducted into the workpiece is a key issue. Namely, the energy partition ratio $\varepsilon$.

In grinding processes, the energy partition ratio is a variable. It is related to the material of grinding wheel, workpiece, workpiece feed rate, grinding wheel speed and depth of cut. It is a very complicated problem and the following are the previous theoretical models of energy partition.

1.5.1 Dry Grinding Energy Partition Model

Ramanath [28] proposed a simplified grinding energy partition model about surface grinding. In this model, for the shallow grinding, the depth of cut is small and the
heat taken away by the chips can be neglected. This grinding heat model can be assumed as a uniform heat source moving between two stationary surfaces. A hypothesis is based on the temperature matching at the grinding zone. It assumes that the energy partition to the workpiece is constant along the grinding area. According to the hypothesis, the average temperature of the workpiece surface is equal to that of the grinding wheel surface. An energy partition equation is:

$$\varepsilon = \left(1 + \frac{(k \rho c)_s}{(k \rho c)_w}\right)^{-1}$$

where $\varepsilon$ is the ratio of energy partition, $(k \rho c)_s$ and $(k \rho c)_w$ are the average thermal properties of grinding wheel and workpiece material. The subscript $s$ stands for grinding wheel and $w$ for workpiece.

This model is regarding to the average thermal properties. The constant energy partition along the grinding area is assumed and no grinding parameters – grinding wheel speed, workpiece feed rate and depth of cut – are involved in this model. This model simplified the grinding processes but can only be used for estimating the energy partition ratio and in qualitatively analyzing the energy partition.

1.5.2 Abrasive Grains Grinding Energy Partition Model

Outwater [29] presented that the grinding heat generated by the friction between the abrasive grain and workpiece surface is composed by three parts.

(a) The interface between the abrasive grain wear plane and workpiece surface.

(b) The shear plane of the grinding chip

(c) The interface between the abrasive grain and grinding chip
The generated heat is conducted into the workpiece and abrasive grain through these surfaces.

Hahn [30] revised this model. The abrasive grain is assumed to slide on the smooth surface and the tangential force acting on the shear plane can be neglected. In this model, the grinding heat is generated from the contact area between the workpiece and abrasive grain, namely, the grinding heat is produced on the abrasive wear plane. Eq. (1.2) is the energy partition equation which represents the percentage of the grinding heat conduction into the workpiece.

\[
\varepsilon = \left(1 + \frac{k_g}{(r_0 \cdot V_s \cdot (k \rho c)_w)^{0.5}}\right)^{-1}
\]  

(1.2)

Rowe [31-34] revised this model by analyzing the energy partition in four different grinding heat transfer models. Using the maximum and minimum energy to calculate the grinding temperature, these models considered the effect of the grinding wheel. Then Rowe combined these four models together, assumed the contact area as a series of discrete abrasive grains to obtain an easier, more accurate mathematic model.

\[
\varepsilon = \left(1 + \frac{0.974k_g}{(r_0 \cdot V_s \cdot (k \rho c)_w)^{0.5}}\right)^{-1}
\]  

(1.3)

where \(k_g\) is the grinding abrasive grain heat conductivity coefficient, \(r_0\) is the effective contact radius of grinding abrasive grain, \(V_s\) is the grinding wheel speed.

1.5.3 Energy Partition Model Including the Grinding Fluid Impact

Guo [35, 36] revised Rowe’s model based on the dry grinding energy partition. This model considers the effect of grinding fluid. By considering the percentage of heat
conduction into the grinding fluid and abrasive grain respectively. Guo proposed a complex mathematics model including workpiece feed rate and depth of cut.

\[
\varepsilon = \frac{1}{1 + 1.06A \left( \frac{(k \rho c)_s}{(k \rho c)_w} \right)^{0.5} \left( \frac{r \pi a_g l_c C_a}{2AV_w} \right)^{0.5}}
\]  

(1.4)

where \( \gamma \) is the geometric coefficient of abrasive grain, \( a_g \) is the heat diffusion of abrasive grain, \( l_c \) is the contact length, \( C_a \) is the effective number of abrasive grain per unit area on grinding wheel surface, \( V_w \) is the workpiece feed rate and \( A \) represents the percentage of abrasive grain wear.

1.5.4 Energy Partition Model Composite Grinding Fluid and Abrasive Grain

Lavine [37, 38] assumed that the grinding wheel is a composite of the grinding fluid and abrasive grain, the grinding fluid is considered to be a composite factor in the grinding contact area. The generated heat is conducted to the grinding wheel surface, workpiece and grinding fluid.

The heat conduct into the workpiece is \( Q_w \):

\[
q_w = \frac{1}{2} (T_m b) \left( 2(k \rho c)_w \cdot V_w \cdot l_c \right)^{0.5}
\]  

(1.5)

The heat conduct into the grinding wheel is \( Q_s \):

\[
q_s = \frac{1}{2} (T_m b) \left( 2(k \rho c)_s \cdot V_s \cdot \frac{A_r}{A_n} l_c \right)^{0.5}
\]  

(1.6)

where \( T_m \) is the melting point temperature of the workpiece, \( A_r \) is the contact area between abrasive grain and \( A_n \) is the geometric contact area between grinding wheel.
In dry grinding, \( A_r / A_n << 1 \). The energy partition is:

\[
\varepsilon = \frac{q_w}{q_w + q_s} = \frac{1}{1 + \left( \frac{(k \rho c)_s \cdot V_s \cdot A_r}{(k \rho c)_w \cdot V_w \cdot A_n} \right)^{0.5}}
\]  

(1.7)

In wet grinding, the energy partition is:

\[
\varepsilon = \frac{q_w}{q_w + q_s} = \frac{1}{1 + \left( \frac{(k \rho c)_s \cdot V_s \cdot A_r}{(k \rho c)_w \cdot V_w \cdot A_n} \right)^{0.5} + \left( \frac{(k \rho c)_f \cdot V_s}{(k \rho c)_w \cdot V_w} \right)^{0.5}}
\]  

(1.8)

Grinding process is influenced by many factors: thermal properties of grinding wheel and workpiece material, machining parameters and the grinding fluid application. Relatively, dry grinding condition is easier to calculate. For wet grinding, more factors need to be taken into account. More concrete analysis is needed to make simulation results according to the actual grinding conditions.

1.6 Previous Studies of Grinding Forces

At present, most of the physical modeling of the grinding process still stays on one-factor model and the effect of this factor on the quality of the machined workpiece. The most two important factors in the grinding process are temperature and force. There are two main directions to build a force model: analytical method and experimental method.

1.6.1 Analytical Method

Malkin [39], based on relations between workpiece and wear flat area on the grinding wheel, decomposed grinding force into two main parts: cutting deformation
force and sliding. Werner [40] built a mathematic model focused on the geometric distribution of the abrasive grains on the grinding wheel and the kinematics of the grinding process. Li [41] developed a grinding force model from the Werner’s that takes friction and chip formation into account; here they separate out the effects of chip formation and frictional forces. Nakayama [42] developed the relationship between the force and elastic deflection of the wheel. Experiments were conducted to measure the deflection associated with the individual grains. Tonshoff [43] built a model from the comparison of a number of chip thickness models. These models include one, two and three dimensional descriptions of the wheel surface as well as each grain in the contact area involved in the chip formation process. Agarwal [44] developed a model based on a new analytical undeformed chip thickness model. This new analytical undeformed chip thickness model is developed on the basis of stochastic nature of the grinding process, governed mainly by the random geometry and random distribution of cutting edges.

1.6.2 Experimental Method

Tang [45] achieved a formula for calculating the chip formation force proposed by analyzing the relationship between specific chip formation energy and chip formation force. Durgumahanti [46] developed a grinding force model by incorporating the effects of variable coefficient of ploughing and sliding force. This is based on the fact that the chip formation during grinding consists of three stages: ploughing, cutting and sliding. All the coefficients were determined experimentally by performing grinding tests at specified conditions. Fuh [47] used BP neural network to simulate and forecast grinding
force in creep feed grinding, improving it with an error distribution function. This can solve the convergence problem and increase the rate of convergence.

1.7 The Research Purpose for This Project

This project builds four comprehensive theoretical models centered on the airflow, grinding fluid, heat transfer and force in grinding. These models are validated experimentally using experiment data. Using the improved prediction capabilities, new and significant knowledge will be gained about the grinding process, thus leading to superior manufacturing decision making. Four types of grinding fluid are carried out in the experiment. Temperature, force and roughness were maintained with different grinding conditions. Two kinds of index are introduced to describe the performance of the grinding fluids with two step experiments.
Chapter 2

Grinding Fluid Parameter Measurement

In this project, the physical properties of grinding fluid are needed. There are many kinds of physical properties of grinding fluid, such as density, viscosity, PH value, specific heat capacity, surface tension, boiling point and flash point. Some of the physical properties are provided by the grinding fluid manufacturer, but some are not. So in this chapter, the specific heat capacity and surface tension measurement are introduced.

Four kinds of grinding fluids are tested in this experiment which is provided by Master Chemical Corporation: TRIM® C270, TRIM® SC520, TRIM® E906 and TRIM® MicroSol® 585XT (The name of the grinding fluids are abbreviated as C270, SC520, E906 and 585XT respectively in the following description). These types of grinding fluid are commercially available and represent different categories of grinding fluids: semisynthetic, emulsion, synthetic, and micro-emulsion (See Table 2.1).

C270 is a state-of-the-art synthetic grinding fluid. C270 provides excellent cooling and chip setting, good tramp oil rejection and machine cleanliness. C270 is compatible with a very wide range of materials, including cast iron, steels and copper alloys, plastics and composites, providing excellent corrosion inhibition on all common ferrous and nonferrous alloys.
Table 2.1: Physical Information of Four Grinding Fluids

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>TRIM® C270</th>
<th>TRIM® E906</th>
<th>TRIM® MicroSol® 585XT</th>
<th>TRIM® SC520</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Colorless</td>
<td>Brown</td>
<td>Amber</td>
<td>Blue</td>
</tr>
<tr>
<td>Color of Working solution</td>
<td>Colorless</td>
<td>Milky White</td>
<td>White Microemulsion</td>
<td>light Blue</td>
</tr>
<tr>
<td>Odor</td>
<td>Mild</td>
<td>Mild Amine</td>
<td>Mild</td>
<td>Mild amine</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>102°C</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>pH of Concentrate</td>
<td>9.2</td>
<td>8.8-9.8</td>
<td>9.3-9.6</td>
<td>9.6-10.0</td>
</tr>
<tr>
<td>Flash Point</td>
<td>212 ⁰F</td>
<td>Non-flammable</td>
<td>Non-Flammable</td>
<td>&gt;200 ⁰F</td>
</tr>
<tr>
<td>Titration Factor (CGF-1 Titration Kit)</td>
<td>0.561</td>
<td>NA</td>
<td>0.685</td>
<td>0.648</td>
</tr>
<tr>
<td>Coolant Refractometer Factor % Brix</td>
<td>3.3</td>
<td>0.9</td>
<td>1.2</td>
<td>1.8</td>
</tr>
</tbody>
</table>

585XT is a nonchlorinated semisynthetic grinding fluid. It can extend useful life in cast iron, copper, titanium and aluminum without the need for tank-side biocides or fungicides.

E906 is low-foaming emulsion. It delivers consistent machining and grinding performance on a wide range of materials and applications. E906 offers a unique blend of both mechanical and extreme pressure lubricity agents.

SC520 is a semisynthetic grinding fluid. It is a general-purpose, cutting and grinding fluid concentrate for the multi-material, multi-operational shop. It has the wetting and cooling characteristics necessary for superior machining results on grinding, milling and turning operations. It also controls chip welding on soft, gummy materials like aluminum.
2.1 Specific Heat Capacity Measurement

Specific heat capacity is the heat capability per unit mass of the material. The specific heat capacity is the amount of internal energy required to absorb or release per unit mass raise or decrease the temperature by one degree Celsius. It is the thermal physical property of the material. Usually it is represented by symbol \( C \). Specific heat is associated with the type and physical condition of the material.

The specific heat capacity of most material is not a constant. In particular, it is dependent on temperature itself, as well as on the pressure and the volume of the material. The Differential Scanning Calorimetry (DSC) is the one of the most common methods...
that is used in the specific heat capacity measurement. It can measure the specific heat capacity of even small qualities. The Perkin Elmer® Pyris 1 Differential Scanning Calorimeter, which measures the temperature related to the internal heat transformation and heat flux, was used in the measurement shown in Figure 2-1. This device has a wide range of applications.

Differential Scanning Calorimetry (DSC) is a thermal analysis method. Figure 2-2 shows principle of acquiring specific heat capacity using DSC. Under the controlled temperature, the device measures the heat conducting into the sample and reference material. $a$ represents the empty pan, $b$ represents the sample, which is the grinding fluid in the measurement. $c$ represents the reference material which is the sapphire in the measurement. X-axis is the temperature changing with time. Y-axis represents endothermic or exothermic rate for empty pan, sample and reference material. Namely,
heat flow rate \( dH/dt \). The measurement conditions for the sample, the reference (a sample with a known specific heat capacity) and the empty pan were the same. The specific heat of the sample was calculated by Eq. (2.1) [48] from the DSC data obtained (\( a, b \) and \( c \) in Figure 2-1).

\[
C_s = \frac{H}{h} \times \frac{m_s}{m_r} \times C_r
\]  

(2.1)

where \( C_s \) is the specific heat capacity of sample, \( C_r \) is the specific heat capacity of reference, \( m_s \) is the weight of sample, \( m_r \) is the weight of reference, \( H \) is the difference of sample and empty pan and \( h \) is the difference of reference and empty pan.

Figure 2-3 shows the heat flow measurement result of the grinding fluid. Based on these measurements, use Eq. (2.1) to calculate the final specific heat capacity of grinding fluid shown in Figure 2-4. The temperature measurement range is from 12°C to 55°C. According to the working temperature, choose the results from 20°C as the grinding fluid.

![Figure 2-3: Heat Flow of the Grinding Fluid](image)

23
specific heat capacity under working temperature. These grinding fluids’ specific energy capacity are used as reference parameters for the following experiment.

2.2 Surface Tension Measurement with Contact Angle

Surface tension is due to the unbalanced molecular attraction effect on any line along the liquid surface. Surface tension is one of the characteristics of the material, it depends on the temperature nature interface.

2.2.1 Contact Angle Measuring Method.

Many kinds of measurements were used by the previous researchers, such as Wilhelmy plate method, spinning drop method, bubble pressure method and drop volume
method. In this project, contact angle measurement are used. Surface tension is calculated by Eq. (2.2).

\[ \cos \theta = 1 + C(\gamma_{LA} - \gamma_{SL}) \]  

(2.2)

In this equation where:

\( \gamma_{LA} \): Surface tension between liquid and gas

\( \gamma_{SL} \): Surface tension between liquid and solid

\( \theta \): Contact angle between liquid and solid

\( C \): Constant

Eq. (2.2) includes four unknown coefficients: \( \gamma_{LA} \), \( \gamma_{SL} \), \( \theta \) and \( C \). The contact angle \( \theta \) can be measured with the contact angle meter, and surface tension between liquid and gas \( \gamma_{LA} \) can be obtained from the previous measured data [49]. All the sample fluids are tested on the same glass plate. The surface tension between liquid and solid \( \gamma_{SL} \) are considered as an unknown constant due to the same solid material. In order to get the

![Figure 2-5: Tantec® Model CAM-MICRO Contact Angle Meter](image)

Figure 2-5: Tantec® Model CAM-MICRO Contact Angle Meter
remaining two unknown coefficients, $\gamma_{LA}$ and $C$, two kinds of liquid were chosen with known contact angle $\theta$ and surface tension $\gamma_{LA}$. Put the data into Eq. (2.2), then $\gamma_{SL}$ and $C$ are concluded. Using Eq. (2.2) with known coefficient, the surface tension can be calculated with measured contact angle.

In this project, Tantec® Model CAM-MICRO Contact Angle Meter was used to measure the contact angle shown in Figure 2-5. This method for measuring contact angles allows you to take direct contact angle measurements, yet eliminates errors associated with arbitrary tangential alignment of a hairline to the droplet image.

The half-angle method is based on the Eq. (2.3) for determining contact angles from the droplet dimensions:

$$\theta = 2 \times \arctan \left( \frac{H}{R} \right)$$  \hspace{1cm} (2.3)

where $\theta$ is contact angle, $H$ is the height of a droplet, and $R$ is the radius of droplet’s base (see Figure 2-6). It becomes apparent from this formula that the angle between a line connecting the contact point $C$ with the apex $A$ of the droplet, and the base line $CO$ itself, is a half of the contact angle. This half-angle, $\theta/2$ can be easily and unequivocally determined using a protractor by aligning the hairline to connect points $A$ and $C$. The dial of the protractor is then calibrated to display the contact angle value which is equal to the doubled value of the angle between lines $AC$ and $OC$, or $2 \times \theta$.

### 2.2.2 Surface Tension Results

The previous researcher, Ham, used Wilhelmy plate method. Under room temperature and standard atmospheric pressure, the surface tension of water and C270 are
72.8 dyn/cm and 41.02 dyn/cm [49]. Also the contact angle of grinding fluid and water are shown in Table 2.2.

Using the method introduced previously, the unknown coefficient $\gamma_{SL}$ and $C$ were obtained, which is 43.1176 and -0.0049 respectively. Using Eq. (2.2) with the known coefficient, the final surface tension of grinding fluids were obtained. Shown in Table 2.2.

![Contact Angle Measurement Method](image)

**Figure 2-6: Contact Angle Measurement Method**

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>C270</th>
<th>SC520</th>
<th>E906</th>
<th>585XT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Angle</td>
<td>64.4°</td>
<td>54°</td>
<td>51.6°</td>
<td>45°</td>
<td>43.8°</td>
</tr>
<tr>
<td>Surface Tension (dyn/cm)</td>
<td>72.8</td>
<td>41.02</td>
<td>39.3</td>
<td>29.25</td>
<td>24.42</td>
</tr>
</tbody>
</table>

**Table 2.2: Contact Angle and Surface Tension Results**

<table>
<thead>
<tr>
<th></th>
<th>C270</th>
<th>SC520</th>
<th>E906</th>
<th>585XT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>989</td>
<td>1035</td>
<td>974</td>
<td>995</td>
</tr>
<tr>
<td>Dynamic viscosity (kg/(m·s))</td>
<td>$1.11\times 10^{-3}$</td>
<td>$1.18\times 10^{-3}$</td>
<td>$1.27\times 10^{-3}$</td>
<td>$1.31\times 10^{-3}$</td>
</tr>
<tr>
<td>Specific Heat (J/(g°C))</td>
<td>2.97</td>
<td>1.62</td>
<td>0.78</td>
<td>2.38</td>
</tr>
<tr>
<td>Surface Tension (dyn/cm)</td>
<td>41.02</td>
<td>39.3</td>
<td>29.25</td>
<td>24.42</td>
</tr>
</tbody>
</table>

**Table 2.3: Physical Properties of Four Types of Grinding fluid**
2.3 Conclusions

In this chapter, two kinds of grinding fluid physical properties are obtained: specific heat capacity and surface tension. The measurement method of specific heat capacity and surface tension are introduced. With the known physical properties of grinding fluids, such density and dynamic viscosity. These parameters are used in the grinding experiments and the grinding process simulations shown in the following chapters. Table 2.3 gives the physical properties of four grinding fluids for the following experiments and simulations.
Chapter 3

Cooling Capability of Grinding Fluid

3.1 Introduction

In the modern industry, grinding fluid is a good choice for cooling and lubrication in common grinding. In this chapter, a new formula is built to describe the cooling capability of grinding fluids with experiments, showing the tendency of cooling in the process and finding what kind of properties can affect this capability in grinding. Four kinds of grinding fluids are carried out in the experiments.

It is a decisive significance of the selection of grinding fluid to achieve favorable cooling and lubrication conditions. Specific grinding fluids have different performance in cooling and lubrication effect. According to the grinding process of contact conditions, cooling and lubrication performance of grinding fluid have substantial impact on the actual working condition of the workpiece and the result.

3.2 Experiment Set-Up

The most modern advances in grinding technology could not be possible without being accompanied by parallel developments in fluid application. The hypothesis is that fluid flow can provide an accurate and comprehensive representation of the grinding
process. In the experiment, a special device was designed and fabricated shown in Figure 3-1. The workpiece is clamped on the heating device. The device heats the workpiece at a certain temperature and then the fluid is applied with the grinding wheel rotating at the working speed, but without removing any material. A gap exists between grinding wheel and workpiece. The thermocouple is embedded in the workpiece to measure the temperature. The time necessary to cool the workpiece at an acceptable (nonburning) temperature will be recorded.

This set of experiments will establish the cooling capacity index, a new original index is introduced:

\[
I_{cc} = \frac{\text{difference of the temperature}}{\text{time}}
\]  

\[\text{(3.1)}\]

Figure 3-1: First Step Experiment Set-Up
3.3 Results

In the common grinding process with grinding fluid, the temperature on the workpiece surface is usually under 700 °C [50-52]. In the experiment, the temperature range is from 200 to 600 °C, with 50 °C intervals. In each experiment, the environment temperature is 20 °C. Cooling time is 90 seconds. Grinding wheel speed is 22.72m/s. Fluid velocity is 12.75m/s. The following Figure 3-2 to Figure 3-5 are the results of the experiments.

From these figures, we find that there are three steps in the cooling process. When grinding fluid is applied on the workpiece, due to the high temperature, the grinding fluid will be granular. After a few seconds, the cooling efficiency increases and the temperature of the workpiece drops quickly, like quenching in the manufacturing process. The temperature will then drop slowly after reaching boiling point, and finally converge to a balance point. Though we tested different temperatures, all the processes have the same tendency.

From these figures we can see that in different temperatures, each grinding fluid has a similar dropping tendency. Also, after cooling in the first step quickly, every grinding fluid will have a change near their boiling point. Therefore, in this experiment, the time of the second step is useful to calculate the $I_{cc}$ for each grinding fluid. The following Table 3.1 is the result of the calculation and Figure 3-6 is the tendency of the cooling capability for each grinding fluid.
Figure 3-2: Experiment of TRIM® C270 for Each Temperature

Figure 3-3: Experiment of TRIM® SC520 for Each Temperature
Figure 3-4: Experiment of TRIM® E906 for Each Temperature

Figure 3-5: Experiment of TRIM® MicroSol®585XT for Each Temperature
Table 3.1: Results of $I_{cc}$ (°C/s)

<table>
<thead>
<tr>
<th>Grinding Fluid</th>
<th>Temperature (°C)</th>
<th>Specific Heat (J/(g°C))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td>585XT</td>
<td>6.27</td>
<td>6.4</td>
</tr>
<tr>
<td>SC520</td>
<td>5.71</td>
<td>6.14</td>
</tr>
<tr>
<td>E906</td>
<td>5.43</td>
<td>5.95</td>
</tr>
</tbody>
</table>

3.4 Discussions

Figure 3-6 indicates that cooling capability increases as specific heat increases.

Based on this simple graphical analysis, we hypothesize that:

(a) Specific heat capacity setting affects the cooling capability.

(b) Higher specific heat capacity settings result in increasing cooling capability.

This will be proved further by ANOVA analysis.
One way to describe this experiment is as a single-factor experiment with four levels of factor, where the factor is cooling capability and the four levels are the four different specific heat capacity of grinding fluids.

Suppose we have \( a \) treatments or different levels of a single factor that we wish to compare. The data can be represented by \( y_{ij} \) which means the \( j_{th} \) observation is taken under factor level or treatment \( i \). There will be, in general, \( n \) observations under the \( ith \) treatment.

We are interested in testing the equality of the \( a \) treatment means. The appropriate hypotheses are:

(a) \( H_0: \mu_1 = \mu_2 = \ldots = \mu_a \)

(b) \( H_1: \mu_i = \mu_j \) for at least one pair \((i, j)\)

The name analysis of variance (ANOVA) is derived from a partitioning of total variability into its component parts. The total corrected sum of squares [53]:

\[
SS_T = \sum_{i=1}^{a} \sum_{j=1}^{n} (y_{ij} - \bar{y}_.)^2
\] (3.1)

Eq. (3.1) is used as a measure of overall variability in the data. If we divide \( SS_T \) by the appropriate number of degrees of freedom (in this case, \( an-1= N-1 \)), we can get the sample variance of the \( y \)'s. So that is a standard measure of variability.

Note that the total corrected sum of squares \( SS_T \) may be written as [53]:

\[
\sum_{i=1}^{a} \sum_{j=1}^{n} (y_{ij} - \bar{y}_.)^2 = \sum_{i=1}^{a} \sum_{j=1}^{n} [(\bar{y}_i - \bar{y}_.) + (y_{ij} - \bar{y}_i)]^2
\] (3.2)

However, the cross-product term in this last equation is zero [53], because

\[
\sum_{j=1}^{n} (y_{ij} - \bar{y}_i) = y_{i.} - ny_{i.} = y_{i.} - n(y_{i.} / n) = 0
\] (3.3)
Therefore, we have [53]

\[
\sum_{i=1}^{a} \sum_{j=1}^{a} (y_{ij} - \bar{y}_{i})^2 = n \sum_{i=1}^{a} (\bar{y}_{i} - \bar{y})^2 + \sum_{i=1}^{a} \sum_{j=1}^{a} (y_{ij} - \bar{y}_{i})^2
\]  

(3.4)

Eq. (3.4) is the fundamental ANOVA identity. It states that the total variability in the data is measured by the total corrected sum of squares which can be partitioned into two parts: one is a sum of squares of the differences between the treatment average and the grand average; another is a sum of squares of the difference of observations within treatments from the treatment average. Thus, we may write Eq. (3.4) symbolically as [53]:

\[
SS_T = SS_{\text{Treatments}} + SS_E
\]  

(3.5)

where \(SS_{\text{Treatments}}\) is called the sum of squares due to treatments and \(SS_E\) is called the sum of squares due to error. There are \(an=N\) total observations, thus, \(SS_T\) has \(N-1\) degrees of freedom. There are \(a\) levels of the factor (and \(a\) treatment means), so \(SS_{\text{Treatments}}\) has \(a-1\) degrees of freedom. Finally, the experimental error has \(N-a\) degrees of freedom.

We see that the ANOVA identity Eq. (3.4) provides us with two estimates of \(\sigma^2\). Due to that, we can get two quantities using sum of squares and degrees of freedom.

The quantities \(MS_{\text{Treatments}} = \frac{SS_{\text{Treatments}}}{a-1}\) and \(MS_E = \frac{SS_E}{N-a}\) are called mean squares.

\[
F_0 = \frac{MS_{\text{Treatments}} / (a-1)}{SS_E / (N-a)} = MS_{\text{Treatments}} / MS_E
\]  

(3.6)

If the null hypothesis of no difference in treatment means is true, Eq. (3.6) is distributed as \(F\) with \(a-1\) and \(N-a\) degrees of freedom. Eq. (3.6) is the test statistic for the hypothesis of no differences in the treatment means [53].

From the expected mean squares we see that if the null hypothesis is false, the expected value of \(MS_{\text{Treatments}}\) is greater than \(\sigma^2\). The expected value of the numerator of
Table 3.2: Analysis of Variance (ANOVA) Table

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>$F_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between treatments</td>
<td>$SS_{\text{Treatments}} = n\sum_{i=1}^{a}(\bar{y}_i - \bar{y})^2$</td>
<td>$a-1$</td>
<td>$MS_{\text{Treatments}}$</td>
<td>$F_0 = \frac{MS_{\text{Treatments}}}{MS_E}$</td>
</tr>
<tr>
<td>Error</td>
<td>$SS_E = SS_T - SS_{\text{Treatments}}$</td>
<td>$N-a$</td>
<td>$MS_E$</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij} - \bar{y}_i)^2$</td>
<td>$N-I$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3: Results of Analysis of Variance

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>$F_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between treatments</td>
<td>229.55</td>
<td>4</td>
<td>57.3875</td>
<td>127.698</td>
</tr>
<tr>
<td>Error</td>
<td>17.9743</td>
<td>40</td>
<td>0.4494</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>247.5194</td>
<td>44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

the test statistic (Eq. 3.6) is greater than the expected value of the denominator, and we should reject $H_0$ on values of the test statistic that are too large. Therefore, we should reject $H_0$ and conclude that there are differences in the treatment means if $F_0>F_{a,a-1,N-a}$, $F_0$ is computed from Eq. (3.6) [53].

The test procedure is summarized in Table 3.2. This is called an analysis of variance (or ANOVA) table.

From statistics table, we find that $F_{a,a-1,N-a} = 2.61$. From Table 3.3, $F_0 = 127.698 > 2.61$, we can reject $H_0$ and conclude that the treatment means differ; that is the specific heat setting significantly affects the coolant fluid cooling capability.
3.5 Conclusions

(a) The whole cooling process of grinding fluid has three stages. Without large changes in temperature due to the distance between the workpiece surface and thermocouples in the first stage, we can put this process as a signal of delay, and then the temperature of the workpiece will drop quickly. After reaching the boiling point, the cooling speed will be slower than the second stage and finally reach the balance point.

(b) The specific heat capacity can significantly affect the cooling capability, the higher of specific heat, the higher cooling capability. Also the higher of temperature, the higher $I_{cc}$ value.

(c) The grinding process is very complex with many parameters involved regarding not only the specific heat capacity, but also the wheel speed and the environment temperature. These sets of experiments can be used as a simplified optimization of the process, considering the rest of the parameters are constant.

(d) In this chapter, brief conclusions of the grinding fluid performance are obtained. These conclusions give an initial understanding of the grinding process and the cooling function of grinding fluid. Combined with the following results from the next step experiments, these conclusions can help to have a more profound understanding of the impact factors in the grinding process.
Chapter 4

Cooling and Lubrication Capability of Grinding Fluid

4.1 Introduction

In this project, temperature and force measurements are employed for research into the mechanics of grinding and for process monitoring. Temperature measurement in grinding presents a number of challenges especially in wet grinding. Fluid can affect the precision of the measurement when using infrared technique or making a short circuit when using a grindable thermocouple. In this chapter, a new temperature measuring method is introduced. This project explores the influence of different grinding conditions for grinding temperature and force. A new formula is built to describe the cooling and lubrication capability of grinding fluids with experiments, showing the tendency of cooling and lubricating in the grinding process and finding what kind of properties can

Table 4.1: Grinding Conditions

<table>
<thead>
<tr>
<th>Work Material</th>
<th>AISI 52100 Steel (62 HRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding Wheel</td>
<td>Norton 32A60-IVBE, Al₂O₃ wheel</td>
</tr>
<tr>
<td>Wheel Speed (m/s)</td>
<td>15.18m/s, 22.72m/s, 30.23m/s</td>
</tr>
<tr>
<td>Feed Rate (m/s)</td>
<td>0.064m/s, 0.085m/s, 0.106m/s</td>
</tr>
<tr>
<td>Depth of Cut (μm)</td>
<td>12.7μm, 25.4μm, 38.1μm, 50.8μm, 63.5μm</td>
</tr>
<tr>
<td>Grinding fluids</td>
<td>TRIM®C270, TRIM®MicroSol®585XT, TRIM®E906, TRIM® SC520</td>
</tr>
</tbody>
</table>
affect this capability. Four types of grinding fluid are tested in the experiments.

4.2 Experiment Set-up

All the tests are carried out on an AISI 52100 steel block in which the dimensions are 152.4mm (6in) * 25.4mm (1in) * 38.1mm (1.5in). This steel is high-carbon chromium alloy steel used in a variety of mechanical applications. With a quenching heat treatment, the steel has a very high hardness and is comparatively easy to machine. For experimental purposes, these steel blocks were hardened to 62 HRC. Table 4.1 and Figures 4-1 and 4-2 provide the outline of the experimental set up.

The grinding fluids used for the grinding in these experiments are the same with the ones used in the first step experiment which is provided by the Master Chemical Corporation (Table 2.1). All the fluid concentrations were 10%. The water mixed with

![Experiment Set-up Schematic](image-url)

Figure 4-1: Experiment Set-up Schematic
grinding fluid is purified by Reverse Osmosis (RO) technology that uses a semipermeable membrane. With various grinding parameters, each grinding fluid has forty-five tests [54, 55].

The temperature measuring method introduced in this chapter is shown in Figure 4-3 and Figure 4-4, which overcomes the limitations mentioned in Chapter 1. The variation is nonlinear beyond the workpiece surface, but based on the previous research [56], the trend of temperature decrease can be treated as linear when the distance is within 300μm underneath the workpiece. So two thermocouples are closely embedded underneath the workpiece surface with different distances to the surface. These two thermocouples are used to simultaneously read temperatures during the grinding process,
then the results are extrapolated to get the temperature of the workpiece surface. This technique can keep the fluid away from directly touching the thermocouples to avoid the inaccuracy in measurement.
Several holes are drilled underneath the workpiece surface shown in Figure 4-5. Every two holes have the exact distance of 50.8μm (0.002in) between them. The two thermocouples are inserted in every two of these adjacent holes to maintain equal distance. Before performing experiments, the distance of every pair of holes to the surface are set. Shorter and longer thermocouples to the workpiece surface are maintained at 152.4μm (0.006in) and 203.2μm (0.008in), respectively. The bottom of every couple of holes has its own exact distance to the workpiece surface. Every pair of holes is 152.4μm (0.006in) lower than the previous pair. Before every experimental pass, several passes are used to get to the distance between the thermocouple tips and workpiece surface. After one experimental pass is finished, we re-fix the thermocouples to the next pair of holes. These distances are important for accurate measurement. The set-up shown in Figure 4-3 and Figure 4-5 allows easy maintenance of these distances.
The thermocouple grinding temperature measurement system is including J-type Inconel standard thermocouple with mini-connector (Figure 4-6), NI® USB-TC01 thermocouple measurement device and the computer (Figure 4-7). During grinding, thermocouples, mini-connector, NI® device and computer are connected as a circuit.

Figure 4-6: J-type Inconel Standard Thermocouple with Mini-connector

Figure 4-7: NI® USB-TC01 Thermocouple Device

Figure 4-8: Kistler® 9257B Dynamometer
Thermoelectric potential is produced by the temperature difference, the thermocouple measurement device can filter and amplify the thermoelectric potential signal. This is the initial temperature signal. The temperature software which built in the thermocouple measurement device can do the post processing of analysis. That is the grinding temperature result in the grinding process.

A Kistler® 9257B dynamometer (Figure 4-8) was used to record the normal and tangential forces. This measurement system is including dynamometer, signal amplifier, signal acquisition card, signal analysis software and computer. In the experiment, the Kistler® dynamometer turns the recording force into electric signal, these signals are amplified as analog voltage signals, and then the signal acquisition card transfers the analog signals into digital signals. Finally, the signal analysis software proceed with the acquisition and processing. The force signal is basically equivalent to an impact load. Because the grinding time is short, the interference signal is also recorded by the dynamometer. Initially, the interference can be filtered by the signal analysis software, then a smooth force signal is obtained. DaDisp® software is used to calculate the average of the force signal, which is the final result of grinding force in a specific grinding condition.

The grinding of AISI 52100 steel was performed on a Thompson® Creep Feed Grinder equipped with a Fanuc® System 3M-Model C Controller. Grinding was performed using an aluminum oxide grinding wheel which was dressed prior to machining and ample grinding fluid was used to prevent excessive heat at the machined surface. The wheel spindle is also equipped with a Dynamic Balance System, which provides real-time dynamic balancing. The balancer eliminates the imbalance of the
grinding wheel to minimize the grinding wheel vibration, as well as maintaining an optimum grinding process.

The second step experiment will determine a global cooling capacity index \( I_{GC} \) of the grinding fluid. In this case, the global index definition is:

\[
I_{GC} = \frac{\text{difference of the temperature} \times \text{Normal Force}}{\text{time} \times \text{Tangential Force}}
\]  

(4.1)

4.3 Results analysis

Grinding heat generated in the process is an important physical phenomenon. It is not an independent phenomenon; it is influenced by grinding forces, grinding power and specific grinding energy. But grinding parameters, such as wheel speed, feed rate and depth of cut are the directly influencing factors in the process.

4.3.1 Temperature Results Analysis

The following figures are the results of temperature and force results during surface grinding. Figure 4-9 to Figure 4-12 show the result of grinding temperatures for all these four types of grinding fluid when the feed rate is constant and wheel speed is varying. For all types of grinding fluid, the results show that when the depth of cut is higher, temperature is increasing. In the grinding process, the grinding contact area is assumed to be a heating source; heat is generated in the process due to the friction between grinding wheel and workpiece. So when the depth of cut is increased, tangential forces increase the heating power of the average heating source; the contact length and material removal rate are also increased. These three reasons cause the temperature to rise
Figure 4-9: TRIM® C270 Grinding Temperature When Feed Rate is Constant

Figure 4-10: TRIM® SC520 Grinding Temperature When Feed Rate is Constant
Figure 4-11: TRIM® E906 Grinding Temperature When Feed Rate is Constant

Figure 4-12: TRIM® MicroSol® 585XT Grinding Temperature When Feed Rate is Constant
with the rise in depth of cut. When grinding wheel rotation speed is increasing, more abrasive grains act on the workpiece, so the total heat generated by the process is increasing, thus the temperature rises.

Figure 4-13 to Figure 4-16 show the result of grinding temperature when the wheel speed is constant and the feed rate is changing. Workpiece feed rate has two main effects to the grinding temperature area in the process. Firstly, when the feed rate increases, it decreases the grinding time and lessens the accumulated heat, so the grinding temperature decreases. Secondly, when the heat source intensity increases, it simultaneously raises the temperature. In grinding, heat source, which is the contact area between wheel and workpiece surface, is the main influencing zone that determines the temperature of surface. In this experiment, the heat source is the main effect; the higher the feed rate is, the higher the temperature is.

Figure 4-13: TRIM® C270 Grinding Temperature When Wheel Speed is Constant
Figure 4-14: TRIM® SC520 Grinding Temperature When Wheel Speed is Constant

Figure 4-15: TRIM® E906 Grinding Temperature When Wheel Speed is Constant
4.3.2 Grinding Force Results Analysis

Figure 4-19 to Figure 4-26 show the results of normal and tangential forces imparted on the workpiece surface. The data is recorded during the grinding process when the feed rate is constant and wheel speed is changed. These figures show the
Figure 4-17: Global Grinding Temperature Performance on 25.4μm

Figure 4-18: Global Grinding Temperature Performance on 38.1μm
influence of changing depth of cut and the wheel speed on the normal and tangential forces respectively. From these two figures, it is observed that when the depth of cut is increasing, normal and tangential forces are increasing correspondingly. This is because at the same grinding condition, increasing the depth of cut makes each abrasive chip thickness increase and causes the grinding wheel contact length to increase. At the same time, the number of abrasive grains participating in the process increases with the increase in material removal rate. So the normal and tangential force is increasing correspondingly.

When the depth of cut and feed rate is constant, higher wheel speed increases lower than normal and tangential forces. Constant depth of cut and feed rate provides a constant material removal rate. If the only parameter that is increased is wheel speed, the number of the total abrasive grains participating in the process per unit areas per unit time is increased. This reduces the chip thickness and cross sectional area of the chip. This result in a decrease of each effective force generated by each abrasive grain, thus the overall normal and tangential force imparted on the surface of the workpiece is reduced. Also when this is happening, the increasing wheel speed brings more fluid into the gap between wheel and workpiece, which can strengthen the lubrication capability of the fluid to decrease the forces. This decrease in the magnitude of the forces measured with increase in wheel speed can also be observed in previous figures.
Figure 4-19: TRIM® C270 Grinding Normal Force When Feed Rate is Constant

Figure 4-20: TRIM® C270 Grinding Tangential Force When Feed Rate is Constant
Figure 4-21: TRIM® SC520 Grinding Normal Force When Feed Rate is Constant

Figure 4-22: TRIM® SC520 Grinding Tangential Force When Feed Rate is Constant
Figure 4-23: TRIM® E906 Grinding Normal Force When Feed Rate is Constant

Figure 4-24: TRIM® E906 Grinding Tangential Force When Feed Rate is Constant
Figure 4-25: TRIM® MicroSol® 585XT Grinding Normal Force When Feed Rate is Constant

Figure 4-26: TRIM® MicroSol® 585XT Grinding Tangential Force When Feed Rate is Constant
Figure 4-27 to Figure 4-34 show the result of normal and tangential forces when the wheel speed is constant and feed rate is varied. These two show that the higher the feed rate is, the higher the forces are. Because when feed rate is increasing, the material removal rate is higher, this increases the chip thickness and cross sectional area of the chip, the forces increase correspondingly.

![TRIM C270 Normal Force](image)

**Figure 4-27: TRIM® C270 Grinding Normal Force When Wheel Speed is Constant**

![TRIM C270 Tangential Force](image)

**Figure 4-28: TRIM® C270 Grinding Tangential Force When Wheel Speed is Constant**
Figure 4-29: TRIM® SC520 Grinding Normal Force When Wheel Speed is Constant

Figure 4-30: TRIM® SC520 Grinding Tangential Force When Wheel Speed is Constant
Figure 4-31: TRIM® E906 Grinding Normal Force When Wheel Speed is Constant

Figure 4-32: TRIM® E906 Grinding Tangential Force When Wheel Speed is Constant
Figure 4-33: TRIM® MicroSol® 585XT Grinding Normal Force When Wheel Speed is Constant

Figure 4-34: TRIM® MicroSol® 585XT Grinding Tangential Force When Wheel Speed is Constant
Figure 4-35 and Figure 4-36 show the different performance of these fluids in the same condition on 12.7μm and 25.4μm. From the figures, synthetic type C270 has the best performance compared with others and it has the lowest force. SC520 and E906 fall in the middle while 585XT has the highest force. It has the same trend with the performance of the grinding temperature. Before analyzing the reason, first it is important to have a global acknowledgement of the performance of these fluids. There are 45 different grinding conditions for each fluid including shallow and heavy passing. In the experiment, not all of the fluids can help the grinding wheel to fully pass through the workpiece. In the heavy grinding, the grinding wheel will stop rotating during the grinding, because in this condition, the material removal rate is too high, the grinder motor’s power is not enough to help the wheel pass through the heavy conditions to finish a full pass.

In all 45 passes, C270 had a 100% full pass, SC520, E906 and 585XT are 95.56%, 88.89% and 82.22% respectively. The blank showing both on temperature and force figures of E906 and 585XT is the lack of full pass and no recorded force records. Also, a full pass means the accomplishment for one pass, but it does not mean that is a perfect or smooth pass. Figure 4-37 and Figure 4-38 give the visualized differences from the dynamometer recording. X-axis is time and Y axis is force. Figure 4-37 is the result in the shallow grinding; the force result is smooth and vibrates in a small district. Figure 4-38 shows the heavy condition result, due to the high material removal rate, more interaction force was generated. The grinder motor’s power is not enough to handle this heavy condition, the wheel speed slows down, and then the wheel slides on the workpiece instead of cutting. Therefore, the force keeps growing shown in the figure. These force
Figure 4-35: Global Force Performance on 12.7μm

Figure 4-36: Global Force Performance on 25.4μm
results are higher than the smooth results in the same grinding condition if grinder motor’s power is inadequate.

From the figures, synthetic type C270 has the best performance compared with others, it has the lowest force and lower temperature, and then is SC 520 and E906, 585XT has the highest temperature and force. Because C270 has a low viscosity with low glutinousness compared with other grinding fluids. The inertia can help C270 easier enter into the grinding contact area and have higher useful flow rate in the same nozzle pressure and angle, reducing the friction between the workpiece and grinding wheel, thus, reducing the force. Also, C270 has a high surface tension compared with the other three types of grinding fluids, C270 is more easier to break up to enter into the grinding contact area, more grinding fluid can help cool down the workpiece during grinding process which decreases the temperature.

Figure 4-37: Force Recording by Dynamometer
4.3.3 Global Cooling Capability Index

Figure 4-39 and Figure 4-40 are the global cooling capability index ($I_{GC}$) on 25.4μm and 38.1μm based on Eq. (4.1). This equation has two parts: cooling capability reflects the function of the grinding temperature and lubrication capability or grinding force ratio reflects the function of grinding force. For the first part, compared with the cooling capability index ($I_{CC}$), this also shows the cooling effects of grinding fluid. But in Chapter 3, higher $I_{CC}$ means the grinding fluid can take a shorter time for cooling, which means the higher $I_{CC}$ is, the better cooling capability of the grinding fluid. For $I_{GC}$, the lower value for the first part means the fluid has a better cooling capability, because the grinding fluid takes more heat generated in the process and decreases the temperature. For the second part, lower dynamic viscosity grinding fluid often translates to its better
performance in lubrication compared to higher dynamic viscosity grinding fluid. In this case, an increase of grinding force ratio is that rubbing predominates material removal. Grinding force ratio is increased in the presence of higher dynamic viscosity grinding fluid, as higher normal forces related to cutting is achieved by lower tangential force. So, in these two figures, C270 has the lowest index followed by SC520, E906 and 585XT. Combined with the previous explanation, lower dynamic viscosity helps more grinding fluid act inside the grinding area, which takes away more heat and decreases the force ratio. Also higher surface tension helps grinding fluid easy to break up to enter into the grinding contact area.

Figure 4-39: Global Cooling Capability Index on 25.4μm
4.3.4 Grinding Roughness Results Analysis

The surface quality in the grinding process consists of many factors, such as the lubrication effectiveness, the minimum tolerance, the working condition etc. A typical parameter that has been used to quantify the quality of surface topography is the surface roughness, which is represented by the arithmetic mean value, $R_a$, the root mean square-average, $R_q$ and the maximum roughness height, $R_t$. In this project, $R_a$ is chosen as the parameter for measuring. In general, the longitudinal surface roughness has a lower value than the traverse surface roughness. Therefore, the latter is used in the experiments. The PocketSurf® portable surface roughness gage is used to measure the workpiece surface roughness. This device is shown in Figure 4-41. Thirty points are measured to get an average roughness result in each grinding condition.
Figure 4-42 and Figure 4-43 show the results of C270 roughness as an example. Figure 4-42 shows the results when the feed rate is kept constant and wheel speed is varied and Figure 4-43 presents the opposite condition. A similar reason to those explained earlier for force can be provided here, roughness increases as depth of cut and feed rate increases, but decreases as wheel speed increases. Roughness $R_a$ is the absolute value of the arithmetic average of offset distance. When depth of cut increases, the chip is thicker and the volume of every chip is larger, which induces a higher offset distance, so the roughness increases. When the wheel speed increases, more abrasive grains act on the surface in a certain length of a unit time and the chip produced in the process is thinner which makes the surface smoother. When the depth of cut increases from 12.7μm to 50.8μm the roughness is mostly below 0.6μm, but when the depth of cut is over 50.8μm, the roughness jumps over 1μm, because at this time, burnout shows on the surface and cracks happen due to the deep depth.

The abrasive grains acting on the workpiece surface during grinding is a random process. The roughness results in each specific grinding condition will be fluctuated. The different results between each grinding fluid are not very clear. To have a complete understanding of the fluid performance, the global roughness for all four types of

![PocketSurf® Portable Surface Roughness Gage](image)

*Figure 4-41: PocketSurf® Portable Surface Roughness Gage*
Figure 4-42: TRIM® C270 Roughness When Feed Rate is Constant

Figure 4-43: TRIM® C270 Roughness When Wheel Speed is Constant
grinding fluid are proposed. The average roughness for C270, SC520, E906 and 585XT are 0.474, 0.495, 0.628 and 0.759 respectively. Figure 4-44 shows the global results. From this figure, C270 has the best performance. This is another demonstration of the useful flow rate which is mentioned previously. The higher useful flow rate lets more grinding fluid go inside the grinding area which increases the function of the fluid lubrication. That makes a better surface quality

4.4 Conclusions

The main factors of grinding temperature are the physical properties of the workpiece, the grinding methods, and grinding conditions. Grinding temperature has significant effects on the quality of the workpiece surface and the performance of the
grinding wheel. In this chapter, a new method to measure the grinding temperature and determine relations among temperature, force, and roughness is proposed.

(a) When the depth of cut is higher, the temperature increases, because when the depth of cut is increased, tangential force increases the heat power of the average heating source. Also, the contact length and material removal rate are increased too. These three reasons cause the higher temperature.

(b) When the grinding wheel rotation speed is increased, although the grinding force is reduced, the total heat generated by the process is increased. As a result, the temperature is increased.

(c) When the feed rate increases, the temperature increases. Workpiece feed rate has two main effects to the grinding temperature area in the process. In this experiment, the heat source is the main effect.

(d) When the depth of cut is higher, the force increases. This is because, at the same grinding condition, increasing the depth of cut makes each abrasive chip thickness, contact length and material removal rate increase, so the normal and tangential force is increased.

(e) When the wheel speed is higher, the forces decrease, because more abrasive grains participate in the process in the time unit. This can lead to a decrease in the depth of cut of each abrasive grain, thinner chips, and smaller cross sections of the chips. Thus, each effective force generated by each abrasive grain decreases, thus the normal and tangential force decreases.

(f) When the feed rate increases, the force increases. Because during the process, more material is removed in the unit time.
(g) Roughness has similar results as forces. When the depth of cut increases, the thickness of the chip is thicker and the volume of every chip is larger, which induces higher offset distance, so the roughness increases. When the wheel speed increases, more abrasive grains act on the surface in a certain length of unit time and the thickness of the chip produced in the process is thinner; this makes the surface smoother.

(h) The magnitude trend of dynamic viscosity and surface tension for each grinding fluid is not the same as that of specific heat. Based on the comparison of temperature and force between different types of grinding fluid, the lower dynamic viscosity with higher surface tension, the lower grinding temperature and force. The effect of dynamic viscosity and surface tension are more significant than specific heat based on physical properties of grinding fluid in Table 2.3. Due to this conclusion, low dynamic viscosity and high surface tension can help more grinding fluid enter the grinding contact area which gives dynamic viscosity and surface tension statuses as key factors in the grinding process. The following chapters will have further research in this area.
Chapter 5

Grinding Air Flow Modeling

5.1 Introduction

Computational fluid dynamics (CFD) is a combination of fluid dynamics, numerical mathematics and computer science. CFD uses computer as the tool with the application of various mathematical method of discretization to solve all kinds of practical problems in the numerical experiment, computer simulation and analysis. In the recent twenty years, CFD technique has a rapid development with the improvement of computer hardware industry. The theoretical analysis and experiment method has many restrictions in the CFD field. For example, due to the complexity of the problem, it cannot do any analytical solution or expensive experiments. Therefore, the CFD method has many advantages such as lower-cost, more complex and ideal experimental process simulation.

In this project, three complex 3-D models are created. These models are built using a commercial CFD software-ANSYS FLUENT. To make precise simulations, these models are focus on the detailed section of the grinding area and its vicinity to simulate the grinding air flow, the grinding fluid flow and grinding heat transfer in the grinding process.
ANSYS FLUENT can be used to simulate complex fluid flow from incompressible to highly compressible flow. With the adoption of a variety of solving method and multiple grid accelerating convergence technology, ANSYS FLUENT can achieve optimal convergence speed and precision. Flexible unstructured grid, adaptive grid technique based on the solution and fully developed model make CFD have wide applications, such as turbulence, heat transfer and phase transition, chemical reaction and combustion, multiple phase flow, rotating machinery, dynamic mesh.

5.2 ANSYS FLUENT Theoretical Analysis

5.2.1 CFD Basic Solution Process

Figure 5-1 is the solution process of CFD. On the discrete grids, constructing approximation discrete equations of flow governing equations – finite difference equation are widely used in this section. Through computer and CFD software, solve the discrete approximation equations and get the approximate solutions of the physical quantities, such as velocity, density and pressure, on the grid points. Using the approximate solution to get the simulation results and fluid flow images.

5.2.2 Meshing

Before doing the fluid simulation, the model need to be meshed. In this project, one professional CAE preprocessing software, ICEM CFD (The Integrated Computer Engineering and Manufacturing code for Computational Fluid Dynamics), is used. It can provide efficient and reliable meshing models for all popular CAE software designs in the world. It has a strong surface repair ability for CAE models, automatic extraction,
unique grid "sculpture" technology, mesh editing techniques and extensive solver support ability. At the same time, as a professional analysis software of ANSYS family, ICEM CFD also can be integrated in ANSYS Workbench platform, getting all the advantages of the Workbench. ICEM CFD provided software standard meshing as ANSYS FLUENT and CFX, replacing the position of GAMBIT.

Figure 5-1: Solutions Process of CFD
ICEM CFD has three main meshing methods: Tetra Meshing, Hexa Meshing and Prism Meshing.

Tetra meshing is suitable to do quick and efficiency meshing for the complex structure geometric model. ICEM CFD can generate tetrahedral mesh automatically. The software generates a topology structure on the existing model. Users only need to set the grid parameters, the software can automatically generate tetrahedral mesh quickly. Software also provides tools to enable users to inspect and modify the quality of the grids.

For Hexa meshing, ICEM CFD hexahedral grid adopted sculpture method from the top of the model to the bottom, it can generate multiple structural and unstructured grid topology. The whole process is semi-automatic, the user can learn this in a short period, which could only be operated by experts previously. ICEM CFD adopts advanced O-Grid technology, users can conveniently mesh irregularly geometry model with high quality of “O”, “Y” and “L” shape hexahedral grid.

Prism mesh is mainly used for tetrahedral mesh boundary layer mesh refinement, or in joint of transitions between different kinds of grids (Hexa and Tetra). Compared with tetrahedral grid, prism mesh is more regular, it can provide a better calculation area in the boundary layer.

5.3 Dimensional Analysis

In the engineering field, dimensional analysis is a kind of important natural science research methods. It is the analysis of the relationships between different physical quantities by identifying their fundamental dimensions. Usually, the dimensions of physical quantities are formed by the combination of the basic physical dimensions, such
as mass, length, time, temperature etc. For example, the dimension of the speed is the length per unit time and the unit is meters per second, miles per hour or other units of measurement. An important principle of dimensional analysis is based on the laws of physics, it is independent of the required measuring units of physical quantities. In any meaningful equation, the left side and the right side of the dimension must be the same. It is a basic step to check whether the dimension analysis is following the rule.

5.3.1 Reynolds Number

In fluid mechanics, the Reynolds number (Re) is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations. The Reynolds number is defined as the ratio of inertial force to viscous force and consequently quantifies the relative importance of these two types of forces for given flow conditions. The Reynolds number frequently rises when performing scaling of fluid dynamics problems, and as such can be used to determine dynamic similitude between two different cases of fluid flow. They are also used to characterize different flow regimes within a similar fluid, such as laminar or turbulent flow:

(a) Laminar flow occurs at low Reynolds numbers. In laminar flow movement, each particle has linear motion along the tube axis direction, no mixing or mutual interference between each particle. The viscous forces are dominant, and laminar flow is characterized as smooth, constant fluid motion;

(b) Turbulent flow occurs at high Reynolds numbers. In turbulent flow, the particle movement is not only linear motion along the tube axis direction, but also accompanied by lateral disturbance. Turbulent flow is dominated by inertial forces,
which tend to produce chaotic eddies, vortices and other flow instabilities.

Turbulence happens under a large Reynolds number. It is called a critical Reynolds number, usually around 2300–4000, when the flow regime has transition.

\[
\text{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho v L}{\mu} = \frac{v L}{\eta}
\]

(5.1)

where

\(\rho\): Density of the fluid (kg/m\(^3\))

\(v\): Mean velocity of the object relative to the fluid (m/s)

\(L\): Characteristic linear dimension (m)

\(\mu\): Dynamic viscosity of the fluid (Pa·s)

\(\eta\): Kinematic viscosity (m²/s)

In this air flow simulation model, the Reynolds number is \(4.09 \times 10^4\), which is much higher than 2300. The air flow in this model is considered as turbulence.

5.3.2 Mach Number

Mach number (\(Ma\)) is an important dimensionless quantity to characterize fluid compressibility. It is defined by the ratio of an object moving through a fluid and the speed of sound in that fluid for its particular physical conditions

\[
Ma = \frac{V}{a}
\]

(5.2)

where \(V\) is the relative velocity of the object to the fluid medium, in this model, this relative velocity is the grinding wheel speed. \(a\) is the sound speed in the medium.
In the incompressible fluid flow with constant density, the Mach number is zero and sound speed is infinite. When the Mach number is larger than or equals to 0.3, the effect of fluid compressibility cannot be ignored.

In compressible fluid flow, Eq. (5.3) gives the relations of Mach number, speed of fluid and density.

\[
\frac{d\rho}{\rho} = M_a^2 \frac{dV}{V}
\]  \hspace{1cm} (5.3)

Namely, in the fluid flow process, the larger the Mach number, the greater compressibility of fluid. In addition, when the Mach number is larger than or equals to 1, the disturbance propagation in the fluid flow is quite different. Therefore, from the aerodynamic view, the Mach number can better describe the characteristic of airflow than fluid speed. According to the magnitude of the Mach number, the airflow can be divided into different types: low speed flow, subsonic flow, transonic flow, supersonic flow and hypersonic flow. For subsonic flow, the Mach number is less than 1, transonic flow is nearly equal to 1 and supersonic flow is greater than 1.2. Usually, hypersonic flow’s Mach number is larger than 5

(a) Incompressible flow:
   Subsonic incompressible flow: Ma < 0.3

(b) Compressible flow:
   Subsonic compressible flow: 0.3<Ma≤0.8
   Transonic compressible flow: 0.8<Ma≤1.2
   Supersonic compressible flow: 1.2<Ma≤ 5
   Hypersonic compressible flow: Ma>5
According to the highest grinding wheel speed in the experiment, the maximum Mach number in air flow simulation model is 0.089, which is less than 0.3. Therefore, incompressible pressure based solver is used.

5.4 Criteria of Turbulence Model Selection

5.4.1 Model types in ANSYS FLUENT

In ANSYS FLUENT, many types of turbulence models can be chosen, such as Spalart-Allmaras, standard k-epsilon, RNG k-epsilon, realizable k-epsilon, standard k-omega, shear-stress transport (SST) k-omega, Reynolds Stress Model (RSM), Scale-Adaptive Simulation (SAS), Detached Eddy Simulation (DES) and Large Eddy Simulation (LES).

Spalart-Allmaras is a one-equation model, it has a modified turbulent viscosity. This model can be used for the coarse grid simulation. It has advantages such as simplification and small amount of calculation.

Standard k-epsilon is the default model of k-epsilon with two equations. The coefficients are given by empirical formulas. This model is applied only to high Reynolds number turbulence, containing viscous heat, buoyancy, compressibility and other options. This model is used for the general simulation in engineering and the calculation amount is moderate to the simulation applications. Its convergence capability and calculation precision can satisfy the requirement of general engineering calculation, but the result of simulations for high curvature and pressure gradient model are not effective enough.

RNG k-epsilon is the deformation of standard k-epsilon model. The coefficients are from the analytical solution. In this type of k-epsilon model, it improves the
simulation capability of the high shear strain flow. It is used to predict the swirl flow and low Reynolds number turbulence.

Realizable $k$-epsilon is another deformation of standard $k$-epsilon model. Using mathematical constrain to improve the performance of the model, it can be used to predict the swirl flow.

Standard $k$-omega is the default model of $k$-omega with two equations. It has a preferable simulation performance for bounded wall and low Reynolds number flow, especially for the problem of flows around circular cylinder.

The shear-stress transport (SST) $k$-omega model is the deformation of standard $k$-omega model. Using the mixed function, standard $k$- epsilon model is combined with $k$-omega model including shear stress.

Reynolds Stress Model (RSM) is the most complex Reynolds-averaged Navier-Stokes (RANS) model. It uses the transport equation to solve the Reynolds stress directly and avoid the other viscous assumptions of the model. It has obvious advantages for simulating high strong strength swirl flow, streamline curvature flow compared with other models.

5.4.2 Criteria for Choosing Turbulence Model

The standard $k$-epsilon model proposed by Spalding and Launder [57] is widely used. This model has many advantages, such as stability and higher calculation accuracy. The standard model is based on model transport equations for the turbulence kinetic energy $k$ and its dissipation rate $\varepsilon$. The model transport equation for $k$ is derived from the
exact equation, while the model transport equation for $\varepsilon$ was obtained using physical reasoning and bears little resemblance to its mathematically exact counterpart.

In the derivation of the k-epsilon model, the assumption is that the flow is fully turbulent, and the effects of molecular viscosity are negligible. The standard k-epsilon model is therefore valid only for fully isotropic homogeneous turbulent flows. So the k-epsilon model has a big error for the inhomogeneous cyclone turbulence.

As the strengths and weaknesses of the standard k-epsilon model have become known, modifications have been introduced to improve its performance: the realizable k-epsilon model. The Realizable k-epsilon model has more accurate prediction for simulating the flat and cylinder fluid injection.

5.5 Grinding Air Flow Field Simulation

In the grinding process, the rotation of the grinding wheel produces disturbance to the surrounding air flow field. At the periphery of a rotating wheel, an air layer will be produced, which hinders the grinding fluid into the grinding contact area, usually it is referred to as “air barrier”. The higher the grinding wheel rotation speed, the more obstacle to the grinding fluid, grinding fluid is harder to enter in the grinding contact area. In addition, in the surface grinding, the gap between grinding wheel and workpiece forms a wedge area. This wedge area prevents the air flow field surrounding the periphery of the grinding wheel, which generates air backflow. In surface grinding, not all the grinding fluid can be ejected into the grinding contact area. Useful flow rate is defined as how much grinding fluid is entering into the grinding contact area. This useful grinding fluid helps the grinding process have a better performance with its cooling and lubrication.
functions. The air backflow constrains the grinding fluid into the grinding contact area, decreasing the useful flow rate. Therefore, the simulation of grinding air flow field helps to study the distribution of speed, pressure and air flow field, which helps to optimize the grinding fluid application.

5.5.1 Grinding Air Flow Analysis

Generally, in surface grinding, there are two main types of air flow: peripheral air flow and radial air flow. The peripheral air flow is produced by the rotation of grinding wheel circumference surface due to the centrifugal force. This kind of air flow has a negative function on the grinding fluid application. The radial air flow is formed by the interactions of air flow on the end face and the centrifugal force. The radial air flow has little influence on the grinding fluid application.

5.5.2 Grinding Air Flow Theoretical Basis

5.5.2.1 Reynolds Averaged Navier-Stokes Equations

Based on the fluid dynamics principles, using the continuity equation, the momentum conservation equation and the energy conservation equation to build mathematic model which describe the characteristic of air flow in the grinding area.

(a) Continuity Equation

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]  \hspace{1cm} (5.4)

(b) Momentum Conservation Equation

\[ \text{x component:} \]
\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uV) = -\frac{\partial \rho}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + \rho f_x
\]  
(5.5)

y component:
\[
\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho vV) = -\frac{\partial \rho}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \rho f_y
\]  
(5.6)

z component:
\[
\frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho wV) = -\frac{\partial \rho}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z
\]  
(5.7)

All above equations are Reynolds averaged Navier-Stokes equations (RANS)

5.5.2.2 Realizable k-epsilon model

The following is the modeled transport equations for \( k \) and \( \varepsilon \) in the realizable k-epsilon model [58]:
\[
\frac{\partial}{\partial t} (\rho k) + \sum_j \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \mu \varepsilon - \frac{\partial \gamma}{\partial t} + S_k
\]  
(5.8)

and
\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \sum_j \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + (\nu \varepsilon)^{0.5}} + C_1 \frac{\varepsilon}{k} + C_2 \frac{\varepsilon}{k} + S_\varepsilon
\]  
(5.9)

where
\[
C_1 = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right], \eta = \frac{S}{S_y}, S = \left( 2S_y S_y \right)^{0.5}
\]

where

\( G_k \): The generation of turbulence kinetic energy due to the mean velocity gradients.

\( G_b \): The generation of turbulence kinetic energy due to buoyancy.
$Y_M$: The contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate.

$C_2$ and $C_{1\varepsilon}$: Constants.

$\sigma_k$: The turbulent Prandtl numbers for $k$.

$\sigma_\varepsilon$: The turbulent Prandtl numbers for $\varepsilon$.

$S_k$, $S_\varepsilon$: The user-defined source terms.

Note that the $k$ equation (Equation 5.8) is the same as that in the standard $k$-epsilon model, except for the model constants. However, the form of the $\varepsilon$ equation is quite different from those in the standard $k$-epsilon model (Equation 5.9). One of the noteworthy features is that the production term in the $\varepsilon$ equation (the second term on the right-hand side of Equation 5.9) does not involve the production of $k$, it does not contain the same $G_k$ term as the other $k$-epsilon models. It is believed that the present form better represents the spectral energy transfer. Another desirable feature is that the destruction term (the third term on the right-hand side of Equation (5.9)) does not have any singularity; its denominator never vanishes, even if $k$ vanishes or becomes smaller than zero. This feature is contrasted with traditional $k$-epsilon models, which have a singularity due to $k$ in the denominator. [58]

This model has been extensively validated for a wide range of flows, including rotating homogeneous shear flows, free flows including jets and mixing layers, channel and boundary, layer flows, and separated flows. For all these cases, the performance of the model has been found to be substantially better than that of the standard $k$-epsilon model [58].
5.5.2.3 Boundary Condition

The initial conditions can be set by given any value, because the final convergent flow field has no relation with the initial conditions. But in order to improve the convergence speed, a high quality of the initial conditions should be provided. Boundary conditions is the key information to determine the flow, the accuracy of the boundary conditions will ultimately decide the reliability of the simulated flow field in the grinding zone. Nonlinear partial differential equations can have no solution, one solution or multiple solutions, not only depended by the types of boundary conditions and also related to the numerical value of boundary conditions. Even if the boundary condition is correct, if the numerical value is different, the stability of the differential equation might be different [58].

Physical boundary condition are described in the form of mathematics. Some of the discrete boundary conditions are stability, some are divergence. Reasonable boundary conditions are not only related to itself, but also related to the chosen interior point difference scheme. Sometimes data format needs more boundary conditions, which are called numerical boundary conditions. Numerical boundary conditions also affect the stability and accuracy of the calculation [58].

In general, the flow field in the grinding zone boundary conditions are composed of four parts: inlet boundary conditions, the outlet boundary condition, the solid wall boundary condition and the moving wall boundary condition [58].

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5.6 Grinding Air Flow Field Modeling

Before using ANSYS FLUENT to the grinding air flow simulation, first use a CAD software to build the geometric model, then use preprocessing software ICEM to mesh the model and set the boundary conditions. In this model, the tetrahedral mesh is chosen as the meshing method. Because geometric configuration in this air flow simulation model is uncomplicated, for this kind of model, tetrahedral mesh and hexahedral mesh have little difference for the simulation result. Tetrahedral mesh is chosen which can adapt to the model shape and easy to inspect and modify the quality of the grids. Figure 5-2 shows the 3D geometry model with meshing. It includes grinding wheel, workpiece and calculation area. The boundary condition of grinding wheel and workpiece is wall and the rest boundary conditions are pressure outlet. This meshing model has 204511 elements and 36492 nodes.

After the meshing and boundary condition setting is finished, output the file from ICEM to ANSYS FLUENT, a series of simulation parameters settings needs to be undertaken. In the simulation parameter setting, using a pressure based solver; k-epsilon is chosen as the turbulence model. In the calculation area, the fluid material is air. The pressure of pressure outlet is 0. The wheel speed used in the simulations are 15.18m/s and 30.23m/s. Four different kinds of gaps between grinding wheel and workpiece are 0.5mm, 1mm, 2mm and 5mm respectively. The workpiece is fixed in the simulation. Figure 5-2 is the meshing of the air flow field.
5.6.1 Grinding Air Flow Pressure Distributions

To study the effect of the clearance between grinding wheel and workpiece and the grinding wheel speed to the air flow field. A global grinding air flow model is established. Table 5.1 is the model parameters and Table 5.2 is simulation methods.

5.6.1.1 When The Clearance between Grinding Wheel and Workpiece is from 0.5mm to 5mm, Grinding Wheel Speed is 15.18m/s

Figure 5-3 to Figure 5-10 is the air pressure acting on the workpiece. In this model, due to the rotation direction of the grinding wheel, the air flows from the negative
Table 5.1: Grinding Air Flow Model Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding wheel diameter</td>
<td>289.8643 mm</td>
</tr>
<tr>
<td>Grinding wheel width</td>
<td>25.4 mm</td>
</tr>
<tr>
<td>Clearance</td>
<td>0.5mm 1mm 2mm 5mm</td>
</tr>
<tr>
<td>Grinding wheel speed</td>
<td>15.18m/s 30.23m/s</td>
</tr>
</tbody>
</table>

Table 5.2: Grinding Air Flow Model Simulation Methods

<table>
<thead>
<tr>
<th>Scheme</th>
<th>SIMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>Green-Gauss Cell Based</td>
</tr>
<tr>
<td>Pressure</td>
<td>PRESTO!</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>k-epsilon</td>
</tr>
<tr>
<td>Momentum</td>
<td>Third-Order MUSCL</td>
</tr>
<tr>
<td>Turbulent Kinetic Energy</td>
<td>Third-Order MUSCL</td>
</tr>
<tr>
<td>Turbulent Dissipation Rate</td>
<td>Third-Order MUSCL</td>
</tr>
</tbody>
</table>

direction to the positive direction on the z axis. From Figure 5-3 and Figure 5-6, when the clearance is 0.05mm, the air pressure is higher than the other clearances. The position 0 on z axis is the smallest clearance between the grinding wheel and the workpiece, in this area, negative pressure is acting in the corresponding position, then the pressure decreases from middle to both sides. When the wheel speed increase, from Figure 5-7 to Figure 5-10, the maximum air pressure increase sharply. In this condition, the thickness of the air flow layer driven by the grinding wheel rotation is smaller than the clearance, the air field will have a negative effect on the grinding fluid injection. When the clearance increases, the air flow pressure decreases, because the clearance increases which gives the air flow layer more space to go through. When the clearance is 5mm, the air flow pressure is much smaller than the previous conditions, the air flow negative effect is not very clear, because the existence of the positive and negative air pressure.
Figure 5-3: Clearance 0.5mm, Wheel Speed 15.18m/s

Figure 5-4: Clearance 1mm, Wheel Speed 15.18m/s
Figure 5-5: Clearance 2mm, Wheel Speed 15.18m/s

Figure 5-6: Clearance 5mm, Wheel Speed 15.18m/s
5.6.1.2 When the clearance between grinding wheel and workpiece is from 0.5mm to 5mm, grinding wheel speed is 30.23m/s

Figure 5-7: Clearance 0.5mm, Wheel Speed 30.23m/s

Figure 5-8: Clearance 1mm, Wheel Speed 30.23m/s
Figure 5-9: Clearance 2mm, Wheel Speed 30.23m/s

Figure 5-10: Clearance 5mm, Wheel Speed 30.23m/s
5.6.2 Grinding Air Flow Velocity Distributions

Figure 5-11 is the global simulation of air flow velocity field when wheel speed is 15.18m/s and clearance is 2mm. Figure 5-13 is the enlarged lower right corner area of the air flow velocity in Figure 5-11. Each arrow represents the velocity vector. In Figure 5-11, the grinding wheel is rotating clockwise which drives the air to form an air flow layer. The air flows in the same direction with the grinding wheel rotation and near the clearance between the grinding wheel and workpiece, the air is accelerated to the maximum speed. The maximum speed increases when the clearance decreases. Because in the previous paragraph, the decrease of the clearance will increase the air pressure acting on the workpiece, this increasing pressure will drive the air flows more rapidly.

Figure 5-11: Global Air Flow
In Figure 5-12, from the enlarged lower right corner area of the air flow velocity in Figure 5-11. The air backflow can be clearly seen near the bottom, the line in the figure divides the air flow field into two sections. Above the line, the air flow has the same direction with the grinding wheel rotation, which helps the grinding fluid go inside the grinding area. Below the line, the air flow has the opposite direction that will prevent the grinding fluid injection. From this conclusion, the injection angle is better above the line. Table 5.3 gives the angles of the lines in all conditions. The angle decreases when the clearance increases. This is because in the smaller clearance, the air pressure produce more air backflow.
Table 5.3: Air Flow Positive-Negative Boundary Line Angle

<table>
<thead>
<tr>
<th>Clearance</th>
<th>Wheel Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15.18m/s</td>
</tr>
<tr>
<td>0.5mm</td>
<td>2.35°</td>
</tr>
<tr>
<td>1mm</td>
<td>2.11°</td>
</tr>
<tr>
<td>2mm</td>
<td>1.41°</td>
</tr>
<tr>
<td>5mm</td>
<td>1.32°</td>
</tr>
</tbody>
</table>

5.7 Conclusions

In this chapter, an air flow simulation model is introduced. The process of building this model is presented in detail, including the dimensionless factors, the criteria for choosing turbulence model. From the simulation results, air pressure distribution and velocity vector figures are obtained. These simulation results can be used for the grinding fluid nozzle angle setting.
Chapter 6

Grinding Area Useful Flow Rate Simulation

6.1 Introduction

To build the model and make an intuitionistic understanding of the work, the grinding fluid flow domain is divided into three zones: the airflow zone, the mixing zone and the grinding zone. The airflow zone, which is formed by the rotation of the grinding wheel simulated in the previous section, and the mixing zone which is the airflow mixed with the grinding fluid injecting from the nozzle. A wedge-shaped area is formed by the profile of the grinding wheel and workpiece. From the previous airflow simulations, grinding fluid can have a backflow due to the small area in grinding zone and the airflow affection. The grinding zone is the grinding contact area.

The energy consumed per unit volume of the material in grinding is much higher than other machining methods. The heat generated in the grinding area effects on the chips, grinding wheel and workpiece, which influences the workpiece surface qualification and grinding process performance. To decrease the grinding area temperature, delivery of cutting fluid via a nozzle in the form of a jet is widely used in the industry. But as mentioned previously, the air layer produced by the rotation of the grinding wheel can prevent the grinding fluid applying into the grinding contact area. On
the other hand, the abrasive grains are randomly distributed on the surface of grinding wheels. In the grinding contact area, the abrasives bonded on the circular surface can be treated as cutting tools, gaps are formed between each abrasive grains. The grinding fluid flows through and fills in these gaps; this part of the grinding fluid is called the useful flow, thus, the grinding area can be analogized to “porous area”. The volume of effective grinding fluid entering into in the grinding contact area is only 5% ~ 35% of the total applied grinding fluid. The grinding fluid which is not entering into the grinding contact area only has the cooling function on the workpiece and grinding wheel. Only the effective grinding fluid in the grinding contact area has both cooling and lubrication functions to prevent grinding wheel wear, decreasing the grinding temperature and increasing the workpiece surface qualification. The useful grinding flow rate is the volume ratio of effective grinding fluid divided by total applied grinding fluid.

In this section, useful flow rate in grinding contact area is simulated with different types of grinding fluid. The relations of useful flow rate with wheel speed, depth of cut and viscosity are built.

6.2 Dimensional Analysis

6.2.1 Reynolds Number

For the pipe with noncircular cross section inlet, the following equation is applied for the Reynolds number:

\[ \text{Re} = \frac{4vR}{\mu} \]  

(6.1)

where
The velocity of grinding fluid from inlet

\( \mu \): The kinematic viscosity of grinding fluid

\( R \): The ratio of nozzle inlet area and perimeter

The Reynolds number for this simulation model is \( 9.34 \times 10^5 \), which is higher than 2300. The grinding fluid flow in this model is considered as turbulence.

### 6.2.2 Turbulence Intensity

For internal flow, the turbulence intensity in the inlet is wholly dependent on the upstream of the flow. If the upstream flow is not fully developed or not disturbed, it can be considered as low turbulence intensity. If the flow is fully developed, the turbulence intensity can use the following empirical formula to calculate. This dimensionless quantity is a relative number to describe the turbulence intensity. Usually, low turbulence intensity is less than 1% and strong turbulence intensity is higher than 10%.

\[
I \approx \frac{0.16}{(Re)^{0.16}}
\]

In this model, the turbulence intensity is 2.15%.

### 6.2.3 Turbulence Length

The turbulence length \( l \) is a physical quantity describing the size of eddies in a turbulent flow. The turbulence intensity is often used to estimate the turbulence characteristics on the inlet of the CFD simulation. The relations between turbulence length and the physical size of the pipe is:

\[
l = 0.07 \cdot D
\]
where D is the diameter of the pipe. In this model, the pipe diameter is 25.4mm, so the turbulence length is 1.778 mm.

6.2.4 Weber Number

The Weber number \( (We) \) is a dimensionless number in fluid dynamics. When interface exists between different types of fluid, especially in multiphase flow with large curvature, the Weber number is used to analyze the surface tension effect in fluid motion.

\[
We = \frac{\rho v^2 L}{\sigma}
\]

(6.4)

where \( \sigma \) is surface tension.

The Weber number represents the ratio of inertial force and surface tension, the smaller the weber number, the greater the surface tension, such as capillary, bubbles, small scale problems. Generally, in the model with large dimension, the \( We >> 1 \), the effect of surface tension can be ignored.

In this model, two types of fluid flow are involved: grinding fluid and air. Due to the interface existence, interaction between these two types of fluid flow generates surface tension. Thus, the Weber number calculation is important to obtain the surface tension effect.

The Weber number in this model is around \( 1.9 \times 10^6 \) which is greater than 1, so the effect of surface tension in this model is not very obvious.

As mentioned in Chapter 4, dynamic viscosity and surface tension are considered as key factors in the grinding process. Due to effect of surface tension in this model is not very obvious. The effect of dynamic viscosity are more concerned about.
6.2.5 Mach Number

The Mach number \((Ma)\) is an important dimensionless quantity to characterize fluid compressibility. It is defined by the ratio of an object moving through a fluid and the speed of sound in that fluid for its particular physical conditions

\[
Ma = \frac{V}{a}
\]  \hspace{1cm} (6.5)

The relative velocity of the object moving through the fluid in useful flow rate simulation model and the model in Chapter 5 is the same, as well as the speed of sound. The Mach number is 0.089. Thus, incompressible pressure based solver is chosen.

6.3 Criteria of Turbulence Model Selection

Due to the sorts of turbulence model emphasis, different types of simulation methods in the same grid quality model have various effects on simulation results. The criterion of turbulence model selection depends on the geometry scale and the complexity of the flow field in the computational domain. Computer CPU requirement and simulation time are also important factors for criterion. The simulation model built in this project contains stationary and moving wall boundaries, porous medium and fluid region. The geometries are complex both in porous region and fluid region. Based on Mihić’s previous research [59], the Reynolds stress model was chosen due to its more accurate performance attributed to the superior Reynolds stress transport model. The Reynolds stress model (RSM) is the most elaborate type of RANS turbulence model that ANSYS FLUENT provides [60]. Abandoning the isotropic eddy-viscosity hypothesis, the RSM closes the Reynolds-averaged Navier-Stokes equations by solving transport equations for
the Reynolds stresses, together with an equation for the dissipation rate. Compared with k-epsilon and k-omega turbulence model, RSM has five additional transport equations required in 2D flows and seven additional transport equations solved in 3D flows [58].

6.4 Governing Equations in the Simulation Setting

The governing equations listed in the solution controls in ANSYS FLUENT are flow, volume fraction and turbulence. The flow equations are including continuity equation and momentum equation which are the same as air flow simulation. The details of turbulence and volume fraction equations are in the following sections.

6.4.1 Reynolds Stress Transport Equations

The exact transport equations for the transport of the Reynolds stresses are written as follows [58]:

\[
\frac{\partial}{\partial t} \left( \rho u_i' u_j' \right) + \frac{\partial}{\partial x_k} \left( \rho u_k u_i' u_j' \right) = -\frac{\partial}{\partial x_k} \left[ \rho u_i' u_j' + p' \left( \delta_{ij} \delta_{ik} + \delta_{ik} \delta_{ij} \right) \right] + \frac{\partial}{\partial x_k} \left[ \mu \frac{\partial}{\partial x_k} \left( u_i' u_j' \right) \right] \\
- \rho \left( u_i' u_k' \frac{\partial u_j}{\partial x_k} + u_j' u_k' \frac{\partial u_i}{\partial x_k} \right) - \rho \beta \left( g, u_i' \theta + g, u_j' \theta \right) + p' \left( \frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i} \right) - 2\mu \frac{\partial u_i'}{\partial x_k} \frac{\partial u_j'}{\partial x_k} \\
- 2\mu \Omega_k \left( u_i' u_m' \varepsilon_{ikm} + u_j' u_m' \varepsilon_{jkm} \right) + S_{user} \tag{6.6}
\]

where

\[
\frac{\partial}{\partial t} \left( \rho u_i' u_j' \right) \text{ is local time derivative}
\]

\[
\frac{\partial}{\partial x_k} \left( \rho u_k u_i' u_j' \right) = C_{ij} \text{ is convection term}
\]
\[-\frac{\partial}{\partial x_k} \left[ \rho u_i' u_j' + p' (\delta_{ij} u_i' + \delta_{ik} u_k') \right] = D_{T,ij} \] is turbulent diffusion term

\[ \frac{\partial}{\partial x_k} \left[ \mu \frac{\partial}{\partial x_k} (u_i' u_j') \right] = D_{L,ij} \] is laminar diffusion term

\[-\rho \left( u_k' \frac{\partial}{\partial x_k} u_j' + u_j' \frac{\partial}{\partial x_j} u_k' \right) = P_{ij} \] is stress production term

\[-\rho \beta \left( g_i u_i' \theta + g_j u_j' \theta \right) = G_{ij} \] is buoyancy production term

\[ p' \left( \frac{\partial u_i'}{\partial x_i} + \frac{\partial u_j'}{\partial x_j} \right) = \phi_{ij} \] is pressure strain term

\[-2\mu \frac{\partial u_i'}{\partial x_k} \frac{\partial u_j'}{\partial x_k} = \varepsilon_{ij} \] is dissipation term

\[-2\rho \Omega_k \left( u_i' u_m' \epsilon_{km} + u_i' u_m' \epsilon_{jm} \right) = F_{ij} \] is production by system rotation term

\( S_{uesr} \) is user-defined source term. \( D_{T,ij}, G_{ij}, \phi_{ij}, \) and \( \varepsilon_{ij} \) are modeled to close the equations but terms \( C_{ij}, D_{L,ij}, P_{ij} \) and \( F_{ij} \) require modeling [58].

### 6.4.2 Modeling Turbulent Diffusive Transport

Daly and Harlow [61] built a gradient-diffusion model to describe \( D_{T,ij} \).

\[ D_{T,ij} = C_k \frac{\partial}{\partial x_k} \left( \rho \frac{k u_k' u_i' \varepsilon}{\varepsilon_{jk}} u_j' \right) \] (6.7)

But as this model can result in numerical instabilities, so a simplified model using a scalar turbulent diffusivity is listing as follows [58]:

\[ D_{T,ij} = \frac{\partial}{\partial x_k} \left( \frac{\mu_k \varepsilon}{\sigma_k} u_k' u_j' \right) \] (6.8)
The turbulent viscosity $\mu_t$ is computed as follows [58]:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (6.9)$$

By applying the generalized gradient diffusion model on Eq. (6.8), a value of $\sigma_k = 0.82$ is derived by Lien and Leschziner [62] to the case of a planar homogeneous shear flow [58].

6.4.3 Modeling the Pressure-Strain Term

Fluid flow over curved surfaces and swirling fluid flows are involved in the grinding processes applications. In ANSYS FLUENT, the low-Re stress-$\omega$ model is perfect for modeling grinding fluid flow. This model is a stress-transport model that is based on the omega equations and $LRR$ model [63].

This low-Re stress-omega model has a wide range of turbulent flows applications due to its accurate predictions by resembling the k-omega model. In addition, it is similar to the k-omega model with low Reynolds number modifications and surface boundary conditions for rough surfaces [58].

Eq. (6.10) is the re-written equation for the low-Re stress-omega model with exclusion of wall reflections [58].

$$\phi_y = \phi_{y,1} + \phi_{y,2} \quad (6.10)$$

Therefore,

$$\phi_y = -C_1 \rho \beta_{RSM} \alpha \left( \overline{\mu_i u_j^i} - \frac{2}{3} \delta_{ij} k \right) - \tilde{\alpha}_0 \left( P_{ij} - \frac{1}{3} P_{kk} \delta_{ij} \right) - \tilde{\beta}_0 \left( D_{ij} - \frac{1}{3} P_{kk} \delta_{ij} \right) - k \tilde{\gamma}_0 \left( S_{ij} - \frac{1}{3} S_{kk} \delta_{ij} \right) \quad (6.11)$$
where $D_{ij}$ is defined as [58]:

$$
D_{ij} = -\rho \left( u_i u_m \frac{\partial u_m}{\partial x_j} + u_j u_m \frac{\partial u_m}{\partial x_i} \right)
$$  \hspace{1cm} (6.12)

The mean strain rate $S_y$ is defined in Eq. (6.13) [58]:

$$
S_y = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
$$  \hspace{1cm} (6.13)

$\beta^*_\text{RSM}$ is defined by [58]:

$$
\beta^*_\text{RSM} = \beta^* f^*_\beta
$$  \hspace{1cm} (6.14)

where $\beta^*$ and $f^*_\beta$ are defined as follows which is the same for standard k-omega model [58].

$$
\beta^* = 0.09
$$  \hspace{1cm} (6.15)

$$
f^*_\beta = \begin{cases} 
1 & \chi \leq 0 \\
\frac{1 + 680 \chi^3}{1 + 400 \chi^2} & \chi > 0 
\end{cases}
$$  \hspace{1cm} (6.16)

where $\chi_k = \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$ [58]

The constants are showing in the following [58]:

$$
\hat{\alpha}_0 = \frac{8 + C_2}{11}
$$

$$
\hat{\beta}_0 = \frac{8C_2 - 2}{11}
$$

$$
\hat{\gamma}_0 = \frac{60C_2 - 4}{55}
$$

$C_1 = 1.8$

$C_2 = 0.52$
6.4.4 Effects of Buoyancy on Turbulence

The buoyancy production terms are shown in Eq. (6.17) [58]:

\[ G_g = -\rho \beta \left( g_i u'_j \theta + g_j u'_i \theta \right) \]  \hspace{1cm} (6.17)

\[ \overline{U'_i \theta} = \frac{\mu_t}{Pr_t} \left( \frac{\partial T}{\partial x_i} \right) \]  \hspace{1cm} (6.18)

where \( Pr_t = 0.85 \) is the turbulent Prandtl number for energy.

\( \beta \) is defined as the coefficient of thermal expansion which is given in Eq. (6.19) [58]:

\[ \beta = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p \]  \hspace{1cm} (6.19)

Ideal gas is expressed as the following [58]:

\[ G_g = -\frac{\mu_t}{\rho Pr_t} \left( g_i \frac{\partial \rho}{\partial x_j} + g_j \frac{\partial \rho}{\partial x_i} \right) \]  \hspace{1cm} (6.20)

6.4.5 Modeling the Turbulence Kinetic Energy

In most cases, a specific term is obtained by taking the trace of the Reynolds stress tensor when the turbulence kinetic energy is needed [58].

\[ k = \frac{1}{2} \overline{u'_i u'_i} \]  \hspace{1cm} (6.21)

In order to obtain boundary conditions for the Reynolds stresses, an option is available in ANSYS FLUENT to solve a transport equation for the turbulence kinetic energy. The following model equation is used in this case [58]:
\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + H_s}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \frac{1}{2} (P_{ii} + G_{ii}) - \rho \varepsilon \left( 1 + 2M_t^2 \right) + S_k \tag{6.22}
\]

where \( \sigma_k = 0.82 \) and \( S_k \) is a user-defined source term. The values of \( k \) obtained are used only for boundary conditions although Eq. (6.22) is solved. In every other condition, the turbulence kinetic energy is calculated by Eq. (6.21) \([58]\).

### 6.4.6 Modeling the Dissipation Rate

The dissipation tensor \( \varepsilon_{ij} \) is modeled as \([58]\):

\[
\varepsilon_{ij} = \frac{2}{3} \delta_{ij} (\rho \varepsilon + Y_M) \tag{6.23}
\]

where \( Y_M = 2\rho \varepsilon M_t^2 \) is proposed by Sarkar, which is an additional “dilatation dissipation” term according to the model \([64]\). The turbulent Mach number is defined as follows in this equation:

\[
M_t = \left( \frac{k}{a^2} \right)^{0.5} \tag{6.24}
\]

where \( a \equiv \left( \gamma RT \right)^{0.5} \) is the sound speed.

Eq. (6.25) is used to compute the scalar dissipation rate \( \varepsilon \) \([58]\):

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + \mu_s}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] C_{\varepsilon 1} \frac{1}{2} (P_{ii} + C_{\varepsilon 3} G_{ii}) \frac{\varepsilon}{k} - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \tag{6.25}
\]

where \( \sigma_\varepsilon = 1, C_{\varepsilon 1} = 1.44, C_{\varepsilon 2} = 1.92 \) and \( S_\varepsilon \) is a user-defined source term \([58]\).

### 6.4.7 Modeling the Turbulent Viscosity

Eq. (6.26) is used to compute the turbulent viscosity \( \mu_t \) \([58]\):

\[

\]

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\[ \mu_i = \rho C_{\mu} \frac{k^2}{\varepsilon} \]  

(6.26)

where \( C_{\mu} = 0.09 \)

### 6.4.8 Wall Boundary Conditions

The boundary conditions is set for individual Reynolds stresses, \( \overline{u'\mu_j} \), and the turbulence dissipation rate \( \varepsilon \) (or \( \omega \) if the press strain term is low Re stress-omega model) in Reynolds stress model. In simulations for this model, these quantities can be derived from the turbulence intensity and characteristic length which is shown in Eq. (6.2) and Eq. (6.3) [58].

The near-wall values of the Reynolds stresses \( \overline{u'\mu_j} \) and turbulence dissipation rate \( \varepsilon \) are computed from wall functions. The wall boundary conditions for Reynolds stresses are explicit. Using the log-law and the assumption of equilibrium method for explicit wall boundary conditions, neglecting diffusion and convection in the transport equations for stresses. This model simulation is running in a local coordinate system, where \( \tau \) is the tangential coordinate, \( \eta \) is the normal coordinate and \( \lambda \) is the binormal coordinate. The Reynolds stresses at the wall-adjacent cells are computed from the following [58]:

\[ \frac{\overline{u_i'^2}}{k} = 1.098, \quad \frac{\overline{u^2}}{k} = 0.247, \quad \frac{\overline{u^2}}{k} = 0.655, \quad -\frac{\overline{u_i'\mu_j'}}{k} = 0.255 \]  

(6.27)

From Eq. (6.22), \( k \) is obtained by the calculation. Even though the calculation of values of \( k \) are only needed near the wall, the equation is solved globally for reasons of computational convenience. In the default setting, the values of the Reynolds stresses near the wall are fixed using the values computed from Eq. (6.26) [58].
Another way to explicitly specify the Reynolds stresses in terms of wall-shear stress, instead of $k$, is [58]:

$$\frac{u_r'^2}{u_r^2} = 5.1, \quad \frac{u_y'^2}{u_r^2} = 1.0, \quad \frac{u_z'^2}{u_r^2} = 2.3, \quad -\frac{u'_i u'_j}{u_r^2} = 1.0 \tag{6.28}$$

where $u_r$ is the friction velocity defined by

$$u_r \equiv \left( \frac{\tau_w}{\rho} \right)^{0.5}, \quad \tau_w$$

is the wall-shear stress. When wall treatments are used as the near-wall treatment, ANSYS FLUENT set Reynolds stress equations wall boundary conditions to 0 [58].

### 6.4.9 Convective Heat and Mass Transfer Modeling

Using the concept of Reynolds’ analogy to turbulent momentum, turbulent heat transport is modeled with the Reynolds stress model in ANSYS FLUENT [58]:

$$\frac{\partial}{\partial t} (\rho E) + \frac{\partial}{\partial x_i} \left[ u_i (\rho E + p) \right] = \frac{\partial}{\partial x_j} \left[ \left( k + \frac{c_p \cdot \mu_e}{Pr_t} \right) \frac{\partial T}{\partial x_j} + u_i \left( \tau_{ij} \right)_{\text{eff}} \right] + S_h \tag{6.29}$$

where $E$ is the total energy and $\left( \tau_{ij} \right)_{\text{eff}}$ is defined in Eq. (6.29) which is the deviatoric stress tensor [58].

$$\left( \tau_{ij} \right)_{\text{eff}} = \mu_{\text{eff}} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij} \tag{6.30}$$

$\left( \tau_{ij} \right)_{\text{eff}}$ represents the viscous heating and usually used in the density-based solver in default setting in ANSYS FLUENT. It can be enabled in the viscous model dialog box for the pressure-based solver. The default value of the turbulent Prandtl number is 0.85 [58].

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It is similarly for turbulent mass transfer, the default value of turbulent Schmidt number is 0.7 [58].

6.5 Modeling of Porous Zone

The key to modeling the grinding contact area between the grinding wheel and workpiece surface is the porous zone, which describes the grinding fluid in the contact area as a flow through a porous medium. This generates complex paths which the grinding fluid must flow through. The grinding fluid changes direction, separates and loses energy when flowing in the porous zone. On the other hand, part of grinding fluid flow in the porous zone is driven by the rotation motion of the grinding wheel. The porous zone is considered as moving with the tangential velocity of the grinding wheel. When the porous medium model is used, this zone can be defined by the ANSYS FLUENT setting.

The porous medium model can be described by the addition of a momentum sink term $S_i$ of Navier-Stokes equations. Eq. (6.31) is the sink term which is composed by two parts: Darcy’s viscous loss term and an inertial loss term [58].

$$S_i = -\left(\sum_{j=1}^{3} D_{ij} \cdot \mu \cdot v_j + \sum_{j=1}^{3} C_{ij} \cdot \frac{1}{2} |v| \cdot v_j\right)$$  \hspace{1cm} (6.31)

where

$S_i$: The source term for the x, y, z momentum equation

$|v|$: The magnitude of velocity

$D_{ij}$ and $C_{ij}$ are prescribed matrices describing the properties of the porous medium, which must be measured or theoretically predicted [58].
This momentum sink is caused by pressure gradient in the porous zone, creating a pressure drop which is proportional to the grinding fluid velocity (Darcy’s viscous loss term) or velocity squared (the inertial loss term) in the cell. The sink term is modeled as a power law of the velocity magnitude in ANSYS FLUENT [58]:

\[ S_i = -C_0 \cdot |v|^C_i = -C_0 \cdot |v|^{(C_i-1)} \cdot v_i \]  

(6.32)

where \( C_0 \) and \( C_i \) are empirical coefficients which are defined by users. For the turbulence flow with large flow velocity, coefficients \( C_{ij} \) corrects the inertial losses in the porous medium. The coefficient is specified as a function of the dynamic head for the pressure drop and it can be viewed as a loss coefficient per unit length along the flow direction.

ANSYS FLUENT modifies the conduction flux and transient terms in the standard energy transport equation which is used for describing porous medium. In the porous area, thermal inertia of the solid region on the porous medium (grinding contact area) is included in the effective conductivity and the transient term of conduction flux [58].

\[
\frac{\partial}{\partial t} \left[ \gamma \cdot \rho_f \cdot \dot{E}_f + (1-\gamma) \cdot \rho_s \cdot \dot{E}_s \right] + \nabla \cdot \left[ \nu \left( \rho_f \cdot \dot{E}_f + p \right) \right] \\
= \nabla \cdot \left[ k_{eff} \nabla \cdot T - \sum_i h_i \cdot J_i \right] + (\bar{\tau} \cdot v) + S^h_f
\]

(6.33)

where \( k_f \) is the thermal conductivity and \( k_s \) is the solid thermal conductivity, both \( k_f \) and \( k_s \) can be computed through user-defined functions. The anisotropic effective thermal conductivity can also be solved via user-defined functions [58].

In this project, the abrasive grains contact in grinding contact area are simulated as porosity model. This model uses permeability and inertial loss coefficients [58]. The following equation is Ergun equation to characterize fluid flow by a wide range of Reynolds numbers. It is a semi-empirical correlation [65].
\[
\frac{|\Delta \rho|}{L} = \frac{150 \cdot \mu}{D_p^2} \cdot \left(1 - \frac{\epsilon}{\epsilon^3}\right)^2 \cdot v \cdot \frac{1.75 \cdot \rho}{D_p} \cdot \left(1 - \frac{\epsilon}{\epsilon^3}\right) \cdot v^2
\]  
(6.34)

where

\( \mu \): Fluid viscosity

\( D_p \): Grain size

\( L \): The length of the grinding contact area

\( E \): The volume of voids divided by the total volume of the grinding contact area, which is equals to the grinding wheel porosity in this project.

Darcy’s Law is expressed as followings [58]:

\[
\nabla p = -\frac{\mu}{\alpha} \cdot v
\]  
(6.35)

where \( \alpha \) is permeability

The porous medium equation can be simplified as [58]:

\[
\alpha = \frac{D_p^2 \cdot \epsilon^3}{150 \cdot (1 - \epsilon)^2}
\]  
(6.36)

and:

\[
C_s = \frac{3.5 \cdot (1 - \epsilon)}{D_p \cdot \epsilon^3}
\]  
(6.37)

### 6.6 Multiphase Models

In Chapter 5, grinding air flow simulation modeling, only one type of fluid involves in the simulation, which is air. But in the model built in this chapter, many flows encounter in which have a mixture of different fluid phases, such as grinding fluid and air. In order to make the model conforms to the real state of the experiment and make it can
simulate the interaction between different fluid phase. Here need to introduce the concept of a multiphase flow model

Usually, a phase is a class of matter with a definable boundary and a particular dynamic response to the surrounding flow or potential field. Phases are generally identified by gas, liquid and solid. So multiphase flow can be grouped into five types: gas-liquid flows, liquid-liquid flows, gas-solid flows, liquid-solid flows and three-phase flows.

6.6.1 Approaches to Multiphase Model

ANSYS FLUENT has two main approaches for the numerical calculation of multiphase model: the Euler-Lagrange approach and the Euler-Euler approach. The Euler-Lagrange approach is used in the discrete phase model (DPM). For the Euler-Euler approach, three different multiphase models are available: the volume of fluid (VOF) model, the mixture model and the Eulerian model.

In the Euler-Euler approach, the different phases are treated mathematically as interpenetrating continua. The volume of a phase is treated as an independent object, it cannot be occupied or exchanged by the other phases. The total volume of these volume fractions, which are assumed to be continuous in space and time, is equal to one. A set of equations are derived from conservation equations for each phase. These equations are closed by providing constitutive relations that are obtained from empirical information.

The volume of fluid (VOF) model is a surface-tracking technique. In this model, the different immiscible fluid phases are solved in a single set of momentum equations. Each volume fraction of the fluids in each computational cell is tracked throughout the
domain. Many types of applications can be used in the VOF model, such as stratified flows, free-surface flows, filling, sloshing, the motion of large bubbles in a liquid, the motion of liquid after a dam break and the prediction of jet breakup (surface tension).

The mixture model is used for two for more phases. A set of mixture momentum equations are solved for mixture model. The types of applications can be used in mixture models, including particle-laden flows with low loading, bubbly flows, sedimentation, and cyclone separators.

In ANSYS FLUENT, the Eulerian model is the most complicated multiphase model. Different from the previous one, $n$ momentum and continuity equations for each phase is solved. Through the pressure and interphase exchange coefficients, coupling is achieved. This coupling handles two types of phases: granular (fluid-solid) flow and nongranular (fluid-fluid) flow. Bubble columns, risers, particle suspension, and fluidized beds are the applications of the Eulerian multiphase model.

6.6.2 Criteria for Choosing Multiphase Model

A few criteria are used for choosing the multiphase model. First of all, we need to have a detailed understanding of the simulation model in the project. Determine which multiphase flow regime is best representing the flow in the simulation model.

(a) For bubbles, droplet and loaded flow, the volume fraction is less than 10%, the discrete phase model (DPM) is chosen.

(b) For bubbles, droplet and loaded flow, if it is discrete phase mixture or separate discrete phase volume fracture exceeds 10%. The mixture model or Eulerian model are chosen.
(c) For bubble flow and plug flow, the VOF model is chosen.
(d) For stratified free surface flow, the VOF model is chosen.
(e) Uniform flow uses the mixture model and particles flow uses Eulerian model.
(f) For fluidized beds, the Eulerian model is chosen.
(g) For mud and water transportation, the mixture model or Eulerian model are chosen.
(h) For sedimentation, the mixture model is chosen.
(i) For more general and contains a variety of multiphase flow pattern, choosing the appropriate flow model according to the flow characteristics. At this time, because the model adopted is a better simulation for partial flow characteristics, not all characteristics are included in the model. The precision is not as accurate as the single multiphase pattern model.

The model built in this chapter includes two phase flows: air and grinding fluid. Each phase is a single phase and cannot be assimilated by any other phase. It is clearly a stratified, immiscible free-surface flows. Based on criteria for choosing the multiphase model, the volume of fluid (VOF) model is a proper option.

6.6.3 Volume of Fluid (VOF) Model Theory

The VOF model is used for modeling two or more immiscible, stratified fluids. This model is solved in a single momentum equation.

6.6.3.1 Steady-State and Transient VOF Calculations

ANSYS FLUENT has two methods to calculate: steady-state and transient-state. The VOF model is generally used to be computed in transient-state, which is a time-
solution. It can also be possible to perform a steady-state calculation when the solution is independent of the initial conditions of the momentum equations. The flow in steady-state calculation has distinct boundaries for each individual phases [58].

The fluid phase in the VOF model is not interpenetrating, the sum of volume fractions of all phases is one. All variables and properties of field are shared by the phases. The value of each phase is represented in volume-averaged level and the volume fraction of each phase is known at each location. In ANSYS FLUENT, the volume fraction of the phase is representative of computational cell. Therefore, each cell in the VOF model represents one phase or a mixture of the phases. The following are three conditions of computation cell [58]:

(a) \( a_q = 0 \): The cell is empty of the \( q^{th} \) fluid

(b) \( a_q = 0 \): The cell is full of the \( q^{th} \) fluid

(c) \( 0 < a_q < 0 \): The cell includes \( q^{th} \) fluid and one or more other fluids. Interface is formed between each fluid.

where \( a_q \) is the volume fraction of the \( q^{th} \) fluid in the cell. The appropriate variables and properties will be assigned to each cell based on the local value of \( a_q \) [58]

### 6.6.3.2 Volume Fraction Equation

For the \( q^{th} \) phase, the following is the continuity equation for the volume fraction of one (or more) of the phases [58]:

\[
\frac{1}{\rho_q} \left[ \frac{\partial}{\partial t} (a_q \rho_q) + \nabla \cdot (a_q \rho_q \mathbf{v}_q) \right] = S_{a_q} + \sum_{p=1}^{q} (m_{pq} - m_{qp})
\]

(6.38)
where $m_{pq}$ is mass transfer from phase $p$ to phase $q$, $m_{qp}$ is mass transfer from phase $q$ to phase $p$ [58].

The primary-phase volume fraction which will not be solved in the volume fraction equation will be computed based on the following constraint [58]:

$$\sum_{q=1}^{n} a_q = 1$$

(6.39)

6.6.3.2.1. The Implicit Scheme

The discretization calculation is ANSYS FLUENT standard finite-difference interpolation scheme. Two schemes can be used to solve the volume fraction equation: implicit and explicit time discretization [58].

The implicit scheme includes four main schemes to solve the face fluxes for all cells inside the domain and near the interface: QUICK, Second Order Upwind, First Order Upwind and the Modified HRIC schemes [58].

$$\frac{a_q^{n+1} \rho_q^{n+1} - a_q^n \rho_q^n}{\Delta t} V + \sum_f \left( \rho_f^{n+1} U_f a_{q,f}^{n+1} \right) = \left[ \sum_{p=1}^{n} \left( m_{pq} - m_{qp} \right) + S_q \right] V$$

(6.40)

In the implicit scheme, the volume fraction values were calculated at the current time step in ANSYS FLUENT’s standard finite-difference interpolation scheme. A standard scalar transport equation is solved iteratively for each of the secondary-phase volume fractions at each time step. The implicit scheme can be used for both steady-state calculations and time-dependent calculations [58].

where

$n+1$: The index for current time step
\( n \): The index for previous time step

\( a_{q,f} \): The face value of the \( q^{th} \) volume fraction

\( V \): Cell volume

\( U_f \): Volume flux through the face

6.6.3.2.2. The Explicit Scheme

Compared with the implicit scheme, explicit requires the volume fraction values at previous time step instead of current time step [58].

\[
\frac{a_{q}^{n+1} P_{q}^{n+1} - a_{q}^{n} P_{q}^{n}}{\Delta t} V + \sum_{f} \left[ \rho_{q} U_{f}^{n} a_{q,f}^{n} \right] = \left[ \sum_{p=1}^{n} (m_{pq}^{n} - m_{qp}^{n}) + S_{a_{q}} \right] V
\]  

(6.41)

An iterative solution of the transport equation during each time step is not required in this equation [58].

6.6.3.3 Material Properties

The material properties, such as density, viscosity and surface tension, in the transport equation are comprehensive performance of the phases’ properties. They are determined by the component phases in each control volume. For example, in a multiphase model including \( n \)-phase, the phases are identified by the subscript 1, 2 until \( n \), if the volume fraction of the first phase is tracked, the viscosity in each cell is given by the following equation [58]:

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\[ \mu = \alpha_i \mu_i + (1 - \alpha_i - \alpha_j - \alpha_k) \mu_2 + \ldots \]
\[ = \sum_{1}^{n} \alpha_q \mu_q \] (6.42)

All the material properties can be calculated in this way.

### 6.6.3.4 Momentum Equation

In the simulation domain, a single momentum equation is solved depending on the volume fractions of all phases through the density \( \rho \) and viscosity \( \mu \), the resulting velocity field is shared among the phases [58].

\[ \frac{\partial}{\partial t} (\rho v) + \nabla \cdot (\rho vv) = -\nabla p + \nabla \cdot \left[ \mu \left( \nabla v + \nabla v^T \right) \right] + \rho g + F \] (6.43)

The accuracy of the calculated velocities near the interface can be adversely affected due to the limitation of the shared-fields approximation. In that area, large velocity differences exist between the phases [58].

### 6.6.3.5 Energy Equation

Eq. (6.44) is the energy equation in the VOF model. This equation, including the properties \( \rho \) and \( k_{\text{eff}} \) (effective thermal conductivity), is shared among the phases. \( S_h \) is the heat source including not only conduction and convection, but also the radiation contributions [58].

\[ \frac{\partial}{\partial t} (\rho E) + \nabla \cdot \left[ \nu (\rho E + p) \right] = \nabla \cdot \left( k_{\text{eff}} \nabla T \right) + S_h \] (6.44)

where energy \( E \) and temperature \( T \) is mass-averaged variables in the VOF model.
Similar to the velocity in momentum, due to the properties vary by several orders of magnitude, the accuracy of the calculated temperature near the interface is limited if large temperature differences exist between the phases [58].

6.6.3.6 Surface Tension and Adhesion

Surface tension is due to the unbalanced molecular attraction effect on any line along the liquid surface. In ANSYS FLUENT, the effects of surface tension along the interface between each phase are taken into account. The surface tension coefficient can be defined as a constant, or as a function of a variable through a User Defined Function (UDF), or as a function of temperature. An additional Marangoni convention tangential stress term is included due to the surface tension coefficient variable functions. Usually, the effects of the surface tension coefficient can only be shown in a zero gravity environment [58].

Two surface tensions are included in ANSYS FLUENT, the continuum surface force (CSF) and the continuum surface stress (CSS) [58].

6.6.3.6.1. The Continuum Surface Force Model

Brackbill [66] presented the continuum surface force model (CSF). The surface tension is added to the VOF calculation results in a source term in the momentum equation. To have a better understanding of the origin of the source term, a special case is
considered. In this case, along the surface, the surface tension is a constant. Consider the normal force on the interface, it can be shown that the pressure drop across the surface depends upon the surface tension coefficient $\sigma$ and the surface curvature as measured by two radii in orthogonal directions $R_1$ and $R_2$ [58]:

$$p_2 - p_1 = \sigma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (6.46)$$

where $p_1$ and $p_2$ are the pressure on both side of the interface in the two fluids.

An equation of the CSF model in ANSYS FLUENT is used, including the computation of surface curvature from local gradients in the surface normal at the interface. Define $n$ as the gradient $a_q$ in the surface normal in the $q^{th}$ volume fraction phase [58].

$$n = \nabla a_q \quad (6.47)$$

The divergence of the unit normal $\hat{n}$ is the curvature $\kappa$ [58]:

$$\kappa = \nabla a_q \quad (6.48)$$

where

$$\hat{n} = \frac{n}{|n|} \quad (6.49)$$

A volume force expressing the force at the surface is added to the source term in the momentum equation in Eq. (6.49) [58]:

$$F_{vol} = \sum_{pairs\ j<i} \sigma_{ij} \alpha_i \rho_i \kappa_j \nabla a_j + \alpha_j \rho_j \kappa_i \nabla a_i \frac{1}{2} \left( \rho_i + \rho_j \right) \quad (6.50)$$

Eq. (6.50) can be simplified if two phases in a cell [58]:

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\[ F_{\text{vol}} = \sigma_{ij} \frac{\rho \kappa_j \nabla \alpha_i}{\frac{1}{2}(\rho_i + \rho_j)} \]  \hspace{1cm} (6.51)

where \( \rho \) is the volume-average density which is proportional to the surface tension in the cell.

6.6.3.6.2. The Continuum Surface Stress Model

An alternative way to modeling surface tension is the continuum surface stress (CSS) model in a conservative manner. Compared with continuum surface force (CSF) model, CSS model can be expressed as an anisotropic variant of modeling capillary forces based on surface stresses with no explicit curvature calculation [58].

In the CSS model, the surface stress tensor is [58]:

\[ T = \sigma \left(1 - \hat{n} \otimes \hat{n}\right)|\n| \]  \hspace{1cm} (6.52)

\[ n = \nabla \alpha \]  \hspace{1cm} (6.53)

\[ \hat{n} = \frac{n}{|n|} \]  \hspace{1cm} (6.54)

where

\( I \): Unit tensor

\( \sigma \): Surface tension coefficient

\( \otimes \): Tensor product of the two vectors: the original normal and the transformed normal

\( \alpha \): Volume fraction

\( n \): Volume fraction gradient

Substitute Eq. (6.53) and (6.54) into Eq. (6.52) yields [58]:
\[ T = \sigma \left( \nabla \alpha |I - \frac{\nabla \alpha \otimes \nabla \alpha}{|\nabla \alpha|} \right) \]  \hspace{1cm} (6.55)

The surface tension force is expressed as follows [58]:

\[ F_{CSS} = \nabla T \]  \hspace{1cm} (6.56)

6.6.3.6.3. Surface Tension Effects

The surface tension effects are determined by two dimensionless quantities in different fluid patterns [58].

When the Reynolds number \( Re >> 1 \), the fluid pattern is turbulence flow, if the Weber number \( We >> 1 \), the effect of surface tension can be neglected. This has been mentioned in Chapter 6.2.4.

When the Reynolds number \( Re << 1 \), if the Capillary number \( Ca >> 1 \), surface tension effect is not very significant. Eq. (6.57) is the Capillary number, and Eq. (6.4) is the Weber number.

\[ Ca = \frac{H \nu}{\sigma} \]  \hspace{1cm} (6.57)

6.6.3.7 Open Channel Flow

The fluid flow pattern in the grinding process can be treated as open channel flow due to the existence of a free surface between the grinding fluid and surrounding air above it. In this condition, the spread of the air and the grinding fluid on the surface is very important. They are driven by gravity and inertia [58].
Open channel flow has two main conditions: upstream boundary condition and downstream boundary condition. Froude number, $Fr$, is a dimensionless number to define the open flow pattern [58].

$$Fr = \frac{V}{(gy)^{0.5}} \quad (6.58)$$

where $V$ is the velocity, $g$ is the gravity and $y$ is the distance from the bottom of the channel to the free surface.

Three different patterns of open channel flows are classified by the Froude number:

When $Fr < 1$, the open channel flow is defined as a subcritical pattern, the disturbances in upstream and downstream condition are the same. In this condition, downstream conditions might affect the flow upstream.

When $Fr = 1$, the open channel flow is defined as a critical pattern, upstream is stationary. In this condition, downstream condition effects upstream condition.

When $Fr > 1$, the open channel flow is defined as the supercritical pattern, disturbances cannot travel upstream. In this case, downstream condition does not affect upstream condition.

In this model, velocity magnitude $V$ of the grinding fluid is higher than $(gy)^{0.5}$, so it is a supercritical pattern, upstream propagating waves cannot be affected by downstream condition [58].
6.6.3.7.1. Upstream Boundary Condition

Upstream boundary condition has two options: pressure inlet and mass flow rate. In pressure inlet, the total pressure \( p_0 \) is [58]:

\[
p_0 = \frac{1}{2} (\rho - \rho_0) V^2 + (\rho - \rho_0) \left| g_1 \right| \left[ g_2 \cdot (b - a) \right]
\]

(6.59)

where

\( a \) and \( b \): The position vectors of the face centroid and any point on the free surface.

\( g_1 \): The gravity.

\( |g_1| \): The gravity magnitude.

\( g_2 \): The unit vector of gravity.

\( V \): The velocity magnitude.

\( \rho \): The average-density of the multiphase mixture.

\( \rho_0 \): The reference density.

The dynamic pressure \( q \) is:

\[
q = \frac{\rho - \rho_0}{2} V^2
\]

(6.60)

and the static pressure \( p_s \) is

\[
p_s = (\rho - \rho_0) \left| g_1 \right| \left[ g_2 \cdot (b - a) \right] - (\rho - \rho_0) \left| g_1 \right| \left[ (g_2 \cdot b) + y_{local} \right]
\]

(6.61)

where the distance from the free surface to the reference position is:

\[
y_{local} = -\left( a \cdot g_2 \right)
\]

(6.62)

The mass flow rate for each phase is defined by

\[
m_{\text{phase}} = \rho_{\text{phase}} \cdot \left( Area_{\text{phase}} \right) \cdot (Velocity)
\]

(6.63)
In the grinding process in this process experiment, the speed of grinding fluid coming from the nozzle is constant, thus, mass flow rate is used in this model.

6.6.3.7.2. Downstream Boundary Condition

Similar to the upstream boundary condition, downstream boundary condition has two options: pressure outlet and outflow boundary.

When the Froude number $Fr < 1$, if there are two phases in subcritical outlet flow, the pressure is taken from the pressure profile specified over the boundary, otherwise the pressure is taken from the neighboring cell.

When $Fr > 1$, in supercritical outlet flow, the pressure is taken from the neighboring cell regardless of how many phases are in the outlet flow.

The mode flow exits are modeled by outflow boundary condition at the outlet of open channel flows. If the details of the flow velocity and pressure are not known prior to solving the flow problem, boundary conditions are unknown at the outflow boundaries, then ANSYS FLUENT will extrapolate the required information from the interior [58].

The mass flow inlet is chosen as upstream boundary condition as mentioned in previous section, either outflow or pressure out boundary condition at the outlet can be chosen as downstream boundary condition. But due to the outflow boundary limitation, outflow splitting is not permitted in open channel flows, which means only single outflow boundary can be used at the outlet, but in the grinding process, the grinding fluid flow is at different outflow boundary condition. Thus, pressure outlet boundary condition is chosen.
6.7 Grinding Fluid Flow Field Modeling

6.7.1 ICEM Meshing

Figure 6-1 is the geometric model of grinding fluid flow simulation. This model is based on Mihic’s previous research [59], using Solidworks to build the geometric, and then importing it into the ICEM to mesh the geometric and set the boundary conditions. Finally, import the ICEM mesh file (.msh) to ANSYS FLUENT to do the fluid simulation. This model is composed by grinding wheel, workpiece and grinding fluid nozzle. The model presents the outline of the grinding wheel. The simulation area includes grinding area and fluid area. The grinding area is the grinding contact area and all the rest in this model is fluid area which is used to simulate the fluid flow.

The boundary condition of grinding wheel and workpiece are wall. The boundary condition of the nozzle is velocity inlet and all the rest are pressure outlet. Figure 6-2 shows the grinding contact area, it is a porous medium.

![Figure 6-1: Geometric Model of Grinding Fluid Flow Field Simulation](image-url)
The mesh type is hexahedral mesh. Relative to tetrahedral mesh, hexahedral mesh has many advantages. Firstly, hexahedral mesh has higher mesh quality. In the case of higher mesh quality, hexahedral mesh is easier to converge than tetrahedral mesh. Secondly, in the same mesh size, hexahedral mesh has a lower mesh number than
tetrahedral mesh which can decrease the simulation time. Thirdly, the direction of hexahedral mesh can cater to flow direction, the discrete error is smaller than tetrahedral mesh. In addition, the calculations of surface tension effects on tetrahedral meshes are not as accurate as on hexahedral meshes. The model needs to be meshed with hexahedral mesh to take the surface tension effects into account.

6.7.2 Quality of Meshing

6.7.2.1 Meshing Quality Standards

In this model, hexahedral mesh is the meshing method, as shown in Figure 6-4. Total elements are 917224 and it has 842100 nodes. In this model, determinant is used as the standard to grade the quality of the hexahedral mesh. It is the ratio of the smallest

Figure 6-4: Hexahedral Meshing Model Mesh Quality
determinant of the Jacobian matrix divided by the largest determinant of the Jacobian matrix, where each determinant is computed at each node of the element. Determinant checks the mesh quality by calculating each hexahedral mesh Jacobian value and standardization of a determinant matrix to characterize the deformation of a unit mesh. A Determinant value of 1 would indicate a perfectly regular mesh element, 0 would indicate an element degenerate in one or more edges, and negative values would indicate inverted elements [67]. In this model, the quality of meshes are all higher than 0.6, 90% are in the range between 0.95 ~ 1, which is highly qualified for the simulation requirement in ANSYS FLUENT. Usually, the determinant number higher than 0.3 is accepted by ANSYS FLUENT.

6.7.2.2 Y-block Meshing

Figure 6-5 shows that the angle of the formation of the grinding wheel profile and upper boundary is acute angle. In hexahedral meshing, acute angle is a potential reason for the low meshing quality. Figure 6-6 shows the meshing quality without a Y-block meshing, part of low quality meshes focus on the range 0 ~ 0.05 due to the degenerate block. Because each element in hexahedral meshing has six surfaces, each surface is a quadrangle. The better orthogonality of the hexahedral will improve the quality of meshing. If an acute angle exists, multiple points from several quadrangles will converge into one point, which causes a poor orthogonality, as shown in the left graph in Figure 6-7. To avoid this problem, Y-block meshing is introduced in this section, which converts a degenerate (wedge) block to a Y-block (quarter O-grid). The good orthogonality grids will
replace the bad ones, as shown in the right graph in Figure 6-7. Y-block is a good method to increase the meshing quality.

Figure 6-5: Acute Angle in Geometric Model

Figure 6-6: Hexahedral Meshing Model with Low Mesh Quality
6.7.3 ANSYS FLUENT Set-up

As mentioned previously, in order to avoid the prevention of the air backflow to the grinding fluid supplication, the angle of the nozzle is set to 3.5°. This helps the grinding fluid enter into the grinding area between the grinding wheel and workpiece smoothly and improves the grinding fluid cooling and lubricant effects.

In the ANSYS FLUENT fluid simulation setting, solver type is pressure-based and gravitational acceleration is 9.81m²/s. In models setting, the volume of fluid (VOF)
multiphase model needs to be chosen, because in the simulation, two kinds of materials are involved: grinding fluid and air. The turbulence model is the Reynolds stress model (RSM). Based on Mihić’s previous research [59], the Reynolds stress model has more accurate performance attributed to the superior Reynolds stress transport model. The materials acting in the simulation are grinding fluid and air. Four types of grinding fluid are used in the simulation: TRIM® C270, TRIM® SC520, TRIM® E906 and TRIM® MicroSol®585XT. The physical properties are listed in Chapter 2. The physical property of air uses the default setting in the ANSYS FLUENT. Air is the primary phase and grinding fluid is the secondary phase in the phases setting. In cell zone condition setting, two cell zones are shown: grinding area and fluid flow area which are created in the ICEM previously. The grinding area has a rotating frame motion. Also it is treated as a porous zone. The grinding wheel used in the experiment is Norton 32A60-I8VBE. The porosity supplied by the manufacturer is 46%, which is set in the ANSYS FLUENT. The grinding wheel boundary speeds in the simulation are 15.18m/s, 22.72m/s and 30.23m/s, and the depths of cut are 12.7μm, 25.4μm, 38.1μm, 50.8μm, 63.5μm respectively.

Table 6.1: FLUENT Simulation Setup for the Model

<table>
<thead>
<tr>
<th>Solve type</th>
<th>Pressure based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation type</td>
<td>Transit state calculations</td>
</tr>
<tr>
<td>Velocity formation</td>
<td>Absolute</td>
</tr>
<tr>
<td>Gradient option</td>
<td>Green-Gauss Cell Based</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>Reynolds Stress Model</td>
</tr>
<tr>
<td>Multiphase model</td>
<td>Volume of Fluid model (VOF)</td>
</tr>
<tr>
<td>Momentum</td>
<td>Third-order MUSCL</td>
</tr>
<tr>
<td>Turbulent kinetic energy</td>
<td>Third-order MUSCL</td>
</tr>
<tr>
<td>Turbulent dissipation rate</td>
<td>Third-order MUSCL</td>
</tr>
<tr>
<td>Reynolds stress</td>
<td>Third-order MUSCL</td>
</tr>
</tbody>
</table>
6.8 Useful Flow Rate Simulation Results Analysis

In the grinding process, the manufacturing mechanism includes cutting, sliding and plowing which produce lots of heat. Grinding manufactures the workpiece in different ways with turning and milling. In turning, about 70% ~ 80% of heat is drained away by the swarf. Only 10% ~ 20% of heat is passing into workpiece interior. But the swarf of the workpiece in grinding is thinner than turning, about 60% ~ 90% of heat conducts into the workpiece, only 10% of heat is taken away by the swarf which generates heat damage and tool wear. Generally, the grinding fluid is used in manufacturing industries. As mentioned previously, it is difficult for grinding fluid to enter into the grinding contact area due to the air flow prevention and the small contact area which is between the workpiece and grinding wheel relative to the workpiece. Thus, the amount of grinding fluid enter into the grinding contact area which is called useful flow is discussed in this section.

The ratio of the useful flow and total nozzle flow is described as useful flow rate. It is a key parameter in grinding which can be used to grade the cooling and lubrication performance of grinding fluid. Only the grinding flow entering the grinding area can be considered as useful flow. It has cooling and lubrication functions to prevent the thermal damage, burning, cracking and grinding wheel wear, maintaining finer surface roughness and lower grinding temperature.

ANSYS FLUENT can monitor the grinding fluid flow mass flow rate in the Report Type. In this section, the monitor is set up to record the grinding fluid mass flow rate in the grinding area between the grinding wheel and the workpiece. Then the useful flow rate can be calculated by the recording data.
The simulation type in this model is transit state calculations. Two parameters need to be set before the grinding fluid flow simulation is initialized: Time Step Size (s) and Number of Time Steps. Time Step Size depends on the ratio of characteristic length and the characteristic flow velocity. Time Step Size has one order of magnitude lower than the ratio. In this simulation, the Time Step Size is set as $1 \times 10^{-4}$ s and the Number of Time Steps is 10000, thus, the simulation of the grinding process time is one second.

Figure 6-9 shows the contours of volume fraction for grinding fluid. The grinding fluid is applied from a nozzle on the right side. It can be seen from the figure, only part of the grinding fluid can go through the grinding contact area, most of it is rejected by the grinding wheel rotation or the workpiece. Thus, knowing how much grinding fluid in the grinding contact area is a key issue.
6.8.1 The Effect of Depth of Cut to the Useful Flow Rate

Figure 6-10 to Figure 6-13 show the effect of depth of cut to the useful flow rate. The abscissa is depth and ordinate presents the useful flow rate. From the figure, when depth of cut increases, the useful flow rate is increasing. Because for the increasing depth of cut, the gap between the grinding wheel and the workpiece is increasing. More grinding fluid can enter in the grinding area at the same time, but the increasing depth of cut is not a proper method to increase the useful flow rate. The grinding force and generated heat increase rate will be greater than the growth of useful flow rate, it will not offset the effects of grinding force nor the generated heat increase rate, which will lead heat damage on the workpiece surface.

Figure 6-10: Useful Flow Rate of TRIM® C270 varies with Depth of Cut
Figure 6-11: Useful Flow Rate of TRIM® SC520 varies with Depth of Cut

Figure 6-12: Useful Flow Rate of TRIM® E906 varies with Depth of Cut
6.8.2 The Effect of Grinding Wheel Speed to the Useful Flow Rate

Figure 6-14 to Figure 6-17 show the effect of wheel speed to the useful flow rate. The increasing grinding wheel speed increases the useful flow rate. In the same grinding
Figure 6-15: Useful Flow Rate of TRIM® SC520 varies Grinding Wheel Speed

Figure 6-16: Useful Flow Rate of TRIM® E906 varies Grinding Wheel Speed
Figure 6-17: Useful Flow Rate of TRIM® MicroSol® 585XT varies Grinding Wheel Speed

condition, when the grinding wheel speed is increasing, more grinding fluid is taken by the grinding wheel into the grinding contact area. This is an explanation for the decreasing grinding force with the increasing grinding wheel speed. More grinding fluid entering into the grinding contact area can improve the lubrication function. But the useful flow growth rate is less than the amplitude of increase of temperature, thus, more grinding fluid entering the grinding contact area cannot stop the temperature increasing, as mentioned in Chapter 4. Also it can be seen in this figure, the rate of increase from 15.18m/s to 22.72m/s is higher than that from 22.72m/s to 30.23m/s. Because, when the grinding wheel speed increases, the rotating grinding wheel drives the air flow which is surrounding its circumference surface and the air flow velocity is increasing. The air flow mixes with grinding fluid and it is a factor that prevents the grinding fluid entering the
grinding contact area. This is proven by the air flow simulation in Chapter 5. So the rate of rise increase is higher in low grinding wheel speed.

6.8.3 The Effect of Different Types of Grinding Fluid to the Useful Flow Rate

Figure 6-18 to Figure 6-20 show the effect of different types of grinding fluid to the useful flow rate. For each grinding fluid, it has similar trend variations with depth of cut and grinding wheel speed. From the figures, C270 has the highest useful flow rate in each grinding condition, then is SC520 and E906, 585XT is the lowest one. Because as mentioned in Chapter 4, C270 has a low viscosity which produces a low glutinousness, in the same nozzle pressure and angle, the inertia can help C270 have more useful flow rate into the grinding zone and reduce the frictions between the workpiece and grinding wheel, then reduce the force. Combined with previous experiment results in Chapter 4, lower dynamic viscosity grinding fluid, which improves the useful flow rate, has lower temperature and grinding force data in the same grinding condition. Higher useful flow rate gives better cooling and lubrication capability. The useful flow rate simulation corresponds to the previous experiment data. Dynamic viscosity and useful flow rate can be treated as key parameters for water-based grinding fluid performance in grinding. Also, even if the effect of surface tension is not very obvious due to the dimensionless analysis of Weber number in section 6.2.4, but high surface tension grinding fluid can help fluid break up easily to enter into the grinding contact area. Thus, surface tension can be used as a supplement parameter in this model analysis.
Figure 6-18: Grinding Fluid Useful Flow Rate Comparison on Grinding Wheel Speed

15.18 m/s

Figure 6-19: Grinding Fluid Useful Flow Rate Comparison on Grinding Wheel Speed

22.72 m/s
6.9 Conclusions

In this chapter, a grinding fluid field model is introduced. Hexahedral meshing are used as the meshing method which can have a better meshing quality and shorter simulation time than tetrahedral meshing. ICEM are employed as the meshing software and ANSYS FLUENT as the fluid flow simulation software. Based on the simulation results, the useful flow rate trends to vary with different depths of cut, grinding wheel speeds and types of grinding fluid are concluded. Useful flow rate will increase with the rise of grinding wheel speed and depth of cut. But low dynamic viscosity grinding fluid can be better entering into the grinding area due to its physics performance. Combined with previous experiments results, lower dynamic viscosity increases useful flow rate,
more grinding fluid entering in the grinding contact area at the same time, improving the cooling and lubrication capability, then decrease the grinding temperature and force.
Chapter 7

Grinding Heat Transfer Modeling

7.1 Introduction

The grinding temperature is a representation of grinding heat which is produced during the grinding process. The grinding process, including the cutting, sliding and plowing mechanisms, are accomplished by the abrasive grains which are randomly distributed on the grinding wheel surface. During the process, each single abrasive grain can be analogous as a heat source. The increasing grinding temperature is a result of the combined action of the single heat resource, which is the average effect of these abrasive grains. Thus, in this chapter, to simplify the model, a surface heat source is used to analyze the surface grinding temperature field instead of the randomly distributed heat source.

7.2 Energy Partition Model

The heat transfer can occur by three main methods: conduction, convection and radiation. In the grinding condition, most of the grinding energy is converted to heat. The heat energy conducts into the workpiece, the grinding wheel and the chip, heat
convection with grinding fluid. The total heat flux $q_t$ includes the workpiece heat flux $q_w$, grinding wheel heat flux $q_s$, chip heat flux $q_c$ and grinding fluid convection heat flux $q_f$.

$$q_t = q_w + q_f + q_s + q_c$$  \hspace{1cm} (7.1)

a) Total heat flux $q_t$

The total heat flux $q_t$ can be solved by tangential grinding force $Ft$, grinding wheel speed $Vs$ and grinding contact area. The grinding contact area is equal to the product of the grinding width and the contact length between the grinding wheel and the workpiece.

$$q_t = \frac{F_t \cdot V_s}{l_c \cdot b} = \frac{F_t \cdot V_s}{b \cdot (a_c d_e)^{0.5}}$$  \hspace{1cm} (7.2)

where $a_c$ is the depth of cut, $d_e$ is the equivalent wheel diameter, $b$ is the grinding contact width or the width of the workpiece.

b) Chip heat flux

Malkin [68] proposed that the heat conducted into the grinding chip can be calculated from the chip’s specific energy. The definition of chip specific energy is the energy needed to rise to the melting temperature per unit weight of chip.

$$e_c = \rho_w \cdot c_w \cdot T_m$$  \hspace{1cm} (7.3)

where $e_c$ is chip specific energy, $\rho_w$ is workpiece density, $c_w$ is workpiece specific heat and $T_m$ is workpiece melting temperature.

The chip heat flux is the ratio of total generated heat taken away by the chip and the contact area. The total generated heat taken away by the chip is equal to the chip specific energy multiplied by the material removal rate.

$$q_c = \frac{e_c \cdot MRR}{b \cdot l_c} = \frac{\rho_w \cdot c_w \cdot T_m \cdot b \cdot a_c \cdot V_w}{b \cdot l_c} = \frac{\rho_w \cdot c_w \cdot T_m \cdot a_c \cdot V_w}{(a_c d_e)^{0.5}}$$  \hspace{1cm} (7.4)
c) Grinding wheel heat flux $q_s$

From Eq. (1.6), the grinding wheel heat flux $q_s$ is:

$$q_s = \frac{1}{2} \left( T_m b \right) \left( 2 k \rho c_s V_s \frac{A_s}{A_n} \right)^{0.5}$$

where $A_s/ A_n \approx 1- \beta$, $\beta$ is grinding wheel porosity. In this project, the porosity of the grinding wheel is 0.46 provided by the grinding wheel supplier.

The model built for the heat transfer simulation in this chapter is focused on the heat transfer in the grinding area and the workpiece, and the grinding temperature on the grinding contact area. Most of the heat is conducted into the workpiece and the grinding fluid. Thus, the heat involved in the heat transfer process are the workpiece heat flux $q_w$ and the grinding fluid convection heat flux $q_f$. The energy partition $\varepsilon_{wf}$ is:

$$\varepsilon_{wf} = \frac{q_w + q_f}{q_t} = 1 - \frac{q_c + q_s}{q_t} = 1 - \left[ \frac{\rho_w \cdot c_w \cdot T_m \cdot a_e \cdot V_w}{a_e d_e} \left( \frac{1}{2} \left( T_m b \right) \left( 2 k \rho c_s V_s \beta \cdot (a_e d_e)^{0.5} \right)^{0.5} \right) \right]^{0.5}$$

$$\left( \frac{F \cdot V_s}{b \cdot (a_e d_e)^{0.5}} \right)$$

(7.5)

This energy partition equation considers the effect of workpiece feed rate, depth of cut, equivalent wheel diameter, tangential grinding force, physics and thermal properties of the grinding wheel and workpiece to the energy partition $\varepsilon_{wf}$.

Table 7.1 is the material physical property. The grinding wheel used in this project is Norton® 32A60-IVBE and the abrasive grain material is aluminum oxide. The workpiece material is 52100 steel.
Table 7.1: Material Physical Property

<table>
<thead>
<tr>
<th>Material</th>
<th>ρc (J/m³K)</th>
<th>Melting Temperature (°C)</th>
<th>Average Thermal Property (kρc)⁰.⁵ (J/m²Cs⁰.⁵)</th>
</tr>
</thead>
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<td>52100 Steel</td>
<td>3.41×10⁶</td>
<td>1424</td>
<td></td>
</tr>
<tr>
<td>aluminum oxide</td>
<td></td>
<td></td>
<td>10300</td>
</tr>
</tbody>
</table>

Table 7.2: Energy Partition for Different Grinding Conditions

<table>
<thead>
<tr>
<th>Depth of Cut (m)</th>
<th>Feed Rate (m/s)</th>
<th>Wheel Speed (m/s)</th>
<th>C270</th>
<th>SC520</th>
<th>E906</th>
<th>585XT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.54E-05</td>
<td>15.18</td>
<td>0.085</td>
<td>85.41%</td>
<td>86.43%</td>
<td>87.30%</td>
<td>89.31%</td>
</tr>
<tr>
<td>2.54E-05</td>
<td>22.72</td>
<td>0.064</td>
<td>86.76%</td>
<td>87.16%</td>
<td>88.07%</td>
<td>89.89%</td>
</tr>
<tr>
<td>2.54E-05</td>
<td>22.72</td>
<td>0.085</td>
<td>86.35%</td>
<td>86.72%</td>
<td>87.33%</td>
<td>90.08%</td>
</tr>
<tr>
<td>2.54E-05</td>
<td>22.72</td>
<td>0.106</td>
<td>86.55%</td>
<td>87.04%</td>
<td>86.81%</td>
<td>90.32%</td>
</tr>
<tr>
<td>2.54E-05</td>
<td>30.23</td>
<td>0.085</td>
<td>87.07%</td>
<td>87.48%</td>
<td>88.16%</td>
<td>90.54%</td>
</tr>
<tr>
<td>3.81E-05</td>
<td>15.18</td>
<td>0.085</td>
<td>85.75%</td>
<td>84.06%</td>
<td>87.49%</td>
<td>91.66%</td>
</tr>
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<td>3.81E-05</td>
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</tr>
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<td>3.81E-05</td>
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<td>85.90%</td>
<td>89.59%</td>
<td>93.79%</td>
</tr>
<tr>
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<td>86.10%</td>
<td>91.50%</td>
<td>93.77%</td>
</tr>
<tr>
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<td>30.23</td>
<td>0.085</td>
<td>86.97%</td>
<td>87.26%</td>
<td>90.63%</td>
<td>94.43%</td>
</tr>
<tr>
<td>5.08E-05</td>
<td>15.18</td>
<td>0.085</td>
<td>84.06%</td>
<td>85.17%</td>
<td>90.89%</td>
<td></td>
</tr>
<tr>
<td>5.08E-05</td>
<td>22.72</td>
<td>0.064</td>
<td>85.69%</td>
<td>86.19%</td>
<td>92.75%</td>
<td>94.73%</td>
</tr>
<tr>
<td>5.08E-05</td>
<td>22.72</td>
<td>0.085</td>
<td>84.28%</td>
<td>85.92%</td>
<td>93.76%</td>
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</tr>
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<td>0.106</td>
<td>85.62%</td>
<td>89.11%</td>
<td>92.69%</td>
<td>93.62%</td>
</tr>
</tbody>
</table>

Table 7.2 shows the energy partition εwf various with different grinding conditions. Most of the grinding condition energy partition is around 85%, so about 15% generated heat is taken away by the grinding wheel and chips. Most of the heat conducted into the grinding contact area increases the grinding temperature. For E906 and 585XT, the energy partition increases on heavy depth of cut. This indicates that less heat is taken away by the grinding wheel and chips. On the other hand, this explains why these grinding fluids have a higher grinding temperature in the heavy grinding condition.
Table 7.3: Generated Heat Energy in Grinding Area for Different Grinding Conditions

<table>
<thead>
<tr>
<th>Depth of Cut (m)</th>
<th>Feed Rate (m/s)</th>
<th>Wheel Speed (m/s)</th>
<th>C270 (W/mm²)</th>
<th>SC520 (W/mm²)</th>
<th>E906 (W/mm²)</th>
<th>585XT (W/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.54E-05</td>
<td>15.18</td>
<td>0.085</td>
<td>22.85</td>
<td>23.12</td>
<td>23.36</td>
<td>23.89</td>
</tr>
<tr>
<td>2.54E-05</td>
<td>22.72</td>
<td>0.064</td>
<td>19.39</td>
<td>19.48</td>
<td>19.68</td>
<td>20.09</td>
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<td>2.54E-05</td>
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<td>0.085</td>
<td>24.77</td>
<td>24.88</td>
<td>25.05</td>
<td>25.84</td>
</tr>
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<td>2.54E-05</td>
<td>22.72</td>
<td>0.106</td>
<td>31.35</td>
<td>31.52</td>
<td>31.44</td>
<td>32.71</td>
</tr>
<tr>
<td>2.54E-05</td>
<td>30.23</td>
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<td>26.45</td>
<td>26.57</td>
<td>26.78</td>
<td>27.50</td>
</tr>
<tr>
<td>3.81E-05</td>
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<td>0.085</td>
<td>28.74</td>
<td>28.17</td>
<td>29.32</td>
<td>30.72</td>
</tr>
<tr>
<td>3.81E-05</td>
<td>22.72</td>
<td>0.064</td>
<td>22.12</td>
<td>22.32</td>
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<td>23.65</td>
</tr>
<tr>
<td>3.81E-05</td>
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<td>28.79</td>
<td>30.02</td>
<td>31.43</td>
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<td>0.106</td>
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<td>35.67</td>
<td>37.91</td>
<td>38.85</td>
</tr>
<tr>
<td>3.81E-05</td>
<td>30.23</td>
<td>0.085</td>
<td>32.06</td>
<td>32.16</td>
<td>33.40</td>
<td>34.81</td>
</tr>
<tr>
<td>5.08E-05</td>
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<td>31.42</td>
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<td>25.14</td>
<td>27.06</td>
<td>27.64</td>
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<tr>
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<td>29.64</td>
<td>30.21</td>
<td>32.97</td>
<td>33.14</td>
</tr>
<tr>
<td>5.08E-05</td>
<td>22.72</td>
<td>0.106</td>
<td>40.96</td>
<td>42.63</td>
<td>44.35</td>
<td>44.79</td>
</tr>
</tbody>
</table>

Table 7.3 shows generated heat energy in the grinding contact area which varies with different grinding conditions. As shown in the table, the generated heat energy is increasing with the rise of depth of cut, grinding wheel speed and feed rate. The grinding temperature has a direct relation with generated heat energy. The energy exchange results produce the grinding temperature. As mentioned in Chapter 4, when the depth of cut is increasing, tangential forces increase the heating power of the average heating source; the contact length and material removal rate are also increased. These three reasons cause the temperature to rise with the rise in depth of cut. When the grinding wheel rotation speed is increasing, more abrasive grains are acting on the workpiece, so the total heat generated by the process is increasing, thus, the temperature rises. Also, when the feed rate is increasing, the grinding process time decreases which reduces accumulated generated grinding heat. Even if less grinding time reduces the heat accumulation, the increasing generated grinding heat due to the increased material removal rate offset the
reduced heat accumulation and the global performance of increasing feed rate increases
generated heat energy.

7.3 Heat Transfer Theory

7.3.1 The Energy Equation

The following term is the energy equation solved in ANSYS FLUENT [58]:

\[
\frac{\partial}{\partial t}(\rho E) + \nabla \cdot [\nu(\rho E + p)] = \nabla \cdot \left[ k_{\text{eff}} \nabla T - \sum_j h_j J_j + (\bar{r}_{\text{eff}} \cdot \nu) \right] + S_h
\]  

(7.6)

where \( \rho \) is the density of the material, \( T \) is the absolute temperature, \( k_{\text{eff}} \) is the effective conductivity and \( J_j \) is the diffusion flux, \( h \) is sensible enthalpy defined by the types of flow [58].

On the right hand side of Eq. (7.6), the first three terms are energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. \( S_h \) includes the heat of chemical reactions and any other defined volumetric heat sources [58].

7.3.2 Energy Equation in Solid Region

Due to the workpiece feed rate considered in the experiment plan, the effect of the transportation of the workpiece to the grinding heat simulation is taken into account. In solid region simulation, the energy transport equation is simplified as the following equation [58]:

\[
\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\nu \rho h) = \nabla \cdot (k \nabla T) + S_h
\]  

(7.7)
The second term on the left-hand side of Eq. (7.7) represents the influence of energy transfer due to the translational motion of the workpiece. This can help to determine the importance of workpiece motion on the temperature field. The velocity \( v \) is the motion specified for the solid region, which is the workpiece feed rate in this model [58].

### 7.4 Grinding Heat Transfer Model

In this chapter, a model is built based on the model in Chapter 6. A workpiece is added underneath the previous model. Figure 7-1 gives three views of this grinding heat transfer model. The objective of this model is to study in detail the heat transfer in the grinding contact area and underneath the workpiece surface. The model is composed by three main sections: fluid flow area, grinding area and workpiece. Similar to the previous

![Geometrical View of Grinding Heat Transfer Model](image)

*Figure 7-1: Geometrical View of Grinding Heat Transfer Model*
Figure 7-2: Workpiece in Grinding Heat Transfer Model

Figure 7-3: Hexahedral Meshing Model Mesh Quality
model, the cell zone type for fluid area and grinding area both fluid and grinding area is treated as a porous zone. The cell zone type setting for the workpiece is solid condition. Hexahedral meshing is used as the meshing method. Total elements in this model are 123706. There is an interface between the bottom of the grinding contact area and workpiece, which is shown in Figure 7-2. The grinding heat generated in the grinding process transfers through this interface into the workpiece. Table 7.4 is the ANSYS FLUENT simulation set-up for the grinding heat transfer model. Figure 7-3 gives the mesh quality which is higher than 0.45, so the model is qualified for the simulation.

7.5 Simulation Results Analysis

The generated heat causes the rising grinding temperature underneath the workpiece surface. Because of the moving heat source on the workpiece surface, the grinding temperature field is constantly moving. This model simulates the temperature
Table 7.4: ANSYS FLUENT Simulation Set-up for Model

<table>
<thead>
<tr>
<th>Solve type</th>
<th>Pressure based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation type</td>
<td>Steady state calculations</td>
</tr>
<tr>
<td>Velocity formation</td>
<td>Absolute</td>
</tr>
<tr>
<td>Gradient option</td>
<td>Green-Gauss Cell Based</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>Reynolds Stress Model</td>
</tr>
<tr>
<td>Multiphase model</td>
<td>Volume of Fluid model (VOF)</td>
</tr>
<tr>
<td>Momentum</td>
<td>Third-order MUSCL</td>
</tr>
<tr>
<td>Turbulent kinetic energy</td>
<td>Third-order MUSCL</td>
</tr>
<tr>
<td>Turbulent dissipation rate</td>
<td>Third-order MUSCL</td>
</tr>
<tr>
<td>Reynolds stress</td>
<td>Third-order MUSCL</td>
</tr>
<tr>
<td>Energy equation discretization method</td>
<td>Third-order MUSCL</td>
</tr>
</tbody>
</table>

Table 7.5: Grinding Condition in Heat Transfer Simulation

<table>
<thead>
<tr>
<th>Grinding Condition</th>
<th>Depth of Cut (μm)</th>
<th>Workpiece Feed Rate (m/s)</th>
<th>Grinding Wheel Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25.4</td>
<td>22.72</td>
<td>0.106</td>
</tr>
<tr>
<td></td>
<td>38.1</td>
<td>15.18</td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td>38.1</td>
<td>22.72</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>38.1</td>
<td>22.72</td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td>38.1</td>
<td>22.72</td>
<td>0.106</td>
</tr>
<tr>
<td></td>
<td>38.1</td>
<td>30.23</td>
<td>0.085</td>
</tr>
</tbody>
</table>

field in grinding and the following figures are the temperature simulation results. Table 7.5 gives the grinding condition used in the heat transfer simulation.

Figure 7-5 to Figure 7-18 provide the grinding temperature distribution various with depth of cut, workpiece feed rate and grinding wheel speed for four different types of grinding fluid. The reason for the effect of grinding parameters has been discussed in Chapter 4. These simulation results compare with previous experiment data and numerically validate the experimental conclusions.

Figure 7-5 to Figure 7-8 give the grinding temperature distribution various with depth of cut for different types of grinding fluid. Two kinds of grinding conditions are chosen in each figure. The grinding workpiece feed rate (0.106m/s) and grinding wheel
speed (22.72m/s) are the same in these two grinding conditions. The first graph in each figure shows the simulation result of 25.4μm depth of cut and the lower graph displays 38.1μm. As mentioned in Chapter 4, when the depth of cut is increased, tangential forces increase the heating power of the average heating source; the contact length and material removal rate are also increased. These three reasons cause the temperature to rise with the rise in depth of cut. As shown in the figures, the generated grinding heat transfer deeper into the workpiece when depth of cut increases.

Figure 7-9 to Figure 7-12 provides the grinding temperature distribution various with workpiece feed rate. Three kinds of grinding conditions are chosen in each figure. The grinding depth of cut (38.1μm) and grinding wheel speed (22.72m/s) are the same in these three grinding conditions. The workpiece feed rate from top to bottom are 0.064m/s, 0.085m/s and 0.106m/s respectively. This model contains the effect of workpiece movement. The moving direction of the workpiece is on the positive z axis direction, which is moving from right to left. The heat accumulation starting from the two objects – workpiece and grinding wheel – contact each other. The red region near the workpiece surface is the grinding contact area, which generates the highest grinding temperature during the process, then the heat dissipates. The area of the workpiece on the left side of the red region is the ground part and the right side is unground. Due to the accumulated grinding generated heat, the temperature on the left side is higher than the right side. The temperature on the right side is near room temperature. The conclusion in Chapter 4 is: with workpiece feed rate increasing, the temperature is increasing. The four figures show the same temperature increasing trend for these four types of grinding fluid, but the temperature distribution trend is different. For C270 and SC520, the depth of grinding..
generated heat transfer underneath the workpiece surface is decreasing with the increasing workpiece feed rate. E906 and 585XT have different distribution trends, because workpiece feed rate has two main functions on the grinding temperature distribution. On the one hand, higher workpiece feed rate has less grinding time, and grinding generated heat is not easy to accumulate and transfer into the workpiece relatively. So like C270 and SC520, with increasing workpiece feed rate, less grinding heat transfers into the workpiece. On the other hand, the increasing workpiece feed rate increases material removal rate, and it simultaneously raises the temperature. There is a threshold in these two aspects. Because E906 and 585XT have a lower useful flow rate, the strength of increasing heat intensity in the grinding contact area offsets the decreasing of accumulated grinding heat. Thus, from Figure 7-11 and Figure 7-12, the generated grinding heat transfers deeper into the workpiece when workpiece feed rate increases.

Only the red region contains the most of generated grinding heat which produces the highest grinding temperature in the process. In this region, the grinding temperature is always increasing when workpiece feed rate is increasing. That area is used for measuring grinding temperature in the experiment. For the rest of the workpiece, if less grinding heat accumulates, it can decrease the potential thermal damage inside the workpiece.

Figure 7-13 to Figure 7-16 provides the grinding temperature distribution various with grinding wheel speed. Three kinds of grinding conditions are chosen in each figure. The grinding depth of cut (38.1μm) and workpiece feed rate (0.085m/s) are the same in these three grinding conditions. The grinding wheel speed from top to bottom are 15.18m/s, 22.72m/s and 30.23m/s respectively. Due to more abrasive grains acting on the
workpiece surface during grinding when the grinding wheel speed increases, the total generated grinding heat is increasing, thus the grinding temperature rises. From the figures, we can clearly see the trend of temperature rise.

Figure 7-17 and Figure 7-18 provides the grinding temperature distribution various with different types of grinding fluid. The grinding fluids from top to bottom are C270, SC520, E906 and 585XT respectively. In Figure 7-17, the grinding condition is: depth of cut (25.4μm), wheel speed (22.72m/s) and workpiece feed rate (0.106m/s). In Figure 7-18, all the parameters are the same with figure 7-17 except depth of cut, which is 38.1μm in figure 7-18. From these figures, the obtained grinding temperature trend is the same with the previous conclusion. Low dynamic viscosity increases the use flow rate which helps more grinding fluid enter into the grinding contact area, increasing cooling and lubricating capability, thus, decreasing the grinding temperature.

Table 7.6 represents the error of the grinding heat transfer simulation results compared with experiment data. Because grinding is a complex process, the total generated grinding heat, grinding energy partition, useful flow rate, grinding parameters setting and physical properties of grinding fluid are the factors effecting the simulations accuracy.

<table>
<thead>
<tr>
<th>Gridding Condition</th>
<th>Type of Grinding Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>aₑ (μm)</td>
<td>Vₑ (m/s)</td>
</tr>
<tr>
<td>25.4</td>
<td>22.72</td>
</tr>
<tr>
<td>38.1</td>
<td>15.18</td>
</tr>
<tr>
<td>38.1</td>
<td>22.72</td>
</tr>
<tr>
<td>38.1</td>
<td>22.72</td>
</tr>
<tr>
<td>38.1</td>
<td>22.72</td>
</tr>
<tr>
<td>38.1</td>
<td>30.23</td>
</tr>
</tbody>
</table>
7.5.1 Effect of Grinding Depth of Cut for Grinding Temperature

Figure 7-5: Temperature Distribution Various with Depth of Cut for TRIM® C270

Figure 7-6: Temperature Distribution Various with Depth of Cut for TRIM® SC520
Figure 7-7: Temperature Distribution Various with Depth of Cut for TRIM® E906

Figure 7-8: Temperature Distribution Various with Depth of Cut for TRIM® MicSol®

585XT

159
7.5.2 Effect of Workpiece Feed Rate for Grinding Temperature

Figure 7-9: Temperature Distribution Various with Workpiece Feed Rate for TRIM®

C270

160
Figure 7-10: Temperature Distribution Various with Workpiece Feed Rate for TRIM®

SC520

161
Figure 7-11: Temperature Distribution Various with Workpiece Feed Rate for TRIM®
E906
162
Figure 7-12: Temperature Distribution Various with Workpiece Feed Rate for TRIM® MicroSol® 585XT
7.5.3 Effect of Grinding Wheel Speed for Grinding Temperature

Figure 7-13: Temperature Distribution Various with Grinding Wheel Speed for TRIM® C270

164
Figure 7-14: Temperature Distribution Various with Grinding Wheel Speed for TRIM®

SC520
Figure 7-15: Temperature Distribution Various with Grinding Wheel Speed for TRIM®

E906

166
Figure 7-16: Temperature Distribution Various with Grinding Wheel Speed for TRIM®

MicroSol® 585XT

167
7.5.4 Effect of Grinding Fluid for Grinding Temperature

Figure 7-17: Temperature Distribution for Different Types of Grinding Fluid
Figure 7-18: Temperature Distribution for Different Types of Grinding Fluid
7.6 Conclusions

In this chapter, a model is built to simulate heat transfer based on the model in Chapter 6. A workpiece is added in this model. The effects of depth of cut, workpiece feed rate, grinding wheel speed and types of grinding fluid are taken into account. The simulation results have the same temperature increasing trend with experiment data. The internal grinding heat distribution in the workpiece is discussed in this chapter. Combined with previous conclusions in Chapter 2, the magnitude trend of dynamic viscosity for each grinding fluid is not the same as that of specific heat. Such as 585XT, which has a higher specific heat capacity, improves the grinding fluid cooling capability. However, it has a higher dynamic viscosity resulting in a lower useful flow rate which does not help more grinding fluid enter into the grinding area compared with low dynamic viscosity grinding fluid. 585XT has the highest grinding temperature compared with other grinding fluids in the same grinding conditions. This indicates that the effect of dynamic viscosity is more significant than specific heat capacity. Higher specific heat capacity do not give enough cooling effect due less grinding fluid entering into the grinding contact area. Also, high surface tension grinding fluid has a specifics of easily breaking up which helps more grinding fluid entering into grinding contact area. In the grinding process, the influence of dynamic viscosity and surface tension to grinding temperature is higher than that of specific heat. This conclusion can help engineers to make better decision when choosing grinding fluid.
Chapter 8

Grinding Force Modeling

8.1 Introduction

In this chapter, a semi-empirical grinding force model is developed combined with the achievements of other researchers by composing effects of normal and tangential grinding forces in two main parts: cutting force and sliding force. Final equations for the total normal and tangential forces components is established. This model is used to predict the total normal and tangential force in the surface grinding. These force components are expressed in terms of the grinding process parameters such as wheel speed, workpiece feed rate, width of the workpiece and depth of cut. The four unknown coefficients in each equation can be determined by experiment results at specific conditions with the variations of wheel speed, workpiece feed rate and depth of cut. The previous grinding experiments have been conducted on an aluminum oxide vitrified cylindrical wheel. An equation for sliding force is established with the effect of specific sliding energy in terms of the experimental parameters. The average contact pressure and friction coefficients are expressed by wheel speed, workpiece feed rate, and width of the workpiece are also taken into account. Four different water-based grinding fluids were tested for different specific grinding conditions. Low dynamic viscosity grinding fluid
can have better performance than the high dynamic viscosity fluid due to the higher useful flow in the grinding contact area. The calculated normal and tangential grinding results are compared with the experimental results. The verifications show that deviations between the real results and calculated results can be affected by the performance of the fluid at heavy grinding conditions due to the sliding friction inside of rolling friction. To have a better agreement with experiment data, shallow grinding conditions are chosen to obtain the modified model.

Grinding is a machining process that employs an abrasive grinding wheel rotating at high speed to remove material from the workpiece. It is a complex process including cutting, sliding and plowing mechanisms which include complicated interactions between a number of factors, such as grinding wheel, workpiece material, wheel speed, workpiece feed rate and type of grinding fluid. Due to the complexity of the process, most grinding force calculation formulas are regression models in the exponent form based on a large number of experiments in a specific grinding condition with a given workpiece material and grinding wheel. Test procedures are costly and uneconomic. In order to reduce the difficulty associated with experimental analysis, the grinding process has been modeled theoretically. The model gives a better understanding of the process mechanism.

Compared to other machining processes, the grinding process involves high specific energy which requires a large amount of energy to be removed from a volume of material. Malkin [69] pointed out that high temperatures and energy generated in grinding affect workpiece quality and productivity. Grinding fluid is one of the most effective ways to protect the workpiece and grinding wheel, and improve quality of the workpiece. If grinding is not performed correctly, it can lead to surface damage to the
work material and unsatisfactory process results due to excessive heat generated and wheel wear. Also a grinding fluid can help reduce the grinding wheel force and achieve greater smoothness in heavy grinding. Therefore, a study of the effect of grinding fluid on grinding forces with varying process parameters in grinding is necessary.

8.2 Grinding Force Model

Grinding force is generated by the individual forces acting from the interactions between the abrasive grit and the workpiece during grinding. The grinding forces can be analyzed into a tangential \( F_t \) and a normal component \( F_n \). Malkin [68] decomposed the grinding force into two main parts: cutting deformation force and sliding or friction force. The cutting deformation force is divided into cutting or chip formation force and ploughing force.

\[
\begin{align*}
F_t &= F_{t,\text{cut}} + F_{t,\text{slid}} + F_{t,\text{plow}} \\
F_n &= F_{n,\text{cut}} + F_{n,\text{slid}} + F_{n,\text{plow}}
\end{align*}
\] (8.1)

The ploughing forces’ effect can be neglected compared with chip formation force. The grinding force can therefore be separated into two parts: cutting force and sliding force.

\[
\begin{align*}
F_t &= F_{t,\text{cut}} + F_{t,\text{slid}} \\
F_n &= F_{n,\text{cut}} + F_{t,\text{slid}}
\end{align*}
\] (8.2)

In this equation, \( F_t \) is the tangential grinding force, \( F_n \) is the normal grinding force, \( F_{t,\text{cut}} \) is the tangential cutting force, \( F_{t,\text{slid}} \) is the tangential sliding force, \( F_{n,\text{cut}} \) is the normal cutting force and \( F_{n,\text{slid}} \) is the normal sliding force.
8.2.1 Cutting Force Component

Specific energy, $u$, is the energy that must be expended to remove a unit volume of workpiece material [70]. Malkin [68] showed that in many cases, especially in fine grinding, the specific energy $u$ is consumed by specific cutting energy $u_{cut}$ and specific sliding energy $u_{slid}$.

$$u = u_{cut} + u_{slid}$$  \hspace{1cm} (8.3)

Specific cutting energy $u_{cut}$ is composed of two parts: static specific cutting energy $u_s$ and dynamic specific cutting energy $u_d$.

$$u_{cut} = u_s + u_d$$  \hspace{1cm} (8.4)

Here, the static specific cutting energy $u_s$ is a constant which is determined by the experiment according to workpiece material and grinding wheel material. The dynamic specific cutting energy $u_d$ is determined by workpiece material, grinding wheel material and grinding processing parameters. Tang [45] expanded the dynamic specific cutting energy $u_d$ by a material’s dynamic plastic constitutive relationship. The cutting force component is based on Tang’s Equation [45]. $u_d$ is in direct proportion to the change of shear flow stress, which is the combined result of shear strain effect and shear strain rate effect. Under the condition of two-dimensional cutting, shear strain is [71]

$$\gamma = \frac{\cos \beta}{\sin \phi \cos(\phi - \beta)}$$  \hspace{1cm} (8.5)

where $\phi$ is the shear angle and $\beta$ is the rake angle of tool.

Shear strain rate is

$$\dot{\gamma} = \frac{10v \sin \phi \cos \gamma_0}{a_c \cos(\phi - \gamma_0)} \approx \frac{vk}{a_c}$$  \hspace{1cm} (8.6)
where \( v \) is the cutting velocity, \( k \) is a constant, \( a_c \) is the cutting depth. \( v \) is corresponding to the wheel speed \( V_s \) in grinding, and cutting depth \( a_c \) corresponds to average thickness of undeformed chip \( a_g \) in grinding. Average thickness of undeformed chip is [71]:

\[
a_g = \frac{1}{2} a_{g,\text{max}} = \frac{V_s^{0.5} d_e^{0.25}}{(Cr)^{0.5} V_s^{0.5} d_e^{0.25}}
\] (8.7)

where, \( a_c \) is the grinding depth of cut, \( d_e \) is the equivalent wheel diameter, \( V_s \) is the grinding wheel speed, \( V_w \) is the workpiece feed rate, \( C \) is the number of effective abrasive grits in unit area of the grinding wheel and \( r \) is the ratio of chip width to chip thickness.

Substituting Eq. (8.7) into Eq. (8.6), the strain rate of grinding progress can be obtained as:

\[
\dot{\gamma} = \frac{k(Cr)^{0.5} V_s^{1.5} d_e^{0.25}}{V_w^{0.5} d_e^{0.25}}
\] (8.8)

Dynamic specific chip formation energy \( u_d \) is in approximate direct proportion to logarithm shear strain rate by the experiment data indicated by Liu [72]:

\[
u_d = C' \ln \left( \frac{\dot{\gamma}}{\gamma_0} \right)
\] (8.9)

where \( C' \) and \( \gamma_0 \) are constant. Substituting Eq. (5.7) into Eq. (5.8), \( u_d \) is yielded as

\[
u_d = C' \ln \left( \frac{k(Cr)^{0.5} V_s^{1.5} d_e^{0.25}}{\gamma_0 V_w^{0.5} d_e^{0.25}} \right)
\] (8.10)

Substituting Eq. (8.10) into Eq. (8.4) yields

\[
u_{\text{cut}} = u_s + C' \ln \left( \frac{k(Cr)^{0.5} V_s^{1.5} d_e^{0.25}}{\gamma_0 V_w^{0.5} d_e^{0.25}} \right)
\] (8.11)

In Eq. (8.11)
\[ C_1 = u_s + C' \ln \left( \frac{k(Cr)^{0.5}}{\gamma_0} \right) \]
\[ C_2 = C' \]

The specific energy is approximated by [39]

\[ u = \frac{F_t V_s}{V_w a_c b} \] (8.12)

Similarly as Eq. (8.12), the specific cutting and sliding energy are:

\[ u_{cut} = \frac{F_{t,\text{cut}} V_s}{V_w a_c b} \] (8.13)
\[ u_{slid} = \frac{F_{t,\text{slid}} V_s}{V_w a_c b} \] (8.14)

where \( b \) is the width of the workpiece.

From Eq. (8.13)

\[ F_{t,\text{cut}} = u_{cut} \frac{V_w a_c b}{V_s} = C_1 \frac{V_w a_c b}{V_s} + C_2 \frac{V_w a_c b}{V_s} \ln \frac{V_s^{1.5} d_e^{0.25}}{V_w^{0.5} d_e^{0.25}} \] (8.15)

Normal cutting force \( F_{n,\text{cut}} \) is related to the tangential cutting force by a constant of grinding force \( \delta \), the normal cutting force is:

\[ F_{n,\text{cut}} = \delta_1 C_1 \frac{V_w a_c b}{V_s} + \delta_2 C_2 \frac{V_w a_c b}{V_s} \ln \frac{V_s^{1.5} d_e^{0.25}}{V_w^{0.5} d_e^{0.25}} \] (8.16)

8.2.2 Sliding Force Component

From Eq. (8.14), based on experimental results, Malkin [68] has correlated the sliding forces with the friction coefficient between the workpiece and the grinding wheel, the average contact pressure, the actual contact area, wheel speed, workpiece speed, depth of cut and the width of the workpiece.
\[ u_{\text{slid}} = \frac{\mu V_s \bar{P} A_p}{V_s a_s b} \] (8.17)

where \( \mu \) is the friction coefficient, \( \bar{P} \) is the average contact pressure, \( A_p \) is the actual contact area between the workpiece and the grinding wheel wear flat area.

The grinding wheel speed \( V_s \) is usually much higher than the workpiece speed \( V_w \), the average contact pressure can therefore be estimated by [73]

\[ \bar{P} = d_1 \frac{4V_w}{V_s d_e} + d_2 \] (8.18)

where \( d_1 \) and \( d_2 \) are linear coefficients that are experimentally defined and can be considered to be a function of the processing environment (grinding machine, coolant type, etc.).

The actual contact area \( A_p \) is the product of the ratio of grinding wheel wear flat area \( \lambda \) and geometric contact length \( l_c \) [70].

\[ A_p = \lambda l_c = \lambda (a_s d_e)^{0.5} \] (8.19)

According to the frictional binomial theorem, the variable friction coefficient is given by the formulation [40]

\[ \mu = \frac{\tau}{\bar{P}} + \eta = \frac{\tau V_s d_e}{4d_1 V_w + d_2 d_e V_s} + \eta \] (8.20)

where \( \tau \) and \( \eta \) are constants in the friction coefficient equation which are determined by the mechanical properties and physical characteristics of the objects involved in the friction process. The ratio of first term on the right side of the equation is effected by the geometric shape of the object, roughness and flexibility in the friction process. The second term \( \eta \) on the right side of the equation is a constant.

Substituting Eq. (8.18) (8.19) (8.20) into Eq. (8.17):
\[ u_{\text{slid}} = \frac{\lambda V_s}{V_w b} \left( \frac{d_e}{a_e} \right)^{0.5} \left( \tau + \frac{4\eta V_{w1} d_1}{V_s d_e} + \eta d_2 \right) \]  

(8.21)

Substituting Eq. (8.21) into Eq. (8.14), the tangential sliding force is:

\[ F_{t,\text{slid}} = \lambda (a_e d_e)^{0.5} \left( \tau + \frac{4\eta V_{w1} d_1}{V_s d_e} + \eta d_2 \right) = \frac{4\lambda \eta d_1 V_{w1} (a_e d_e)^{0.5}}{V_s} + (\tau + \eta d_2) \lambda (a_e d_e)^{0.5} \]  

(8.22)

The normal sliding force is given by the following equations [68]:

\[ F_{n,\text{slid}} = \lambda \bar{P} b \sqrt{a_e d_e} \]  

(8.23)

Substituting Eq. (8.18) into Eq. (8.23)

\[ F_{n,\text{slid}} = \frac{4\lambda d_1 V_{w1} b (a_e d_e)^{0.5}}{V_s} + \lambda d_2 b (a_e d_e)^{0.5} \]  

(8.24)

Substituting Eq. (8.15) and (8.22), Eq. (8.16) and (8.24) yields the final total tangential and normal force equations:

\[
\begin{cases}
F_t = \left( C_1 + C_2 \ln \frac{V_s^{1.5} d_e^{0.25}}{a_e^{0.25} V_w^{0.5}} \right) \frac{V_w a_b}{V_s} + C_3 \frac{V_w}{V_s} \left( \frac{a_e}{d_e} \right)^{0.5} + C_4 (a_e d_e)^{0.5} \\
F_n = \left( C_5 + C_6 \ln \frac{V_s^{1.5} d_e^{0.25}}{a_e^{0.25} V_w^{0.5}} \right) \frac{V_w a_b}{V_s} + C_7 \frac{V_w b}{V_s} \left( \frac{a_e}{d_e} \right)^{0.5} + C_8 b (a_e d_e)^{0.5}
\end{cases}
\]  

(8.25)

where

\[ C_1 = u_s + C' \ln \left( \frac{k(Cr)^{0.5}}{\gamma_0} \right) \]
\[ C_2 = C' \]
\[ C_3 = 4\lambda \eta d_1 \]
\[ C_4 = \lambda (\tau + \eta d_2) \]
\[ C_5 = u_s + C' \ln \left( \frac{k(Cr)^{0.5}}{\gamma_0} \right) \]
\[ C_6 = C' \]
\[ C_7 = 4\lambda d_1 \]
\[ C_8 = \lambda d_2 \]

In this semi-empirical model, grinding depth of cut, wheel speed, workpiece feed rate and width of the workpiece are taken into account. It also includes some coefficients
which are sensitive to the grinding wheel or grinding conditions. For example, $C$ is the number of effective abrasive grits in the unit area of the grinding wheel, and it certainly depends on the different types of grinding wheels. All these coefficients are simplified as unknown parameters $C_i \sim C_8$, once we calculate the unknown parameters which is based on the grinding experiment data. The effects of types of grinding wheel, types of grinding fluid, and dressing conditions are taken into account. Namely, different experiment set-ups will have different parameters in the final equations.

8.3 Experiment Result and Analysis

In the experiment, five different depths of cut, three different wheel speeds and three different feed rates were carried out for forty-five different grinding conditions for each type of grinding fluid. Four types of fluids were used in the experiment: TRIM® C270 (Synthetic), TRIM® SC520 (semisynthetic), TRIM® E906 (Emulsion) and TRIM® MicroSol® 585XT (Micro-emulsion semi-synthetic). All the fluids concentration are 10%. The water mixed with grinding fluid is purified by Reverse Osmosis (RO) technology that uses a semipermeable membrane. With various grinding parameters, each grinding fluid has forty-five tests.

Based on the semi-empirical force model, four unknown parameters are in each equation. To obtain these four unknown coefficients, the procedure is to choose four

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<th>$V_w$ (m/s)</th>
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Table 8.2: Equation Parameter

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result groups from the forty-five grinding conditions, solve four unknowns in each linear equation in order to yield the final model. Table 8.1 shows the experiment results. Table 8.2 presents the parameter $C_{1-8}$ for each type of fluid.

Substituting the constant parameters $a_c$, $V_s$, $V_w$ and $d_e$ into Eq. (8.25) with the known coefficients $C_{1-8}$, the calculated grinding force can be obtained. The results are shown from Figure 8-1 to Figure 8-4. The X coordinate axis represents the workpiece feed rate variables from 0.06m/s – 0.11m/s. The Y coordinate axis represents the normal force results. Three lines represent the calculated results with three different grinding conditions: 12.7μm, 25.4μm and 50.8μm. The points represent the experimental data. The figures also indicate that the deviations between the experiment results and calculation results of C270 and SC520 are small both in shallow and heavy grinding, but E906 and 585XT are not very identical, especially on the heavy grinding condition.

Before analyzing the reason, it is first necessary to recognize the basic differences between these fluids. As mentioned in Chapter 4, there are 45 different grinding conditions for each fluid including shallow and heavy cuts. In the experiments, not all the fluid manages to enter the grinding contact between the grinding wheel and the
workpiece. In heavy grinding, the grinding wheel may stop rotating during grinding. Because in this condition, the material removal rate is too high, the machine motor power is insufficient to rotate the wheel passing through under the heavy conditions to finish a full pass. Of all 45 passes, C270 completed 100% full pass while SC520, E906 and 585XT completed 95.56%, 88.89% and 82.22% respectively. Also, a full pass

Figure 8-1: Model Results Vs Calculated Results for TRIM® C270

Figure 8-2: Model Results Vs Calculated Results for TRIM® SC520
Figure 8-3: Model Results Vs Calculated Results for TRIM® E906

Figure 8-4: Model Results Vs Calculated Results for TRIM® MicroSol® 585XT
means the achievement of the cut in one pass, but it does not mean that it is a perfect or smooth pass. In heavy grinding conditions, due to the high material removal rate, more interaction force was generated. The motor power was insufficient to handle the heavy condition, grinding force is too high to exceed the limitation of motor power, so that the wheel speed slows down and the wheel slides on the workpiece instead of cutting. Sliding friction is greater than the rolling friction. This causes the force to keep increasing as shown in the figure. In the same heavy grinding condition, if the grinder motor power is inadequate, the force recorded will be higher than the smooth force. Synthetic type C270 has the best performance compared with others, because it gives a lower force than SC 520 and E906, 585XT gives the highest force. Because C270 has a low dynamic viscosity and high surface tension showing in Table 2.3, it has a low glutinousness and can be break up easily, in the same nozzle pressure and angle, the inertia helps C270 achieve a more useful flow rate into the grinding zone and reduces the friction between the workpiece and grinding wheel, thus reducing the force. In heavy grinding conditions, low dynamic viscosity and high surface tension grinding fluid can finish more pass in deep depth of cut than other grinding fluids.

Back to the results from Figure 8-1 to Figure 8-4, deviations between the experimental results and calculation results for C270 and SC520 are small both in shallow and heavy grinding, except for some points under heavy conditions, because those points are not in a smooth passing condition which generates a higher force than calculated ones. E906 and 585XT are not very identical, both in the shallow and heavy grinding condition. That is because in the four chosen result groups, the fourth group is not a smooth pass in which the force is higher than expected in E906 and 585XT results.
Table 8.3: Experiment Data

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<th>(V_n) (m/s)</th>
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<th>C270</th>
<th>SC520</th>
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This affects the accuracy of the calculated results.

To solve this problem, it was decided to choose another four result groups for shallow grinding. Table 8.3 shows the experiment results. Table 8.4 presents the parameter \(C_{1-8}\) for each type of fluid. The results are shown in Figure 8-5 to Figure 8-8. The figures indicate that the deviations between the experimental results and calculated ones for C270 and SC520 are both still small in shallow and heavy grinding, except for some points under heavy conditions. E906 and 585XT are more nearly identical in the shallow condition. These results show that, in the smooth pass condition, this semi-empirical equation is accurate for calculating the tangential and normal forces.
Figure 8-5: Modified Model Results Vs Calculated Results for TRIM® C270

Figure 8-6: Modified Model Results Vs Calculated Results for TRIM® SC520
Figure 8-7: Modified Model Results Vs Calculated Results for TRIM® E906

Figure 8-8: Modified Model Results Vs Calculated Results for TRIM® MicroSol® 585XT
In order to further prove this conclusion, more grinding conditions are considered with the modified parameter $C_{1-8}$ for each type of grinding fluid, as shown from Figure 8-9 to Figure 8-12. These grinding conditions are chosen from 12.7μm to 38.1μm depth of cut varies with different workpiece feed rates. The calculated value and experiment data are basically identical. This semi-empirical model can help engineers to have an intuitionistic acknowledgement of the different types of grinding fluid performance in the same grinding process set-up.

Figure 8-9: Supplement Modified Experiment results Vs Calculated results for TRIM® C270
Figure 8-10: Supplement Modified Experiment results Vs Calculated results for TRIM® SC520

Figure 8-11: Supplement Modified Experiment results Vs Calculated results for TRIM® E906
8.4 Conclusions

a) A new semi-empirical force model is derived based on the analysis of specific grinding energy, taking the grinding parameters into account.

b) For validating the model, four result groups were chosen from forty-five grinding conditions, solving the linear equations with four unknown coefficients which yield the final model. In the initial model, the figures indicate that the deviations between the experiment results and calculated results for C270 and SC520 are small both in shallow and heavy grinding except at some points, but E906 and 585XT are not nearly identical, especially in the heavy grinding condition. This is because in the four chosen result groups, the fourth group was not a smooth pass which gives a
higher force than expected using E906 and 585XT. This affects the accuracy of the calculated results. To overcome the inaccuracy, another four results groups were chosen for shallow grinding to derive another model. The deviations between the experiment results and calculated results are small with little variation compared to heavy grinding. The results support the accuracy and effectiveness of this semi-empirical grinding model.

c) Synthetic C270 performed well in both shallow and heavy grinding conditions. Due to the low dynamic viscosity and high surface tension, C270 achieves a more useful flow rate into the grinding zone, which reduces the friction between the workpiece and grinding wheel.
Chapter 9

Conclusions

9.1 Finished Research

In this paper, two steps of experiments were taken to get the properties of the grinding fluids: cooling capability index and global capability index. These two step experiments give an initial cooling and lubrication performance of grinding fluid.

In the first step experiment, a heating device is set-up to heat the workpiece to a certain temperature and then the fluid is applied with the grinding wheel rotating at the working speed, but without removing any material. A gap exists between grinding wheel and workpiece. The thermocouple was embedded in the workpiece to measure the temperature. In this experiment, the cooling capability of each grinding fluid is concluded combined with specific heat capacity, which is measured by Differential Scanning Calorimetry (DSC) method. The experiment results prove that higher specific heat capacity gives higher cooling capability. This is an initial conclusion used for comparing with the conclusion in the second experiment.

In the second step experiment, a set of experimental equipment is set-up. A new grinding temperature measurement method is introduced. The effect of depth of cut, grinding wheel speed and workpiece feed rate to the grinding temperature is explored.
These grinding parameter combinations become different grinding conditions. In this experiment, dynamic viscosity and surface tension are considered as key parameters for the grinding fluid cooling and lubrication performance. The magnitude trend of dynamic viscosity and surface tension for each grinding fluid are not the same as that of specific heat. Based on the comparison of temperature and force between different types of grinding fluid, the lower dynamic viscosity and higher surface tension, the lower grinding temperature and force. The effects of dynamic viscosity and surface tension are more significant than specific heat. Due to this conclusion, low dynamic viscosity and high surface tension can help more grinding fluid entering the grinding contact area which gives useful flow rate a status as a key factor in the grinding process to grade the grinding fluid performance.

Then an air flow simulation model is built. This model is a global model of the grinding process including grinding wheel and workpiece. From the simulation results, air pressure distribution and velocity vector figures are obtained. These simulation results can be used for the grinding fluid nozzle angle setting.

After this, a grinding fluid field model is built. Based on the simulation results, the useful flow rate trend varies with different depth of cut, grinding wheel speed and types of grinding fluid are concluded. Useful flow rate increases with the rise of grinding wheel speed and depth of cut. But low dynamic viscosity grinding fluid can have a better entering into the grinding area due to its physics performance. Combined with previous experiments results, lower dynamic viscosity increases useful flow rate, more grinding fluid enters in the grinding contact area at the same time, improving the cooling and lubrication capability, then decreases the grinding temperature and force. The simulation
results are actually in accordance with experiment results. Also, even if the effect of surface tension is not very obvious due to the dimensionless analysis of Weber number in section 6.2.4, but high surface tension grinding fluid can help fluid break up easily to enter into the grinding contact area. Thus, surface tension can be used as a supplement parameter in this model analysis.

A model is built to simulate heat transfer based on the useful flow rate simulation model in Chapter 6. A workpiece is added in this model. The effects of depth of cut, workpiece feed rate, grinding wheel speed and types of grinding fluid are taken into account. The simulation results have the same temperature increasing trend with experiment data. Combined with previous conclusions in Chapter 2, the magnitude trend of dynamic viscosity for each grinding fluid is not the same as that of specific heat. Such as 585XT, it has higher specific heat capacity which improves the grinding fluid cooling capability, but it has higher dynamic viscosity resulting in lower useful flow rate which does not help more grinding fluid enter into the grinding area compared with low dynamic viscosity grinding fluid. 585XT has highest grinding temperature comparing with other grinding fluid in the same grinding condition. This indicates that the effect of dynamic viscosity is more significant than specific heat capacity. Also, high surface tension grinding fluid has a specifics of easily breaking up which helps more grinding fluid entering into grinding contact area. In the grinding process, the influence of dynamic viscosity and surface tension to grinding temperature are higher than that of specific heat. This conclusion can help engineers to make a better decision for choosing grinding fluid.
A semi-empirical grinding force model is developed combined with the achievements of other researchers by composing effects of normal and tangential grinding forces in two main parts: cutting force and sliding force. Final equations for the total normal and tangential force components are established. A new semi-empirical force model is derived based on the analysis of specific grinding energy, taking the grinding parameters into account. An equation for sliding force is established with the effect of specific sliding energy in terms of the experimental parameters. The average contact pressure and friction coefficient expressed by wheel speed, workpiece feed rate and width of the workpiece are taken into account. Four different water-based grinding fluids were tested for different specific grinding conditions. Low dynamic viscosity and high surface tension grinding fluid can have better performance than the other grinding fluids due to the higher useful flow rate in the grinding contact area. This conclusion on the other hand confirmed previous conclusion. The calculated normal and tangential grinding results are compared with the experimental ones. The verifications show that deviations between the real results and calculated ones can be affected by the performance of the fluid at heavy grinding conditions due to the sliding friction inside of rolling friction. To have a better agreement with experiment data, shallow grinding condition is chosen to obtain the modified model.

This project explores the influence of grinding parameters in different grinding conditions for grinding temperature, force and roughness. Four models are built: grinding air flow simulation, grinding useful flow rate simulation, grinding heat transfer simulation and a semi-empirical grinding force model. The simulation results for useful flow rates, grinding temperature and grinding forces matched with experiment results
consistently. The effects of depth of cut, grinding wheel speed and workpiece feed rate for useful flow rate, heat transfer, grinding force are explored. The influence of grinding parameters and types of grinding fluid are essential in understanding the grinding process, which helps to determine the grinding fluid choice and the supplying parameter in the industrial applications.

9.2 Future Research

For future research, this model can be modified in different aspects:

a) A global simulation model can be built from the current model including grinding wheel and workpiece. The heat distribution on grinding wheel and deformation of grinding wheel and workpiece can be taken into account.

b) Viscosity is variable affecting by the change of environment temperature. This effect can be taken into account in the grinding fluid field simulation model with a user defined function.

c) The influence of grinding motor power can be taken into account for the semi-empirical force model, including the effect of heavy grinding condition

d) The useful flow rate experiment can be taken to further validate simulation result.

e) Roughness is a measurement criteria for grinding. A more precise instrument can be used for roughness measurement and roughness result can be involved in the simulation to have a further study on solid-solid friction in grinding.

f) Consider the abrasive grain’s size effect in the model.
Extensions of these models that in order to make a more proper approach that would bring simulations even closer to the physical reality of grinding process and deep understanding of grinding mechanism.
References


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