Advances in Abrasive Technology XII

Edited by
Han Huang, Liangchi Zhang, Jun Wang, Zhengyi Jiang, Libo Zhou, Xipeng Xu and Tsunemoto Kuriyagawa
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Selected, peer reviewed papers from the 12th International Symposium on Advances in Abrasive Technology (ISAAT2009), 27-30 September 2009, Gold Coast, Australia

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Preface

Abrasive technologies are central to the modern manufacturing for a large variety of products across many disciplines from nanoscale elements to large equipment and from biomedical devices to aerospace structures. Over the past decades, significant worldwide research effort has been to develop sophisticated abrasive technologies and to achieve their cost-effective implementations for environmentally conscious productions.

This book tends to collect the latest advancement and applications of abrasive technologies. The articles included are peer-reviewed, covering a broad range of research topics, including design, fabrication, truing and dressing of grinding wheels, precision grinding, abrasive jet processing, lapping, honing, polishing and non-conventional finishing, semiconductor processing, micro/nano- machining, fabrication and forming, advanced machining and rock cutting technologies, tribology in manufacturing, process monitoring and measurement, and other novel techniques and advanced studies related to abrasive technologies.

The editors hope that this book would be a useful reference for the professionals in the area of manufacturing who wish to keep abreast with the state-of-the-art development of abrasive technologies and who are interested in the fundamentals of the technologies.

We would like to express our sincere appreciations to all the authors for their contributions to this book. We are indebted to all the reviewers for their dedicated hard work. We would also like to acknowledge Mr. Zhigang Dong and Mr. Yueqin Wu for their invaluable assistance in communicating with the authors and in formatting the articles.

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I. Grinding and Grinding Wheels
Temperature fields in workpieces during grinding-hardening with dry air and liquid nitrogen as the cooling media

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Keywords: Grinding-hardening; Temperature field; Liquid Nitrogen; Heat Treatment

Abstract. This paper presents a temperature-dependent finite element heat transfer model, incorporating a triangular moving heat source and various cooling conditions, to predict the three-dimensional temperature field in plunge surface grinding. The model was applied to analyse the grinding-hardening of quenchable steel 1045 using dry air and liquid nitrogen as the cooling media. The temperature field variation under such grinding conditions was also measured experimentally. It was found that the temperature history predicted by the model agrees well with the measured results. The model provides a fundamental study as a first step in optimisation and control of the hardened layer thickness and its compositions in grinding-hardening technology.

Introduction
Grinding-hardening is a technology that uses the heat generated in grinding to promote the phase transformation in a steel workpiece to create a hardened surface layer. It has been concluded [1] that the layer hardened in this way has a remarkable improvement in wear and fatigue resistance. It has also been found [2] that when liquid nitrogen is used as a cooling medium in the grinding-hardening process, a ground component will have compressive surface residual stresses and the ground surface will be free from oxidisation.

The kinetics of phase transformations in steel depends greatly on the temperature and time during a heat treatment process [3]. Unlike a conventional heat treatment by quenching where the heating-cooling cycle can be relatively easily controlled, the thermal cycle in grinding is complex. The grinding heat source, approximately triangular [4, 5], is generated within a small wheel-workpiece area. While this heat source is moving along a workpiece surface during grinding, the materials in the heat source vicinity experiences convective cooling. Such a transient heat transfer process can result in a variation of the grinding-hardened layer in both its thickness and microstructure.

The heat transfer analysis of grinding to date is limited to two-dimensional cases. There is no investigation on the grinding-hardening under cryogenic conditions. The purpose of the present study is to establish a temperature-dependent, three-dimensional (3D) heat transfer model based on the finite element method to predict the temperature field during the processes of grinding-hardening.

Mathematical modelling
Moving heat source. The calculation of the temperature field in grinding-hardening can be based on a 3D unsteady-state heat conduction [6]

$$\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

(1)
where \( k \) is the thermal conductivity of a workpiece material, \( \alpha = k/\rho C_p \) is the thermal diffusivity in which \( \rho \) is the density and \( C_p \) is the specific heat. As shown in Fig.1, they are temperature-dependent, which can be accommodated in the calculation when Eq. (1) is solved numerically by finite element method using ANSYS.

The surface heat flux due to grinding, \( q_g \), can be viewed as a moving heat source on a moving coordinate system, \( \chi-\zeta-\psi \), at a constant speed, \( V_h \), along a workpiece surface with a fixed coordinate system, \( x-y-z \). In a plunge grinding, a heat source has a constant width in the \( \psi \)-direction which is the same as that of a workpiece, \( B \), as illustrated in Fig.2. For an up grinding, the distribution of the heat flux is triangular, having a linear distribution over the contact length, \( L_c \), as illustrated in Fig. 2, and can be expressed as

\[
q_g(\chi)\bigg|_{\text{const}} = q_0 - \frac{q_0}{L_c} |\chi| \quad 0 \geq \chi \geq -L_c
\]  

(2)

where \( q_0 \) is the peak heat flux that can be obtained from an experiment [8], i.e.,

\[
\bar{q}_g = \frac{1}{L_c} \int_{-L_c}^{L_c} q(\chi) d\chi = 0.5q_0 = \frac{\eta F_v V_h}{B L_c}
\]  

(3)

where \( \bar{q}_g \) is the average grinding heat flux, \( \eta \) is the fraction of total energy conducted into the workpiece (heat partition ratio); \( V_s \) is the wheel speed; \( F_t \) is the tangential component of the grinding force; \( B \) is the grinding width; and \( L_c = \sqrt{D d} \) [8] is the contact length between the wheel and the workpiece with \( D \) the wheel diameter and \( d \) the wheel depth of cut. The heat partition ratio, \( \eta \), can be determined according to the analysis of burn prediction [9]:

\[
\eta = \left\{ 1 + 1.06 \left[ \left( \frac{k \rho C_p}{\rho} \right) \frac{V_s}{V_h} \right]^{-1.5} f(\xi)A_0G_a \right\}^{-1}
\]  

(4)

where

\[
f(\xi) = \frac{2}{\pi^{0.5}} \frac{\xi}{1 - \exp(-\xi^2) \text{erf}(\xi)}
\]  

(5)

\[
\xi = \left( \frac{\gamma \pi V_s L_c}{2 A_0 V_h} \right)^{0.5}
\]  

(6)
In the above equations, subscripts g and w denote wheel-grain and workpiece, respectively; \( \gamma \) is an abrasive shape factor and is taken to be unit since grains used in making the grinding wheels are approximately equiaxed [10]. \( A_o \) is the average single grain-workpiece contact area; and \( G_a \) is the number of active grains per unit area of the wheel surface.

**Initial & boundary conditions**

Initial conditions:

\[
T_{\infty} = 22^\circ C \quad \text{(constant ambient temperature)}
\]

\[
T(x, y, z, t) = T_0
\]

\[
t = 0, 0 \leq x \leq L, 0 \leq y \leq B, -H \leq z \leq 0 \quad \text{(uniform temperature)}
\]

The Neumann boundary condition for cooling:

\[
-k \frac{\partial T}{\partial n} = q''_{\text{con}} + q''_{\text{rad}} = h(T - T_{\infty}) + \varepsilon \sigma (T^4 - T_{\infty}^4)
\]

where \( n \) is the unit vector normal to the surface of a boundary, \( h \) is the heat transfer coefficient applied to the boundary surface, \( T_{\infty} \) is the surrounding temperature, \( \sigma \) is the Stefan-Boltzmann constant and \( \varepsilon \) (\( \varepsilon = 0.21 \) for steel [6]) is the emissivity.

The convective heat transfer coefficient applied on the surface normal to \( n_x \) and \( n_y \) is

\[
h_{z=0} = h_a
\]

where \( h_a \) is the heat transfer coefficient due to air flow.

However, on the top surface where the grinding heat flux is applied, there is only the area outside the grinding zone is subjected to convective cooling. Depending on the coolant applied, the heat transfer coefficient normal to \( n_z \) is determined as follows.

For the dry air,

\[
h_{z=0} = \begin{cases} 0 & 0 \geq \chi \geq -L_c \quad \text{(within the grinding zone)} \\ h_a & \chi < -L_c, \chi > 0 \quad \text{(outside the grinding zone)} \end{cases}
\]

For the liquid nitrogen,

\[
h_{z=0} = \begin{cases} 0 & 0 \geq \chi \geq -L_c \quad \text{(within the grinding zone)} \\ h_b & \chi < -L_c, \chi > 0 \quad \text{(outside the grinding zone)} \end{cases}
\]

where \( h_b \) is the heat transfer coefficient due to boiling of liquid nitrogen ejected from a nozzle.

Radiation is also applicable for the boundary surface exposed to the ambient, i.e.,

\[
q_{\text{rad}} = \begin{cases} 0 & 0 \geq \chi \geq -L_c \quad (z = 0) \\ \varepsilon \sigma (T^4 - T_{\infty}^4) & \chi < -L_c, \chi > 0 \quad (z = 0) \cup z < 0 \end{cases}
\]

**Heat transfer coefficients** \( h_a \) and \( h_b \). In dry grinding, the heat transfer coefficient, \( h_a \) is estimated following the empirical relation for a square section with a characteristic length \( B \) subjected to a cross flow of air [6, 11].
\[ Nu = \frac{h_B B}{k_a} = 0.102 Re^{0.675} Pr^{1/3} \]  

(14)

where \( Nu, Pr \) and \( Re \) are the Nusselt, Prandtl and Reynolds numbers, respectively, i.e.,

\[ Re = \frac{(V_s \pm V_h) B}{\nu} \approx \frac{V_s B}{\nu} \]  

(15)

where \( \nu \) is the viscosity of air. The thermal properties of air \((k_a, \nu \text{ and } Pr)\) are functions of temperature. The dependence of heat transfer coefficient on the film temperature therefore can be computed and the result is illustrated in Fig. 3.

In grinding with liquid nitrogen, data from the experiments conducted by [12] for a liquid nitrogen jets vertically impacting on a steel surface is adopted in the present study. The boiling curve representing the relation of heat transfer coefficient, \( h_b \), on the superheat temperature \((\Delta T)\) is reproduced and represented in Fig. 4.

![Fig. 3 The dependence of heat transfer coefficient on the film temperature – dry air grinding.](image)

![Fig. 4 Boiling curve for liquid nitrogen jet impacting on steel surface.](image)

<table>
<thead>
<tr>
<th>Table 1 Experimental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wheel speed</strong> (m/s)</td>
</tr>
<tr>
<td><strong>Table speed</strong> (mm/min)</td>
</tr>
<tr>
<td><strong>Depth of cut</strong> (µm)</td>
</tr>
</tbody>
</table>
| **Cooling** | - Dry air, \( T = 22^\circ C \)  
- Liquid nitrogen: flow rate = 36.3 cc/sec |

![Fig. 5 Experimental setup](image)

**Results and Discussion**

The results we are going to discuss below are from the grinding conditions listed in Table 1 using the experimental setup shown in Fig. 5.

**Temperature rise in the grinding zone.** Figs. 6 and 7 show the prediction of temperature responses in grinding with dry air and liquid nitrogen, respectively. Due to the surge response of thermocouple sensor attached to the moving workpiece subjected to liquid nitrogen impacting jet, there is a small fluctuation of temperature occurring behind the grinding zone (Fig. 7).
prediction however, agrees with the measurement where the differences of the peak values are small (4.7% and -1.5% for the cases of dry air and liquid nitrogen, respectively). Due to the surge response of thermocouple sensor attached to the moving workpiece subjected to liquid nitrogen impacting jet, there is a small fluctuation of temperature occurring behind the grinding zone (Fig. 7). It shows that the use of liquid nitrogen does not significantly reduce the peak temperature in the grinding zone. This is because, as revealed experimentally [2], the penetration of liquid nitrogen into the grinding zone is extremely limited such that the high heat dissipation due to the boiling of liquid nitrogen is effective only outside the grinding zone. The cooling condition was accounted in the model as represented by Eq. (12). The model verified by experimental results (Fig. 6) confirms for that statement, concluding that grinding-hardening can be achievable under the application of liquid nitrogen since the austenite temperature Ac3 can be reached for the initiation of phase transformation.

Fig. 6 Temperature response – dry air grinding  
Fig. 7 Temperature response – liquid nitrogen grinding

**Temperature fields.** Figs. 8 and 9 show the temperature fields in grinding with dry air and liquid nitrogen, respectively. Due to the heat transfer on the sides of the block, isothermal lines are in the parabola form with the highest temperature occurring at the adiabatic plane at the middle of the block.

**Fig. 8 Temperature field – dry air grinding**  
**Fig. 9 Temperature field – liquid nitrogen grinding**
The front of the component ground with liquid nitrogen shows a distinct feature of the “tail” of the isothermal lines. At a certain distance from the surface, temperature is higher than that at the surface. This is because the high heat transfer rate of liquid nitrogen makes the top surface under the liquid nitrogen jet experiencing a higher cooling rate. This occurs until at a distance in the subsurface at which the heat flow rate to the upper surface and that to the bottom of the ground component reaches a balance. Therefore, the kinetics of the phase transformations in components ground with liquid nitrogen can be different from those with dry air.

Conclusions

A temperature-dependent heat transfer model incorporating the moving heat source has been developed to predict the temperature field in plunge grinding. The model has been applied to investigate the temperature variations in the grinding-hardening of steel 1045 using dry air and liquid nitrogen as the cooling media. It was found that the application of liquid nitrogen can generate a temperature field enabling a specific microstructure.

Acknowledgement

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References

Research on microscopic grain-workpiece interaction in grinding through micro-cutting simulation, part 1: mechanism study

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Keywords: Grinding, micro-cutting, simulation, mechanism.

Abstract. Grinding is regarded as a special multiple edge cutting process, which can be decomposed into grain-workpiece interface, chip-workpiece/bond interface, and bond-workpiece interface at microscopic level. The grain-workpiece interface, which resembles a micro-cutting process, directly modifies the workpiece surface and dominates all the output measures of a grinding process. Therefore, the study of the grain-workpiece interaction through micro-cutting analysis becomes necessary. As the emergence of the packaged FEM software for micro-cutting simulation, apart from single grit cutting test, it enables another qualitative and quantitative investigation method on grain-workpiece interface mechanism in an efficiency and effective manner. In this paper, the efficacy of the commercialized cutting simulation software Third Wave AdvantEdge\textsuperscript{TM} is evaluated, and the possibility of using AdvantEdge\textsuperscript{TM} for in-depth understanding of grain-workpiece interface as well as grinding process modeling is studied, too.

Introduction

Grinding is a special machining process with large numbers of parameters influencing each other, which can be considered as a process where thousands of irregular cutting edges interact simultaneously with the workpiece at high speed. However, irrespective of the choice of variables in the input categories, for every grinding process it is possible to visualize the basic microscopic wheel-workpiece interactions in terms of grain-workpiece interaction, bond-workpiece interaction, chip-workpiece interaction, and chip-bond interaction in Fig. 1. Among all the interfaces, the most fundamental interaction in grinding is still grain-workpiece interface which modifies the workpiece surface directly and dominates the material removal efficiency. Moreover, the chip generation within the grain-workpiece interface would also contribute to the chip-bond interface and chip-workpiece interface. Therefore, mechanisms of grain-workpiece interaction at microscopic level should be established for comprehensive understanding of grinding.

Investigations of the grain-workpiece interface using micro-cutting with a single grit is an important contribution to the explanation of the physical processes that occur during grinding. From this point of view, a number of single grit micro-cutting tests were conducted [1, 2]. For the orthogonal cutting with large negative rake angles that was performed as a simplified model 3D cutting, mechanisms proposed so far have not yet described the grinding process satisfactorily. Due to the difficulties in measurement of material deformation in 3D, even if cutting forces, cutting temperature and the profile of produced grooves were measured, it is still quite difficult to establish the mechanisms quantitatively [3].

The capability to characterize the material removal mechanism through FEM simulations provides an alternative and explicit method for understanding the effect of varying parameters, such as cutting speed, depth of cut, grain geometry. This may quantitatively illuminate some phenomena, which are difficult to measure in single grit cutting and to explain based on existing understanding of grinding. In this paper, the efficacy of commercialized FEM simulation software Third Wave AdvantEdge\textsuperscript{TM} for single grit cutting simulation in 3D is testified through comparing the simulation results and experimental values. And the possibility of using FEM software for a factorial analysis and grinding process from a phenomenological perspective is explored, too.
Material Modeling in AdvantEdge™

For the FEM cutting simulation, the primary modules should cover at least, but not limited to material constitutive model, chip formation criterion, heat transfer model, and FEM computation algorithms. Among all the modules, the material constitutive model is of the most importance, through which the material properties at high strain rates, large strains, and short heating times are determined. And the material constitutive model is essential for prediction of cutting force and chips formation during cutting. For metallic material, the power law model is used in AdvantEdge™ package, which is expressed as in Equation 1. \( g(\varepsilon^p), \Gamma(\varepsilon) \) and \( \Theta(T) \) stand for the effect of strain \( \varepsilon \) hardening, strain rate sensitivity, and thermal \( T \) softening, respectively. And \( \varepsilon \) and \( T \) stand for the plastic strain and temperature. Detailed explanation of the power law constitutive model used in AdvantEdge™ can be found in its user manual. In the simulation, the cutting tool is always considered to be perfectly rigid.

\[
\sigma(\varepsilon^p, \varepsilon, T) = g(\varepsilon^p) \cdot \Gamma(\varepsilon) \cdot \Theta(T)
\]

(1)

The material separation or chip formation criterion is determined by material damage in AdvantEdge™, which is represented in Equation 2. The dimensionless cumulative damage \( D \) is expressed as the summation of ratio between instantaneous increment of strain and the instantaneous strain to failure. When the cumulative damage \( D \) exceeds a critical value given by the uniaxial tensile test [4], the material failure starts in the form of chip formation. The heat transfer model and FEM computation algorithm are well embedded into the FEM software, and will not be described in the paper in detail.

\[
D = \sum \frac{\Delta \varepsilon^p}{\varepsilon_i^p}
\]

(2)

The primary practice for validating the FEM cutting models is the evaluation of machining force and chip formation [5]. Comparison over a wide range of cutting conditions establishes the efficacy of the numerical-constitutive integration response. Once the models have been validated further analysis may be performed over a wider range of perspectives in terms of shear angle, Mises stress and plastic deformation, taking advantage of the numerical computation capability of FEM.

Simulation Results and Discussions

In order to compare with the experiments, the simulation parameters are chosen as specified in literature [1]. The abrasive grain is a conically shaped diamond grain with apex angle of 140° and nose radius of 0.06mm. The workpiece material is AISI 52100, and the single diamond grain is selected as a conical shape. The cutting speed is 30m/min; the depth of cut is 0.015mm, 0.02mm, 0.025mm, 0.03mm, and 0.035mm, respectively. Machining force, specific force, critical depth of cut, and chip formation are compare with the experiments to validate the software. In addition, the
workpiece material stress field in the cutting zone, which is hardly obtained in experiments, is investigated for the mechanism understanding.

**Machining Force and Specific Force.** The average steady state cutting and thrust forces at various DOC level are extracted and examined from the simulation results. A linear relationship can be obtained for the cutting force and material removal cross-section area in Fig. 2(b), which is in correspondence with the experiment results [1]. To be able to compare the simulated cutting forces with the ones in literature the specific cutting forces were calculated. The calculation of specific cutting force is shown in Equation 3. And Fig. 2(c) reveals that the specific cutting force agrees with the experiment data, and decreases with an increase in the cross-sectional engagement area. The nonlinear trend in the specific cutting force occurs when the undeformed chip thickness is about 0.015mm. This so-called “critical depth of cut” separates plowing and cutting modes. The values of the critical depth of cut are, therefore, effective for separating the cutting grains and plowing grains when the grain-workpiece engagement condition is determined from grinding kinematics simulation.

*Specific cutting force* = \( \frac{\text{Cutting force}}{A} \) \hspace{1cm} (3)

where, \( A \) is the cross-section area of the grain, as shown in Fig. 2(a).

![Graph showing cutting and thrust forces vs. cross-section area](image1)

![Graph showing specific cutting force vs. cross-section area](image2)

**Fig. 2 Specific Force Calculation Comparison of Simulation and Experiments**

**Chip Formation.** Although generated chip morphology and the chip thickness were not reported in literature [1], the material side flow cross-sectional area was plotted in the literature. In the simulation, the relationship between grain-workpiece engagement cross-sectional area and pile-up material cross-section area is analyzed to evaluate the chip formation. The geometry of side flow pile-up material is equivalent to a triangular shape, which can be characterized by the width \( d \) and height \( h \). And the calculation of side flow cross-section area is indicated in Equation 4. The corresponding chip formation efficiency \( \eta \) can be calculated in Equation 5. As the grain-workpiece cross-section area increase, the area of pile-up material increases accordingly. An approximate linear relationship can be found for both simulation and experiment as in Fig. 3.

*Side flow cross – section area* = \( A_1 + A_2 = \frac{1}{2} \cdot (b_1 \cdot h_1 + b_2 \cdot h_2) \) \hspace{1cm} (4)
The comparison of machining force and chip formation indicate a remarkable agreement of simulation results with the experiments, which testifies the efficacy of the software. Furthermore, the stress and plastic strain status of the workpiece material in and around the cutting zone are analyzed in order to reveal the mechanism that cannot be directly depicted from experiments.

**Workpiece Material Stress/Strain Analysis**

Unlike experiments, the stress and strain status can be quantified in the simulations in a straightforward manner. Therefore, the examination of the stress and strain in the cutting zone enables more sophisticated explanation of phenomena in grinding.

**Mechanism of Material Plastic Flow.** Much effort is made to explain the mechanism of material removal in grinding, however, the material plastic flow and deformation mechanism is still not clear so far. The examination of the workpiece maximum pressure and Mises stress profile may open up a new vista for the understanding of material behavior and plowing occurrence. In the highlighted zone on the grain-workpiece interface, highest pressure and lowest Mises stress are achieved simultaneously. This phenomenon can be observed in all the simulations rather than occasionally. A careful examination and analysis of the stress status would help understand the material behavior in this area. Mises stress, which is known as the maximum distortion energy criterion, is often used to estimate the yield of ductile material in 3D. The Mises stress of material is defined as:

\[
\sigma_v = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}{2}} \tag{6}
\]

where, \(\sigma_1, \sigma_2,\) and \(\sigma_3\) are the principle stresses in 3D.

And the maximum principle stress \(\sigma_{\text{max}}\) is defined as the maximum stress value of the principle stresses in 3D.

\[
\sigma_{\text{max}} = \text{MAX}(\sigma_1, \sigma_2, \sigma_3) \tag{7}
\]
Therefore, it can be deduced that when the Mises stress achieves the maximum status, the differences of all 3 principle stress values are minimized. As one of the principles stresses reaches the maximum, the 3 principle stresses are all at their maximum status for the highlighted material compared with the material surrounding it. Then it can be inferred that the material in the highlighted area are experiencing most severe deformation than its immediate material, where most probably the material separation takes place and material plastic flow initiate. This finding suggests that the separation of chip from the matrix workpiece material initiated from some point on the rake face other than the tool nose tip. Even when the depth of cut exceeds the critical depth, the plowing effect still attains, which has been reported in the literatures [4, 6].

The single grain cutting simulation provides another explicit explanation for the typical residual stress profile of grinding [7]. For the single grain cutting, the maximum Mises stress can be observed several microns beneath the grit cutting trace. This extreme stress would retain after the grain passing by, which contributes for the residual stress formation. This phenomena explains why the maximum stress usually occurs beneath the workpiece surface rather than the workpiece surface [8]. From this perspective, the extreme stress in subsurface would be inherent with the negative rake angle cutting associated with grinding, and a proper selection of cutting parameter and grain geometry combination could minimize the residual stress without causing subsurface crack.

The shear angle represents the orientation of the primary shear plane/zone in the work material during chip formation. This parameter can be derived from measurements of the deformed chip thickness and the tool rake angle. This is usually a tedious work, and involves a lot of measurement error. From the simulation, the maximum shear stress profile enables an efficient and accurate representation of the shear angle, as indicated in Fig. 6.

Conclusions
AdvantEdge™ is used to compare the simulation results with experiment data, and proved to be efficient and effective for understanding the grinding process with abrasive grains. A factorial study
of the single grain cutting is carried out in the second paper of this series. And the following conclusions can be summarized.

1. The simulation is capable to predict the cutting force, thrust force, and chip formation satisfactorily, and the “critical depth of cut” can be apparently deduced from the simulation, which is in agreement with the value from the experiment.

2. The pressure, Mises stress, and maximum shear stress profile of the material are quantified and visible from the simulation, which help explain the material plastic flow, residual stress formation and shear angle calculation in single grit cutting.

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Research on Microscopic Grain-workpiece Interaction in Grinding through Micro-cutting Simulation, part 2: Factorial Study

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Keywords: single grain cutting, finite element method (FEM), (specific) cutting force, material removal rate, critical depth of cut, shear angle

Abstract: The grinding process can be considered as micro-cutting processes with irregular abrasive grains on the surface of grinding wheel. Single grain cutting simulation of AISI D2 steel with a wide range of cutting parameters is carried out with AdvantEdge\textsuperscript{TM}. The effect of cutting parameters on cutting force, chip formation, material removal rate, and derived parameters such as the specific cutting force, critical depth of cut and shear angle is analyzed. The formation of chip, side burr and side flow is observed in the cutting zone. Material removal rate increases with the increase of depth of cut and cutting speed. Specific cutting force decreases with the increase of depth of cut resulting in size effect. The shear angle increases as the depth of cut and cutting speed increase. This factorial analysis of single grain cutting is adopted to facilitate the calculation of force consumption for each single abrasive grain in the grinding zone.

Introduction

The fundamental process of grinding is microscopic cutting with irregular abrasive grains on the wheel periphery. A huge number of three-dimensional micro cuttings are performed with different shape of grains. Therefore, mechanisms study of single abrasive grain cutting is important for comprehensive understanding of grinding.

A number of grinding experiments with a single abrasive grain were performed [1, 2, 3]. However, chip formation and groove topography was always different and complicated because of irregular grain shapes. Thus, it was quite difficult to establish the mechanisms of single grain cutting even if cutting forces, cutting temperature and the profile of produced grooves were measured. On the other hand, a number of finite element models had been presented to describe the metal cutting processes [4, 5]. Early finite element analyses were performed by Usui and Shirakashi, Iwata, Strenkowski and Carroll [6] who analyzed the steady-state metal cutting simulations. The material model which considered deformation hardening, thermal softening and strain-rate sensitivity tightly coupled with a transient heat conduction analysis appropriate for finite deformations was presented by Marusich and Ortiz [7]. Most of the early investigations on the FEM modeling of orthogonal cutting were limited by the assumption of a perfectly sharp cutting edge which satisfies the fundamental 2D cutting model proposed by Ernst and Merchant. In recent years, a few trials were undertaken by Yen and Yang et al. Fang N who extended the FEM modeling technique to real non-sharp cutting tool geometries including round and chamfer edges. Thus, various types of chip formation became predictable by the finite element method [8, 9]. Hence, there are great possibilities that finite element modeling can be applied to cutting processes with abrasive grains under a wide range of grinding conditions, for example, from ordinary to ultrahigh
grinding speed, different depth of cut, grain shape and etc. This may quantitatively clarify some phenomena, which are difficult to explain based on only the common sense of grinding.

In this study, a finite element model of single abrasive grain cutting process has been developed to obtain a quantitative analysis of grinding processes. Thirdwave AdvantEdge™ 3D is applied to construct finite element model of single grain cutting process.

Single Grain Cutting Model

There are mainly three aspects which influence the results of single grain cutting, grain, workpiece and cutting parameters, as show in Fig. 1. Take alumina abrasive grain as an example, 46# grain is selected as the 46# grinding wheel is widely used in the coarse grinding of steel. In conventional cutting, the tool edge radius is of no concern because it is so small compared to the depth of cut of a few millimeters. Most metal cutting theories are based on the assumption that the tool edge is infinitely sharp [10]. But in micro cutting, the ratio of the depth of cut to the tool edge radius is comparatively small. Hence it is important to discuss the tool edge radius in single grain cutting process. In this case, the shape of abrasive grain is irregular because the grains are made from breaking of crystal, and they are very difficult to classify geometrically. However, it is clarified by experiment that the most of chip formation processes in actual grinding can be approximated as cutting with cone and sphere [11]. In this study, the grain is considered as a cone with cone angle $2\theta$ and tip nose radius $r$, as seen in Fig. 1. Point A is the tangency point between tip arc and cone generatrix. In this case, when depth of cut is below point A, the contact zone is ball. It is regarded cutting with ball-shape grain. When depth of cut is above point A, the cone and ball part are both involved in the cutting. For 46# alumina grain, average tip nose radius and cone angle is 0.032mm and 80°, respectively [11]. The workpiece is considered as a block because the cutting speed is much higher than the feed speed. The direction of cutting speed is parallel to the top surface of workpiece, as shown in Fig. 2. Different sets of simulations have been conducted from conventional grinding to high speed grinding, with depth of cut ranging from 0.006mm to 0.12mm, as shown in Table 1. The material constitutive model and the damage model have been discussed in [12].

![Fig. 1 Single grain cutting model](image1)

![Fig. 2 Single grain cutting](image2)
Table 1 Simulation data with different cutting parameters

<table>
<thead>
<tr>
<th>Grain Material</th>
<th>46° Alumina (10~15% ZrO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Shape</td>
<td>2θ = 80°; r=0.032mm</td>
</tr>
<tr>
<td>Workpiece material</td>
<td>D2 steel</td>
</tr>
<tr>
<td>Cutting speed (m/min)</td>
<td>1200, 1800, 4200, 5400</td>
</tr>
<tr>
<td>Depth of cut (mm)</td>
<td>0.006, 0.008, 0.01, 0.012, 0.032, 0.08, 0.12</td>
</tr>
<tr>
<td>Grinding coolant</td>
<td>Dry</td>
</tr>
</tbody>
</table>

Results and Discussion

Cutting force. The cutting force ($F_c$) for different cutting speed and depth of cut is shown in Fig. 3. When depth of cut is relative small compared to tip nose radius, cutting force goes up slowly and barely change at different cutting speed. As depth of cut continues to increase, cutting force increases sharply. At the conventional speed cutting, the cutting force increases with the increase of cutting speed. But cutting force decreases with the increase of cutting speed in the high speed cutting. It may be because of thermal softening of the material at high cutting speed enables material to be removed more easily, which yields smaller cutting force.

Specific cutting force. The specific cutting force ($SF_c$) is an important index to evaluate the grinding process as well as the single grain cutting process. It may reflect the physical characteristic of workpiece materials in the cutting processes. Specific cutting force has the similar physical meaning with the specific energy. Fig. 4 shows the specific cutting force with different cutting parameters. It is found that specific cutting force at small depth of cut is close to the specific melting energy of steels, 10.35J/mm³, namely $10.35 \times 10^3$ N/mm². So the material flow occurs in the cutting zone, which is the main reason to form side flow. The specific cutting force decreases with the increase of depth of cut and it is approximately constant when the depth of cut is large compared to grain tip nose radius.

![Fig. 3 Effect of cutting parameters on cutting force](image)

![Fig. 4 Effect of cutting parameters on specific cutting force](image)
It is found that there is a point where material flow velocity is smaller compared to other place, as point Q in Fig. 5. The material above point Q forms chip. \( h_{\text{crit}} \) is the height between machined workpiece surface and point Q. It can be defined as the critical depth of cut which differentiates cutting from plowing. The critical depth of cut has compared with specific cutting force at cutting speed of 5400m/min, as seen in Fig. 6. When depth of cut is smaller than 0.012mm, an approximate linear relationship between specific cutting force and depth of cut can be found, namely size effect. The specific cutting force barely changes when the depth of cut is larger than 0.012mm, which can be considered as a constant value. So when the specific cutting force is adopted to facilitate the calculation of force consumption for each single abrasive grain in the grinding zone, different specific cutting forces should be used to calculate grinding force. When the depth of cut is smaller than the critical depth of cut, the linear model of specific cutting force should be used; when the depth of cut is greater than the critical depth of cut, both the linear model and uniform model of specific cutting force should be used.

**Chip formation.** There are three types of cutting deformation in single grain cutting: chip, side burr and side flow, as shown in Fig. 7. Continuous chips are obtained at small depth of cut. The chip is removed directly from the workpiece. With the increase of depth of cut, side burr which is hardened material with layer shape occurs. By analyzing the plastic strain, it is found that the material in the side burr area is experiencing severe deformation compared with side flow area, as shown in Fig. 8. It can be inferred that the material area of side burr would be easily removed by the next cut.

At conventional speed cutting, 1200m/min and 1800m/min, severe side bur occurs when depth of cut is above 0.01mm; while in high speed cutting, 4200m/min and 5400m/min, it occurs when depth of cut is above 0.032mm. Take speed of 4200m/min as an example, the material deformation is chip formation and side flow at small depth of cut, as shown in Fig. 7(a); while the material deformation is chip formation, side flow and side burr at larger depth of cut, as seen in Fig. 7(b).
Material Removal Rate. Chip and side flow are the main types of cutting deformation in single grain cutting. Side flow is the pile-up of materials pushed to the groove edges by plastic deformation, and it does not result in the removal of workpiece material. The material removal rate at different depth of cut and cutting speed is shown in Fig. 9. The material removal rate $\eta$ increases with increase of the depth of cut. And it increases as the cutting speed increases. As depth of cut continues to increase, material removal rate $\eta$ seems to be constant value which means material removal rate does not increase anymore due to severe side flow.

![Fig. 9 Effect of cutting parameters on material removal rate](image)

![Fig. 10 Effect of depth of cut and cutting speed on shear angle](image)
Shear angle. The shear angles are derived from simulation results of the strain rate profile. It can be seen from Fig. 10 that the shear angle increases with depth of cut up to 0.012mm for cutting speed of 5400m/min and 4200m/min. When depth of cut is larger than 0.016mm, the shear angle of cutting speed of 5400m/min is larger than that of cutting speed of 4200m/min. A consequence of the larger shear angle is a smaller cutting force. This can be seen in Fig. 3 where, for depth of cut larger than 0.016mm, the cutting force of 5400m/min cutting speed is smaller than that of 4200m/min cutting speed.

Conclusions
The single grain cutting of AISI D2 steel is simulated by the finite element method. And the following conclusions can be summarized:

- Cutting force increases slowly and barely change at different cutting speed when depth of cut is small compared to grain tip nose radius. When cutting with larger depth of cut, cutting force increases rapidly. At low speed cutting the cutting force increases with the increase of cutting speed. But cutting force decreases with the increase of cutting speed in the high speed cutting.

- Specific cutting force decreases nearly linearly with the increase of depth of cut due to size effect at small depth of cut; it remains almost constant value at large depth of cut.

- Continuous chips are obtained at small depth of cut. But side burr occurs with the increase of depth of cut.

- Material removal rate increases with the increase of depth of cut and cutting speed, but it does not increase due to severe side flow when depth of cut is in the high level.

- Shear angle increases with the increase of depth of cut. It also increases with the increase of cutting speed at large depth of cut which results in smaller cutting force.

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References
Effects of vibration-assisted grinding on wear behavior of vitrified bond Al₂O₃ wheel

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Abstract. The total removal of grinding wheel material includes two main parts. The larger of the two is the result of dressing and truing operation and the other relatively small part is due to the wheel wear which takes place during the actual grinding process. The frequency of dressing and truing operations depends on the cutting conditions, wheel characteristic, etc. However in dry grinding as there is no cutting fluid to transfer the heat from the contact zone, the wheel wear during grinding and the frequency of dressing is much higher due to the higher grinding forces and temperatures. Vibration grinding reduces wear of the grinding wheel during the process considerably and decreases the frequency of dressing operation significantly. Hence it increases the efficiency of the process and reduces the cost. The investigation carried out in the KSF institute shows the improvement on the surface roughness, reduction of the grinding forces, thermal damage of the ground surface and radial wear of the grinding wheel in case of using vibration grinding comparing to conventional grinding. The designed and developed ultrasonically vibrated workpiece holder and the experimental investigation show a decrease of up to 80% of radial wear of the grinding wheel.

Introduction

Grinding can be considered as a simple abrasion process. Grit penetrates into the workpiece and plows the material away. To maintain a high material removal rate, the grain needs to be sharp. Once the abrasives are worn, the penetration depth is reduced and the material removal rate drops. The wear rate of the abrasive layer is a very important parameter in the grinding process. It has a vast effect on the material removal rate, G ratio and the efficiency and the cost of the process. Normally up to 80 percent of the conventional grinding wheel may be utterly wasted due to dressing [1]. The main wear mechanisms of abrasive grains during grinding are adhesive wear, diffusive wear, abrasion, fracture of grain and grain break out. However in the fine grinding when high accuracy and low surface roughness are required, abrasion, adhesive and diffusive (due to the high instantaneous temperatures and thermal stresses) wear are the most common form of wear. In order to maintain the required material removal rate, cutting ability and surface integrity of the workpiece, the grinding wheel should be dressed frequently. The regularity of dressing and truing operations is governed by the wheel life which in turn is determined by the cutting parameters, properties of the wheel and the workpiece, machining accuracy, surface finish, etc. The depth of removed layer of the grinding wheel in dressing is defined by grinding process and is aimed to regenerate the cutting abilities of the grains and reinstate the required surface integrity of the workpiece. The wheel wear during grinding and the frequency of dressing is much higher in dry grinding as there is no cutting fluid to transfer the heat from the contact zone and the process undergoes higher grinding forces and temperatures. However dry machining has been increasingly investigated in order to decrease the negative environmental impact of the cutting fluids, diminishing problems concerning waste
disposal demand and also due to interest in decreasing manufacturing costs. Though, generally in
dry grinding problems frequently occur in terms of high heat generation on grinding wheel surface
and workpiece surface, increasing the grinding energy, wear of grinding wheel, low material
removal rate (regarding relatively low depth of cuts) as well as poor surface roughness compared to
conventional grinding (CG) [2-5].

Ultrasonic-assisted grinding (UAG) increases the material removal rate and simultaneously
decreases the wear of the grinding wheel and decreases the frequency of dressing operation. Hence
it increases the efficiency of the process and reduces the cost of the process. Significant
improvements in material removal rate, tool wear, cutting forces, burr size, heat generation and
surface finish, by using ultrasonic assisted machining have been reported. Jin and Murakawa [6]
found that the chipping of the cutting tool can effectively be prevented by applying ultrasonic
vibration and tool life can be prolonged accordingly. Tawakoli et al [7-10] demonstrated that in
ultrasonic assisted grinding and dressing, considerable reduction in grinding forces, surface
roughness, grinding wheel wear and dresser wear is achievable.

In this investigation, an UAG system has been designed, fabricated and tested. Reduction in the
radial wear of the grinding wheel, the grinding forces and improvements of surface roughness due to
superimposing of ultrasonic vibration in the grinding of 100Cr6 have been achieved. Besides, the
effect of vibration amplitude, feed speed and depth of cut on wheel wear, surface roughness and the
grinding forces has been presented.

Experiments

Tests were carried out on 100Cr6 steel. The dimensions of the workpiece were 60*50*30 mm. The
samples were attached to the acoustic head which in turn was held in a fixture. A series of surface
grinding tests were conducted on a CNC universal surface grinding machine (Elb Micro-Cut AC8)
using a vitrified bond Al$_2$O$_3$ (A 120) grinding wheel (Ø400 mm). The wheel speed during all tests
was maintained at 60 m/s whilst the depth of cut, $a_c$, varied between 50 and 300 µm and feed speed,
$v_f$, at 1000 and 2000 mm/min.

**Fig. 1. Experimental set-up for ultrasonic assisted grinding.**

Fig. 1 shows the experimental set-up. The grinding wheel was dressed before each long time test
using a diamond disc dresser with $R_{sp}$ (radius) = 0.2 mm. Dressing conditions were as follows:
dressing ratio $q_d$=0.8, wheel speed $v_{cd}$= 60, depth of dressing $a_{cd}$= 5 µm, overlapping ratio $U_d$=4,
total depth of dressing $a_{cd-total}$= 10 µm. In order to generate high frequency electrical impulses an
ultrasonic vibration generator (Mastersonic MMM generator-MSG.1200.IX) was used, which
produced a vibration with a frequency of $f$=23 kHz and 10µm Amplitude (A). The amplitude of
vibration was measured by an eddy current displacement measurement system (Micro epsilon
A surface roughness tester (Hommel-Werke: T-8000), a dynamometer (Kistler piezoelectric dynamometer model 9255B), measuring grinding forces, and a digital microscope (Keyence: VHX, magnification: 1000), observing grinding swarfs, were used. Vibration is applied to the workpiece in the feed direction of the grinding wheel. The amplitude of the ultrasonic vibration can be adjusted by changing the setting on the generator. The tests were carried out for both UAG and CG with the same instrument. However, during the CG the ultrasonic generator was switched off.

**Experimental results and discussion**

In order to study UAG, an actuated workpiece holder was developed. The workpiece holder consists of a piezoelectric transducer, a booster, a sonotrode and a special fixture. On the basis of previous experiments and experiences the vibration amplitude, A, was selected to be 10 µm. It was noticed that in this range of amplitude the grinding forces will reduce significantly [4,5]. In order to achieve reliable data each test was repeated 3 times. In all figures, lines were formed by calculating the least-squares fit through the data points for a second-order polynomial equation. Fig. 2 compares specific grinding energy, \( e_c \), produced by UAG with CG under different equivalent chip thickness (a measure of the depth of penetration of the abrasive grains into the workpiece). This figure represents the efficiency of the grinding process. The smaller the specific grinding energy at the same equivalent chip thickness, \( h_{eq} \), the higher the efficiency of the grinding process. The specific grinding energy and the equivalent chip thickness were calculated through the use of equations 1 and 2, using the measured tangential grinding force:

\[
e_c = \frac{F'_t \cdot v_c}{(v_{ft} \cdot a_c)} \quad (1)
\]

\[
h_{eq} = \frac{Q'_w}{v_c} = \frac{v_{ft} \cdot a_c}{v_c} \quad (2)
\]

\( F'_t \): Specific tangential grinding force
\( v_c \): Cutting speed
\( v_{ft} \): Feed speed
\( a_c \): Depth of cut

**Fig. 2. Specific grinding energy vs. equivalent chip thickness.**

It is clear from the figure that the efficiency of the ultrasonic-assisted grinding is much higher than the efficiency of the conventional grinding. The specific grinding energy decreases with increasing (equivalent) chip thickness due to the size effect.

Figs. 3–6 show the changes of radial wear of the grinding wheel \( \Delta r \), specific grinding forces \( F'_t \), \( F'_n \), and surface roughness \( R_a \), \( R_z \), produced by UAG with CG, with increasing material removal \( V'_w \). Experiments were carried out at \( v_c=60 \text{ m/s}, f=23 \text{ kHz}, A=10 \mu m \). In regard to previous
experiments [4,5] the depth of cut and the feed speed values were selected so that the ground workpiece would not experience apparent thermal damages. However CG's with specific material removal more than 200 mm$^3$/mm (in feed speed of 1000 mm/min) were unsuccessful due to the thermal damage on the ground workpiece surface. As the grinding forces in specific material removal of more than 200 mm$^3$/mm are significant, the heat generation in the contact zone will increase and hence lead to thermal damage on the ground surface.

Fig. 3. Effect of specific material removal on radial wear of grinding wheel.

In UAG grinding forces and temperature are very low and therefore the wear of the abrasive grain and the fluctuations in grinding forces and surface roughness of the ground workpiece is not high. Therefore the need for dressing is significantly reduced and the grinding wheel life is increased considerably. Thus leading to a more time and cost efficient process. However the situation is completely reversed in CG. During the conventional dry grinding process an increase in the grinding forces leads to an increase in cutting temperature and wear of the abrasive grain. Hence the abrasive grains will become dull, in turn the grinding forces and temperature will increase and the surface roughness will improve. However the reduction in grinding forces and increase in surface roughness in figs. 4 and 5 at specific material removal of 300 mm$^3$/mm is most probably
due to the phenomenon of self sharpening of abrasive grains, fracture of the grains and producing new sharp cutting edges.

The reason for these improvements is the change in the nature of the cutting process, which is transformed into a process with a multiple-impact interaction between the abrasive grits and the formed chip. The maximum oscillating velocities (up to 87 m/min) and accelerations (up to $20.8 \times 10^4$ m/s$^2$) are generated at the amplitude of 10 µm and a frequency value of 23 kHz. The larger the vibration amplitude, the greater the material removal rate per active grain and the higher the kinetic energy with which the grits strike the work surface. Due to the high frequency interaction of active grains on the workpiece, the cutting process in UAG becomes discontinuous and ultrasonic impact action occurs, thus causing the material to begin to rollover more easily as well as more micro cracking propagation in the cutting zone which both make an effective interaction between grits and workpiece surface. Therefore the grinding forces and frictional effects are decreased, so that less plastic deformation occurs.

In order to better understanding of UAG process, grinding swarf of experiments were studied under a digital microscope. Fig.7 shows photos of grinding swarf produced in CG and UAG. The comparison between grinding chips in Fig 7.a and Fig7.b shows that grinding chips in UAG are

![Fig. 5. Effect of specific material removal on surface roughness, $R_a$.](image)

![Fig. 6. Effect of specific material removal on surface roughness, $R_z$.](image)
much shorter. The molten spheres in Fig 7.a show that the cutting temperature in CG is higher than that in UAG.

Fig. 7. Photos of grinding chips obtained at \( v_c = 60 \text{ m/s}, v_f = 1000 \text{ mm/min}, a_e = 20 \mu\text{m} \).

**Conclusion**

Comparison of the UAG and CG methods demonstrate considerable advantages of the former technology for grinding 100Cr6.

- The efficiency of ultrasonic-assisted grinding (UAG) process is much higher than that in conventional grinding process, i.e. specific grinding energy at the constant equivalent chip thickness is lower in UAG.
- Comparative experiments demonstrated up to significant reduction in radial wear of the grinding wheel and grinding forces for the workpieces machined with superimposed ultrasonic vibration.
- The fluctuations of grinding wheel wear, grinding forces and surface roughness at several specific material removal points are much lower in UAG in comparison to those in CG.

**References**

Influence of Particle Effects on the Material Removal Rate utilizing Electrokinetic Phenomenon

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Keywords: Abrasion, Erosion, Removal, Nanometer, Electrokinetic, Particle.

Abstract. With the demand for precise nanometric material removal with minimal defects, several non-contact ultraprecision machining techniques were developed over recent decades. The electrokinetic material removal technique [1] is one such method that allows material to be removed without any physical contact between the tool and the workpiece.

In this work, the influence of the slurry mixture on the material removal rate for the electrokinetic material removal process is studied. During the process, it was observed experimentally that the mixture of the slurry affected the material removal rate. The parameters varied in the slurry mixture experiments were the size and concentration of the particles. Explanations for the behaviour of the material removal rate were also suggested during the study to further understand the electrokinetic material removal technique.

Introduction

Microsystem Technology (MST) has raised great interest over the past few decades due to its potential in producing miniature, light and functional devices at relatively low prices. Eventually, this trend may shift towards nanotechnology in the near future with the increased demand of producing even smaller devices with more functionality and better performances. To cater to this impeding need, one of the main criteria would be to improve the fabrication technologies that produce these miniature products. This can be fulfilled by either optimizing the existing fabrication machineries or introducing novel fabrication techniques that enable better precision and machining features for future manufacturing needs.

To satisfy the demand of producing devices with higher dimensional accuracy and minimal defects, a novel removal technique based on the electrokinetic phenomenon was recently proposed. This material removal technique is mainly due to the combination of both the electrokinetic and hydrodynamic effects that act on the abrasive particles. The effects are due to the applied electric field and the fluid flow respectively. It is primarily through the combination of the two effects that embody the abrasive particles in the slurry with sufficient velocity to collide onto the surface of the workpiece to create material removal.

An illustration of the particles’ idealized motion is shown in Fig. 1. Fig. 1(a) demonstrates the horizontal motion of the particle in the x-direction due to the hydrodynamic effect only while Fig. 1(b)–(d) shows the motion of the particle when it is under the influence of both the hydrodynamic and different electrokinetic effects. When the particle is under the influence of an alternating current (AC) electric field only (Fig 1. (b)), the particles are expected to make oscillations across the centre of the channel due to the electrical polarity switching. When the particles are merely under the influence of direct current (DC) electric field (Fig. 1(c)), the particles are brought to closer
proximity with the surface of the workpiece to enhance particle interactions with it. It is only with the combination of the AC and DC electric field (Fig. 1(d)) that cyclic collisions of the particle with the surface of the workpiece are expected to create material removal.

Fig. 1 The expected behaviour of the particles when they are under the influence of fluid flow velocity and (a) no electric field (b) AC electric field only (c) DC electric field only (d) AC electric field with a DC biased.

Preliminary results of the material removal method were reported and showed that the technique was capable of removing material in rates of Angstroms/Hr [1]. Parametric studies on the material removal rate by varying the AC electric field and the flow rate of the abrasive particles across the channel were conducted. It was demonstrated that the material removal rate on the workpiece could be precisely controlled by varying these parameters. To provide a better understanding on the electrokinetic material removal technique, Leo et al [2] attempted to study the trajectory of the particles by looking into the body force diagram of a single particle caused by both the electrokinetic and hydrodynamic effects during the process. They suggested that the material removal mechanism for the process was mainly considered as a mechanical one as the velocity of the particles during the experiments far exceeded the minimum particle velocity necessary to break the material bonds. Other material removal mechanisms were considered negligible as there was insufficient evidence of such activities.

Since slurry based material removal techniques are generally affected by the particle parameters, this paper aims to look into the relationship among some of the particle parameters of the slurry and how they would affect the material removal rate of the electrokinetic process.

**Electrokinetic material removal concept**

The electrokinetic material removal process is mainly dominated by the electrokinetic and hydrodynamic effects that are acting on the charged abrasive particles within the slurry. The electrokinetic effect provides the particles with a velocity in the direction perpendicular to the surface of the workpiece (y-direction) while the hydrodynamic effect provides the particles with a velocity in the direction parallel to the surface of the workpiece (x-direction) as shown in Fig. 1.

When a particle is submerged in the aqueous solution of the slurry, it carries electrostatic charges on the interface due to the formation of electric double layer. The surface charge of the charged particle is related to the zeta potential and size which is given by [3]:

\[
\text{Surface charge} = k \cdot \text{zeta potential} \cdot \text{size}
\]
\[ Q_E = 4\pi a\varepsilon \varepsilon_0 \zeta \]  

(1)

where \( Q_E \) is the surface charge of the colloidal particle, \( a \) is the radius of the particle, \( \varepsilon \) is the permittivity of the fluid, \( \varepsilon_0 \) is the permittivity of vacuum, and \( \zeta \) is the zeta potential of the fluid.

Consequently, the electrokinetic effect that acted on the abrasives under the influence of the electric field in y-direction can be accounted by:

\[ F_x = Q_E E_{AC+DC\text{Bias}} \]

\[ = 4\pi a\varepsilon \varepsilon_0 \zeta \left[ \frac{V_{AC} \sin(2\pi ft)}{d} + \frac{V_{DC\text{Bias}}}{d} \right] \]

(2)

where \( V_{AC} \) is the AC voltage of the electric field, \( V_{DC} \) is the DC voltage of the electric field, \( d \) is the distance between the two electrodes where an AC electric field with DC bias is applied, and \( f \) is the frequency of the AC electric field.

Conversely, the hydrodynamic effect that acted on the abrasive particles due to the flowrate of the fluid in the x-direction can be described by:

\[ u = 6U \left[ \frac{1}{4} \left( \frac{y'}{H} \right)^2 \right] \]

(3)

where \( u \) is the localized fluid velocity, \( U \) is the general fluid velocity, \( y' \) is the height of the localised element of the fluid at the centre of the channel and \( H \) is the height of the microchannel.

Besides embodying the particle with a certain amount of velocity to create material removal, the constant flowrate of the slurry was also used to facilitate a steady supply of slurry into the channel.

During the material removal study, dielectrophoresis was assumed to be negligible as there were no electric gradient between the electrode and the workpiece. Electroosmotic flow was also assumed to be negligible as the experimented fluid was assumed to be a weak electrolyte.

**Experimental procedure**

Fig. 2 illustrates the schematic of the experimental setup. The setup consisted of a base substrate and a workpiece (gold sputtered wafer) that were attached together with a metallic clamp. The base substrate consisted of a channel that was patterned from polydimethylsiloxane (PDMS from Dow Corning) through photolithography processes to allow fluid flow during the material removal process. The channel in the PDMS was 500 µm wide and 25 µm deep (20 µm after compression during clamping). Electrical voltage was subsequently applied to the electrode and workpiece to create the electrokinetic effect on the abrasives. The AC electric field with a DC offset was supplied to the electrodes in a manner such that the workpiece was positively biased while the electrode was negatively biased with the DC electric field. In conjunction, the abrasive (silica particles from Alfa Aesar) suspended fluid (ethanol from Sino Chemical) was introduced into the channel through a syringe pump to create the hydrodynamic effect on the particles. The process was carried out for 1 hour before the workpiece was characterized to study the material removal rate.

The depth of the material removal was determined by using both white light interferometry (Wyko NT2000 from Veeco) and stylus profilometry (Dektak ST from KLA-Tencor). The material removal rate was calculated by dividing the depth of the material removed by the experimental time span. For each data point on the graph, a total of 10 measurements were made. Outliers from each set of measurements were removed such that a more robust and accurate account on the material removal rate could be reflected. The sample mean and standard deviation of the wear depth for each
data point was then calculated and plotted along with a best fit line. Table 1 lists the experimental conditions which were varied and the values selected.

Table 1. Experiments carried out to study the influence of the particles parameters

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Time (hr)</th>
<th>Particle size (µm)</th>
<th>Concentration of particles (g/ml)</th>
<th>DC electric field (kV/cm)</th>
<th>AC electric field (kV/cm)</th>
<th>AC electric field frequency (Hz)</th>
<th>Fluid velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>1</td>
<td>0.5−1.5</td>
<td>0.01</td>
<td>12.5</td>
<td>50</td>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>1</td>
<td>1.5</td>
<td>0.001−0.350</td>
<td>12.5</td>
<td>50</td>
<td>10</td>
<td>0.4</td>
</tr>
</tbody>
</table>

**Results and discussion**

**Influence of particle size effect on the material removal rate of the workpiece.** It was observed that the material removal rate increased with increasing particle size. Tillet [4] had reported that there was a specific particle size effect that required increasing abrasive velocity on smaller particle size to create material removal of the same effect as that compared to a lower abrasive velocity with a larger particle size. Hence, one would expect the material removal rate of the workpiece to decrease with smaller particle size if the particle velocity does not differ very much. This is evident in Fig. 3 where we observed an increase in the material removal rate of the workpiece with increasing particle size.

Fig 3. The influence of particle size on the material removal rate of the workpiece

**Influence of particle concentration on the material removal rate of the workpiece.** A study on the relationship between the material removal rate and the concentration of the abrasive particles in the slurry during the material removal process was conducted during the experiment. It was...
observed that the material removal rate of the particles reached an optimal 2500 Angstrom/Hr before a decrease occurred. This could be explained by the illustration as shown in Fig. 5.

Fig 4 The influence of particle concentration on the material removal rate of the workpiece

![Material removal rate Vs concentration](image)

**Fig. 5** A schematic showing the packing of the particles when they are approaching the surface of the workpiece during the material removal process at concentration 0.01 g/ml

Fig. 5 illustrates the packing of the particles when they approach the surface of the workpiece during the material removal process. The illustration was drawn after a mathematical calculation was made to determine the number of layers of the particles that were packed together when they approached the workpiece during each AC electric field cycle. When the concentration of the particles is too low (i.e. 0.001 g/ml), only a mono-layer of the abrasive particles approached the surface of the workpiece. However, when the concentration of the particles was increased, the material removal rate increased. One of the possible reasons was due to the increase in the participation of the particles on the material removal process. Compounding to this, the particles were reaching the surface of the workpiece with increasing inertia. This is because the layer of particles on the surface of the workpiece are “pushed” against it by the incoming particles in the subsequent layers which aided in overcoming the drag force on the layer of particles that were closest to the workpiece. Conversely, when the concentration of the particles was higher, the particles were unable to collide onto the surface of the workpiece with sufficient velocity to cause material removal on it. This is because the particles were not given enough distance to gain sufficient velocity before collision. In addition, when the concentration of the particles was above 0.03 g/ml, the material removal rate began to decrease as the channels were fully packed with particles.

**Conclusion**

In this paper, a study was aimed to understand the correlation between the slurry mixture and the material removal rate of the electrokinetic process. During the study, it was observed
experimentally that the size and the concentration of the abrasives in the slurry significantly affected the material removal rate. It appeared that the material removal rate increased with increasing particle sizes. At the same time, an optimal material removal rate was observed when the concentration of the particles was about 0.01g/ml. To further understand the electrokinetic material removal process, possible reasons for the behaviour of material removal rate with respect to the varying particle parameters were suggested during the study.

References


Diamond tools for the grinding of complex ceramic implant surfaces

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Abstract. Until now, the complex kinematics and geometries as well as high quality requirements have prevented the use of all-ceramic prostheses for the medical treatment of knee joints. High-precision grinding and polishing processes for free-formed ceramic surfaces are essential for this purpose. Constantly changing contact conditions have to be considered to ensure a constant material removal. Within this work, appropriate tools are introduced which are able to adjust to the form variation of the component contour.

Introduction

With 500,000 prostheses per year, the knee is the most frequently medically treated joint in the world. Because the implant lifetime reaches only 10 years, which is mainly due to implant loosening, knee implants are a particularly relevant research topic. Up to now, no ceramic total knee replacement with pure hard-hard material pairing has been introduced. However it is a fact that most failures of prostheses occur due to wear particles produced by polyethylene components [1-3].

For implant material pairings, a trend towards hard materials and coatings [4-6] can be observed, which is a result of their superior friction properties and biocompatibility. Ceramics are particularly qualified as prostheses material because of their characteristic pressure and wear resistance. Owing to the small fracture toughness even at low tensile loads, ceramic components can break due to brittle fracture. Among other factors, the fault state range has a significant influence on the wide distribution of the strength properties. Therefore finishing with high accuracy has a significant effect on the durability and functionality of ceramic components [7]. “As (...) new production methods are being developed, we anticipate excellent acceptance and growth of the ceramic total knee replacement market”, a European implant manufacturer expressed the demand for novel manufacturing techniques for the finishing of complex ceramic surfaces [8].

Machining of complex ceramic surfaces

Strategy. Standard metallic knee implant components are milled and then vibratory ground within one or more steps. Up to today, often the last process step, i.e. polishing, is performed manually. As a result of purely force-controlled processes or worker, depended experience deviations worsen the shape accuracy.

Especially for complete ceramic implants without incongruence-compensating polyethylene inlays, high-precision machining processes for grinding and polishing have to be realized. Automated processing in one clamping with one machine is the objective of the research work (Fig. 1). Firstly the near-net-shape sintered part is pre-ground. The intended macro geometry is then produced by a multiaxial grinding process, with already very good surface quality corresponding to the intended contour. Afterwards a polishing

Fig. 1 Machining strategy
process is conducted, which has no influence on the present component shape, but only smoothens the roughness peaks of the contour.

For this process, the tools have to adjust to the complex shape of the component contour and to compensate the constantly changing contact conditions for a preferably steady material removal.

**Toric grinding pins**, depicted in figure 2, are appropriate to adapt to complex geometries due to their bond geometry in combination with their adjustable orientation towards the work piece. If an orthogonal orientation towards the work piece is used, big convex radii can be machined, whereas small concave radii can be machined with a defined contact angle of the toric tool. Even flat areas can be ground without receiving a profiled surface. Furthermore, it is possible to adjust the tool position to the constantly changing contact conditions by a variation in the contact angle, which is necessary to achieve high shape accuracy.

Due to the special tool geometry and the various application modes apart from orthogonal positioning, the terms and calculations of classical grinding processes like peripheral and face grinding cannot be conferred to grinding processes with toric pins. For example, the material removal rate, which is directly related to the cutting cross section $A_w$, is an important parameter for the process design. Depending on whether the grinding processing is performed sideways or frontal (Fig. 2), the cutting cross section can differ and has to be calculated on another manner.

![Fig. 2 Toric grinding pins – five-axis positioning](image1)

The sideways processing is shown in Fig. 3 with a focus on the contact conditions. In the top of Fig. 3, the back view is illustrated and beneath the side view. Characteristic for the sideways
application of the toric pin is that the cutting cross section is mainly the penetration of the small minor torus ring radius into the work piece in a depth of the cutting depth $a_e$. Depending on the tool angling via the lead angle $\beta_{\text{fN}}$, which is oriented perpendicular to the feed speed direction, the tangent of the tool bond geometry can also play a role, but only if $\beta_{\text{fN}}$ is smaller than $\beta_{\text{fN limit}}$ (Fig. 3 right).

Usually the cutting cross section $A_w$ is calculated by the product of the depth of cut $a_e$ and the width of cut $a_p$. In this process, the cutting cross section is a function of different additional values like the minor toric ring radius $r$ and the lead angle $\beta_{\text{fN}}$. The geometrical cutting cross section can be calculated using the sections $A_1$ to $A_5$ (Eq.1-8).

\[
\text{For } \beta_{\text{fN}} \leq \beta_{\text{fN limit}} \text{ with } \beta_{\text{fN limit}} = \arccos\left(\frac{r - a_e}{r}\right) \quad (1)
\]

is $A_1 > 0$ and $A_{\text{wS}} = \sum_{i=1}^{5} A_i = A_1 + 2 \cdot A_2$ \quad (2)

otherwise is $A_1 \leq 0$ and $A_{\text{wS}} = 2 \cdot A_5$. \quad (3)

The sections of (Fig. 3) are calculated as follows:

\[
A_1 = \left( \frac{(a_e - h)^2}{\tan(\beta_{\text{fN}})} \cdot \frac{1}{2} \right) - A_2 \quad (4)
\]

\[
A_2 = A_5 - (A_3 - A_4) \quad (5)
\]

\[
A_3 = r \cdot \sin(\beta_{\text{fN}}) \cdot (a_e - h) \quad \text{wheras } h = r \cdot (1 - \cos(\beta_{\text{fN}})) \quad (6)
\]

\[
A_4 = \frac{r^2}{4} \cdot \left( \frac{\Pi \cdot \beta_{\text{fN}}}{90} - \sin(2 \cdot \beta_{\text{fN}}) \right) \quad (7)
\]

\[
A_5 = \frac{r^2}{4} \cdot \left( \frac{\Pi \cdot \left( 2 \cdot \arccos\left( \frac{r - a_e}{r} \right) \right)}{180} - \sin \left( 2 \cdot \arccos\left( \frac{r - a_e}{r} \right) \right) \right) \quad (8)
\]

In Fig. 4 the resulting cutting cross sections $A_{\text{wS}}$ for three minor toric ring radii are depicted against the lead angle $\beta_{\text{fN}}$. For comparison, the classical values $A_w$ are presented in broken lines. It can be observed that the values taking into account the geometric penetration are lower than the classical values. Furthermore, it can be observed that the values depend on the minor toric ring radius $r$. With an increase in the ring radius, the cross section $A_{\text{wS}}$ also increases. Additionally, it can be observed that the toric pin tangent area $A_1$ is only relevant for small lead angles. $\beta_{\text{fN limit}}$ increases with decreasing radii.

The cutting cross section $A_{\text{wS}}$ is necessary to calculate the specific removal rate $Q'_{\text{wS}}$ (Eq.9).

\[
Q'_{\text{wS}} = \frac{A_{\text{wS}} \cdot v_f}{b_{\text{gS}}} \quad (9)
\]

This parameter also decreases if the geometrical penetration is taken into account. It is independent of the minor toric ring radius $r$, but also influenced by the lead angle if this is smaller
than $\beta_{\text{N limit}}$. Compared with the classical value, $Q'_{wS}$ is 40% lower. Consequently, a much higher feed speed can be applied if the same value is intended.

With the knowledge about the contact conditions, the theoretical roughness $R_{th}$, which corresponds to the roughness $R_z$ (Fig. 5), can be calculated. For the purpose of the investigations, electroplated toric diamond grinding tools were used to reproduce ceramic coated femurs, which were ground using NC-controlled simultaneous five-axis tool paths. The initial roughness of the coating was reduced to a $R_a$ of about 1 $\mu$m with a relatively high sideways infeed $f$ of 0.16 mm. With about 14 $\mu$m, the calculated roughness is nearly the same as $R_z$. If frontal grinding with a lower sideways infeed $f$ is used, roughness values $R_a$ of 0.1 $\mu$m can be attained. By additional polishing with a flexible diamond tool, $R_a$ decreases down to 10 nm.

**Frontal toric grinding** enables roughness ranges one magnitude smaller due to the special contact conditions differing from those of sideways grinding (Fig. 6). The side view makes clear that from a tilt angle $\beta_f$ which is oriented in feed speed direction of 90° to 0° the relevant contact point $P_{\text{cRel}}$ rambles from the biggest relevant diameter to smaller ones $D_{\text{cRel}}$. These diameters projected in the front view penetrate the work piece on the depth of cut $a_e$. With a decreasing tilt angle $\beta_f$, there is an increase in both the contact width $a_{pF}$ and the geometrical contact width $b_{gF}$. In the right is depicted, that with a constant sideways infeed $f$, the theoretical roughness decreases with...
a decrease in $\beta_f$. With $\beta_f = 90^\circ$, the overlapping areas are parts of circles, while with $\beta_f = 0^\circ$, they mirror a part of the cross-sectional area of the toric pin. For values of $\beta_f$ between $0^\circ$ and $90^\circ$, they are parts of ellipses.

**Summary and Outlook**

For grinding with toric pins a closer look on the contact conditions was focused. For the sideways application the calculation of the cutting cross section was introduced as well as the influence on the specific removal rate.

Calculation equations have to be set up for the frontal processing. The actual cross sections for complex work pieces with free-form segments can be defined using a simulation tool, and the theoretical roughness can be predicted by means of the results. With an adjustment of the feed speeds $v_f$ by means of the calculated local removal rate $Q'_w$, constant grinding conditions are to be achieved.

**Acknowledgment**

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**References**

Optimization of Coated SiC Belt Grinding of Alumina Ceramics

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Key words: Ceramic, Belt grinding, Alumina, Surface roughness, Material removal

ABSTRACT. Advanced structural ceramics have been increasingly used in automotive, aerospace, military, medical and other applications due to their high temperature strength, low density, thermal and chemical stability. However, the Grinding of advanced ceramics such as alumina is difficult due to its low fracture toughness and sensitivity to cracking, high hardness and brittleness. In this paper, surface integrity and material removal mechanisms of Alumina ceramics ground with SiC abrasive belts, have been investigated. The surface damage have been studied with scanning electron microscope (SEM). The significance of grinding parameters on the responses was evaluated using Signal to Noise ratios. This research links the surface roughness and surface damages to grinding parameters. The optimum levels for maximum material removal and surface roughness been discussed.

INTRODUCTION

Advanced engineering ceramics have been extensively used in industrial applications in the recent years. This is mainly because of the poor machinability of these ceramics \[1–5\]. Grinding is used as the most efficient and effective technique to finish ceramic workpieces. As a result, great efforts were made towards the development of grinding technology for advanced ceramics in an efficient mode \[6–8\]. In this research belt grinding method has been studied for achieving a high material removal rate, low abrasive wear and good surface finish in the machining of alumina ceramics by SiC abrasives. The grinding belt, which is the cutting tool, consists of coated abrasives and is attached around at least two rotating wheels. The workpiece to be ground is pushed onto one of these wheels which is called the contact wheel, as shown in Fig. 1. The materials are cut off under non-permanent touches between the workpiece and the abrasives.
EXPERIMENTAL DETAILS

Specimen. The work materials taken for this research are Alumina ceramics (Al₂O₃) of three different purity levels (90%, 92% & 94% pure alumina) manufactured by Carborundum Universal. The specimens are in the form of hollow tubes having dimensions of external diameter 30mm, 5mm wall thickness and 100mm in length.

Grinding Set-up. The Grinding belt is of specifications 2000mm in length and 50mm in width, butt jointed at the ends to form a loop. The abrasive material used for this study is black silicon carbide (SiC) of Grit 60. The grinding belt is mounted over two wheels of which one is the contact wheel (bigger wheel), which acts as the driver, connected with the motor for drive and the latter acts as an idler (smaller wheel). The experiments were carried on an Auto Belt Grinding Machine (Auto-BGM). The machine is capable of running up to 2880rpm with 300 mm of diameter contact wheel. The power drive motor is 0.7kW. The contact wheel is a rubber backing wheel used for mounting the abrasive belt. The contact wheel has a diameter of 300 mm and a width of 50mm. Three different backng wheels are used for varying the gripping force of the belt, namely 1:1, 1:2 and 1:3 (Land to groove ratio) serrated wheels.

Grinding Parameters to be varied
1. Belt speed (m/sec) : 38, 41 and 44
2. Rotation of the Work piece (rpm): 720, 840, and 960
3. Material: 90%, 92% and 94% purity Alumina
4. Contact wheel serration: 1:1, 1:2, 1:3 (Land to groove ratio)

Experimental Results. The abrasive belt grinding experiments were conducted based on the L9 orthogonal array and the output parameters material removal and surface roughness are calculated and tabulated in Table 1. Since the work piece was getting chipped off on continuous grinding of more than 4 minutes. Each experiment was carried out for 4 minutes.

<table>
<thead>
<tr>
<th>Ex. no</th>
<th>Belt Speed (m/s)</th>
<th>Workpiece Rotation (rpm)</th>
<th>Alumina Material (purity %)</th>
<th>Contact Wheel (Land to groove ratio)</th>
<th>Material removal (gms)</th>
<th>Surface Roughness, Ra (µm)</th>
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</table>

SIGNAL TO NOISE RATIOS AND MODELING OF RESPONSES

The experimental results were used to calculate the signal to noise ratio, which gives the optimal solution for obtaining the maximum material removal rate and good surface roughness (Ra).

Effect of Process Parameters on the Material Removal. The experimental observations were calculated for S/N ratio (Table 2) using taguchi larger the better technique for obtaining the maximum material removal. The interaction of abrasive grains with the surface of ceramic materials is considered similar to the effects induced by a sliding indenter. In particular when a sharp indenter is pressed into a ceramic surface, a critical load value exists, at which lateral and radial cracks develop, responsible for material removal and loss of strength, respectively. The S/N ratios shows that for a maximum material removal the optimal setting is at belt speed of 44m/s, rotation of the
work piece at 720rpm with 1:1 wheel for 94% purity alumina. Alumina of 94% purity is a compacted material, characterized by an inhomogeneous microstructure with small slightly elongated grains and occasional large grains in size. Alumina of 90% purity is a low purity alumina, with many intrinsic defects, characterized by the presence of agglomerates and low porosity; the grains are very small, elongated and grouped in a narrow range. Thus the material removal is maximum in alumina of 94% purity.

| Table 2 S/N Ratio for Material Removal |
| Factors      | Level 1 | Level 2 | Level 3 | Optimum |
| Speed        | -14.94  | -15.30  | -14.21  | 44m/sec  |
| Rotation of work piece | -14.40  | -15.19  | -14.85  | 720rpm   |
| Contact wheel | -12.50  | -16.56  | -15.39  | 1:1      |

| Table 3 S/N Ratio for Surface finish |
| Factors      | Level 1 | Level 2 | Level 3 | Optimum |
| Speed        | 17.8    | 16.5    | 17.75   | 38m/sec  |
| Rotation of work piece | 17.7    | 16.2    | 17.6    | 720rpm   |
| Material     | 24.56   | 23.7    | 6.5     | 90% Alumina |
| Contact wheel | 18.3    | 16.8    | 17.4    | 1:1      |

Effect of Process Parameters on the Surface Roughness. Grinding is traditionally regarded as a final machining process in the production for dimensional tolerance and surface finish. The belt grinding operation tends to improve the reliability of the quality of the cut surface roughness, irrespective of the alterations caused by the wear[13-14]. The surface finishing processes often result in serious damage in the form of both residual stresses, tensile and compressive, and surface and sub-surface cracks. In particular grinding process induces compressive stress near the surface. These detritus effects can be reduced by optimizing the machining parameters which is shown table 3. The optimum condition was Exp 1 of the experimental observations mentioned in table 1. The low belt speed, low work piece rpm and more contact area results in less grinding force hence better surface finish.

Modeling of Responses for Process Parameters. Based on the observed results of the trials, a mathematical model was formulated using the multiple regression method by using a non-linear fit between the response and the significant parameters. Multiple regression analysis is practical and relatively easy for use and widely used for analyzing experimental results[8]. The following mathematical models were formulated

\[
\text{Material Removal} = K_1 S^w R^x A^y C^z \text{ .......................................................... Eq.1}
\]

Where K, w, x, y, z are constants and S, R, A and C are grinding variables.
S – Belt Speed (m/s),
R – Rotation of the work piece (rpm),
A – Density of Alumina (g/cm³),
C – Contact area (mm²/rev).

EFFECT OF PROCESS PARAMETERS ON THE SURFACE DAMAGE OF ALUMINA

To quantitatively evaluate the effect of grinding parameters on surface damage of ceramics, the ground ceramics were inspected using SEM images. The SEM images of the surface of ground samples shows no major chipping or crack propagation leading to failure of samples, but some micro cracks are formed due to the grinding parameters [9-11]. It is observed that ground surfaces consisted of two features: (1) smeared area (2) micro fractured area. The smeared products are generated when the material removed from the surface is trapped between the abrasives and work piece and is crushed against the surface. The extent of micro fracture on the ground surface
indicates that the micro fracture removal mode is the dominant material removal mechanism in grinding of ceramics. All samples are ground with 60 grit SiC abrasive with a feed rate of 0.8mm/min.

Alumina of 90% purity

It can be inferred from the surface images of the 90% alumina that the surface is free from cracks and a high surface finish is obtained. On comparison with Fig 2a with Fig 2b, it is clear that material is removed more by micro fracture of the surface on the sample in Fig 2a, while in Fig 2b the material is almost smeared on to the surface, leading to less material removal.

Alumina of 92% purity

The SEM images of 92%alumina shows that surface finish is lesser or nearer to the surface finish of 90% Alumina. The specimen of Fig 3 shows more micro fractures hence high material removal.

Alumina of 94% purity

The samples of 94% alumina shows poor surface finish compared to 90 and 92% alumina. The surface finish of 90 % and 92% alumina nearly 7-8 times smoother than the surface finish of 94% alumina. This is due to the fact that material removal is more in 94% alumina which leads to poor surface finish.

CONCLUSION

Experimental observations show that the belt grinding of alumina ceramics is possible with silicon carbide abrasives. The investigations of this study indicate that the input parameters such as belt speed, rotation of the work piece, and contact area available for grinding are the primary influencing factors, which affect the surface integrity of alumina during belt grinding. In 90%
alumina and 92% alumina samples, it is observed that micro fractured surface have good surface finish and more material removal.

The following points can be concluded,

a) The material removal rate increases with a increase in belt speed of the grinding and contact area per revolution of grinding.

b) The surface roughness increases with an increase in belt speed of the grinding and contact area per revolution of grinding while grinding.

c) It is observed from the SEM images that ground surfaces consist of two features: (1) smeared area (2) micro fractured area. The smeared products are generated when the material removed from the surface is trapped between the abrasives and work piece and is crushed against the surface. The extent of micro fracture on the ground surface indicates that the micro fracture removal mode is the dominant material removal mechanism in grinding of ceramics. The grinding parameters could be, therefore, considerably controlled by taking advantage of this phenomenon. This provides an important insight into ceramic manufacturing that the alumina could be efficiently ground without causing a significant loss to the surface integrity.

REFERENCES

Development of CBN Internal Grinding Machine for Precision Grinding of the Air-conditioner Compressor Piston Hole

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Keywords: internal grinding, CBN wheel, self-adapting control, compressor piston.

Abstract. According to the demand for internal grinding machine in precise machining of air-conditioner compressor piston hole, a kind of high-precise CNC internal grinding machine with CBN wheel is developed by adopting self-adaptive control for grinding process. Meanwhile, grinding precision and stability are achieved by overcoming many problems emerging from high-speed grinding process with CBN wheel. More than 100000 times’ grinding experimental results show that the whole performance of grinding machine developed is the same as that of the same kind of international machine. In order to study grinding mechanism with CBN wheels and then improve machine’s capability, grinding data in several machining cycles is analyzed.

Introduction

Appliance of CBN wheels in high-speed grinding becomes reality after a great deal of practical grinding research in recent 30 years and this grinding manner is considered as the most efficient way for precision grinding metals containing Fe [1]. However, high rigidity of machine structure, stable state of wheels and effective monitoring for grinding process are needed for CBN grinding compared with machine tools using common wheels [2]. TOYO and UVA which are from Japan and Sweden are widely used in grinding holes of precise parts mounted in air-condition compressor. These machines have many characteristics, one key point of which is that DN value of grinding spindle is more than 1.5 million, another is that even-temperature cooling with water is adopted to maintain stability of the whole structure, the last is that controlled-force grinding is achieved by detecting power signals [3,4]. Owing to these measures, wheels’ lineal speeds are mostly from 45 to 60 meters per second, machining cycles are from 10 to 40 seconds and machining accuracy is no more than 3µm. On the other hand, high-efficient grinding with CBN wheels hasn’t come true in domestic companies’ machines because they don’t know the exact grinding process [5]. The internal grinding machines from best manufacturing companies such as Shanghai Rabbit and Wuxi Machine-Tool Company can’t be used in compressor field due to low wheel speed(<30m/s) and long machining cycle(>40s). In order to meet the need for machines from the air-conditioner compressor companies, a kind of CBN internal grinding machine for precision grinding of the Air-conditioner Compressor Piston Hole is developed by absorbing advanced technology from home and abroad and this paper is a partial summary of this research.
Development of grinding machine

This machine with type of M2010 is used to grind inner of compressor piston (such as Fig. 1) and similar parts. It is fit for mass production of high precise workpiece and it can work solely or in production line.

Distribution and structure features of machine. The distribution type is a kind of centreless machine sample with headstock and dresser fixed and wheel spindle box moving. The wheel box was mounted on two crossing rails which can finish axial and radial feed for piston hole. This machine works full automatically including loading and unloading and dimensions’ consistency can be guaranteed by on-line gauge. This machine has several features as follows.

Wheel spindle can work stably and precisely at very high speed. Wheel spindle is one of the most important parts for machine and it has direct effect on grinding performance. According to the special demands of high speed and rigidity for CBN grinding, this spindle was designed with large power (13kW) and high rotate speed (max 60000r/min), so the DN value is over two million. Furthermore, the axial and radial runout are no more than 1.5µm which is ensured by ceramic ball bearing mounted in it.

Workpiece fixed by centreless clamp ensures location and rotate accuracy easily. Workpiece is located by electromagnetic chuck in axial direction and bracket in radial direction then it’s fixed by magnetic force, so the rotate accuracy has no relation with spindle runout. Consequently the axial and radial runout of workpiece can be limited within 1µm, moreover, this structure is also suitable for auto loading and unloading for its convenient operation.

Dressing with nature diamond roller ensures dressing accuracy and efficiency. Single-point diamond dresser is easy to be broken because of CBN wheel’s big hardness and high speed, therefore, nature diamond roller is adopted as dressing tool and dressing accuracy is guaranteed by high precise electro-spindle. Furthermore, dressing can be finished much sooner and dressing tool has longer life and better shaperetention.

Effects of manufacturing accuracy on machining accuracy. The workpiece machined may be out of tolerance due to variation by one micrometer of core parts’ accuracy, so the affecting factors on machining accuracy should be analyzed in design phase and the manufacturing accuracy of machine tool must be ensured.

Analysis of effects on roundness. Roundness of workpiece has direct relation with rotate accuracy of workpiece

![Fig. 1 Sketch map of workpiece](image1)

![Fig. 2 Structure sketch of machine tool](image2)

![Fig. 3 Position of workpiece](image3)
and wheel. Workpiece is located by electromagnetic chuck in axial direction and bracket in radial direction (Fig. 3), so its rotating accuracy is affected by face runout of main spindle and verticality of face with bracket. In order to achieve roundness within 3µm, these two variations shouldn’t exceed 1µm and outer of workpiece must match with bracket precisely.

**Analysis of effects on straightness.** Straightness of workpiece depends on the linearity of moving rail and wheel, so the straightness of rail must be ensured. The variation of straightness for rail should be within 1µm in the range of 50mm and 8µm in the whole length (400mm). In order to achieve so high accuracy, the slat-v rail must be shoveled and scraped. Moreover, rigidity of dressing spindle and parallelism of grinding spindle with rail are other important affecting factors which should also be considered.

**Analysis of effects on surface quality.** Surface quality means roughness and waviness of workpiece. Roughness mainly depends on grinding process and wheel performance. However, waviness is caused by vibration[6]. Degree of waviness depends on the amplitude of vibration and the density depends on the vibration frequency. Furthermore, the type of vibration maybe chatter or forced vibration. It can be confirmed whether chatter vibration exists by detecting acoustic signals [7,8]. Whichever vibration has relation with static-dynamic rigidity of machine, so natural frequency of main parts should be differentiated from rotate spindles. In addition, contacting and connecting stiffness of driving portion should be enough.

Scientific and reasonable precision index is made according to these analyses above and manufacturing of a high precise machine is achieved after machining and assembling carefully.

**Optimization trial for machining process.** Compared with design and assemblage, debugging process is more complex and hard which is bottleneck for internal machine manufacturer to make CBN machine tool. There are several reasons: first, grinding force varies very much in a dressing cycle, so burn and poor precision are easily caused; second, wear of expensive CBN wheel mostly occurs in dressing, but it’s hard to achieve wheel in good state by little dressing; last, it’s critical and hard work to eliminate useless time then gain high efficiency which is the priority of CBN grinding.

**Optimization for grinding process.** Fifty workpieces in a dressing cycle are ground constantly using the same process parameters and change rule of dimension and taper is found observing curve in Fig. 4.

![Fig. 4 Distribution of dimensions](image)

According to Fig. 4, dimension varies much at first stage then turns stable gradually and taper changes from negative to positive value then becomes stable. The phenomenon has relation with elastic deflection of wheel quill caused by grinding force change. However the elastic deflection
can restore by a certain degree through extending sparking time, it will waste lots of time, so some change of process in rough and finish grinding stages should be adopted to meet grinding force.

Acoustic emission (AE) sensor was mounted to test grinding force. The AE sensor has faster response and better sensitivity compared with conventional power test [9]. Utilizing its feedback signals, plc indicates driving components to act accordingly. At present, domestic machine manufacturers only use AE in eliminating air grinding time and anti-collision and several foreign manufacturers use it to monitor dressing and test wheel wear [8,10]. In addition to these functions, self-adapting grinding process was developed by us. The feedback value standing for grinding force from AE sensor is compared with the optimal curve (Fig. 5) then plc send out indicators to adapt the actual curve to the optimal process by changing feed rate [11]. As a result of this, stable dimension and taper can be achieved by eliminating change of elastic deformation for wheel quill. Meanwhile, wheel’s durability can be increased by preventing burn and abnormal wear of wheel.

**Optimization for dressing process.** Surface condition of wheel dressed has something to do with roughness. Change rule of roughness along with velocity ratio $\gamma(V_D/V_W)$ of dressing to wheel spindle (such as Fig. 6) was proved by former experts [12]. The ratio of 0.6~0.8 is fit for dressing vitrified bond CBN wheel with natural diamonds roller [13].

Some methods should be adopted to improve dressing efficiency and wheel life after confirming dressing process. Dressing according to fixed stroke program is the conventional way which may cause overdressing or lack of dressing. However, this problem is solved by monitoring dressing process with AE signals. The state of wheel surface before dressing is like the first two curves in Fig. 7 and the curve standing for the optimal wheel state is like the third one [11]. The feedback curve reaches optimal one gradually along with dressing course and dressing stops as soon as the actual curve goes into the allowance range. Obviously, it’s the most scientific dressing manner.
Grinding experiments and analysis.

In order to examine accuracy and stability of this grinding machine, massive grinding experiments of 100000 workpieces which were parts of air-condition compressor in some product line were made and the results were compared with that gained in T117 type machine from TOYO using the same wheel.

Grinding experiments were carried according to self-adaptive program and main accuracy items of workpiece ground were tested by precise surface roughometer and roundtest from Taylor-hobson. The average results in one dressing cycle were compared in Table 2.

Experimental results show that the CBN grinding machine developed has same grinding performance as international advanced machine. In order to test machine performance further and study rule for CBN grinding, change rules of grinding cycle and accuracy in a dressing cycle were accurately measured and recorded (Table 3).

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</table>

It can be seen from Table 3 that grinding cycle became shorter gradually then stable after twenty and straightness and roughness deteriorated along with number increasing, while the changes of
roundness and waviness were not evident. Change trends of main items reflect surface state of wheel dressed. CBN wheel is very blunt soon after dressed because truing is the main form, so grinding force and specific grinding energy are very high and roughness of workpiece is good. However, grinding force fell soon then stable after ten workpieces and roughness value became bigger gradually because the wheel was sharper and sharper along with grain fracture and detachment. Meanwhile, straightness deteriorated for wheel’s uneven wear. These problems can be improved adopting more intense wheels with bigger air hole.

Conclusions

Grinding efficiency for compressor piston is largely raised applying large stiff spindle on high-speed grinding with CBN wheel and this grinding manner is very suitable for large-scale production.

The problem that unstable quality is gained by CBN grinding is solved by adopting self-adaptive grinding manner and wheel’s life is also prolonged by monitoring dressing with AE sensor.

Numerous results of the productive grinding experiments show that the grinding machine developed for internal hole of compressor piston has the same grinding performance as the most advanced machine in the world. In addition, its price is only about 50% of machine abroad with the same functions.

References

Surface Characteristics and Roughness Prediction of TC4 Titanium Alloy in High Speed Grinding

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Keywords: titanium alloys; high speed grinding; evolutionary neural network; surface integrity.

Abstract: This paper reports a systematic investigation of high speed grinding of hard-to-machining of titanium alloys. The ground surfaces were characterized using scanning electron microscopy, and the effects of different grinding parameters on roughness were discussed. A numerical model was established to predict surface roughness based on the evolutionary neural network optimized by Genetic Algorithm (GA). The modeled results were in good agreement with the experimental results.

Introduction

Titanium alloys have been widely used in the engineering fields because of their excellent properties. Known as typical hard-to-machining materials, it is difficult to obtain high machining efficiency and good surface quality by using traditional grinding methods [1]. With the recent development of high speed grinding technique [2-5], it is highly possible to machine titanium alloys with high efficiency and surface integrity. In high speed grinding, ground surface integrity is mainly evaluated by means of off-line contact measurement of roughness. It is hard to timely find the deterioration of surface roughness in the grinding process. So, it is necessary to predict the surface roughness in high speed grinding processes and ensure surface quality and machining accuracy.

In this work, systematic grinding tests of TC4 titanium alloy were conducted under high speed grinding conditions. This paper analyzed the ground surface micro-morphology characteristics by using scanning electron microscopy (SEM), and discusses the effects of different grinding parameters on surface roughness. To avoid some disadvantages in traditional back propagation (BP) algorithm, such as low rate of convergence, easily falling into local minimum point and weak global search capability [6], Genetic algorithm (GA) was used to train the BP neural network to replace classical learning algorithm. A model based on evolutionary neural network optimized by GA was established to predict the surface roughness.

Prediction Model of High Speed Surface Grinding

Establishment of BP neural network In this paper, three-layer back propagation (BP) neural network is used. As shown in Fig. 1, the three layers are input layer, hidden layer and output layer. Here inputting data \( X_i (i = 1, 2, 3) \) are values of wheel speed \( v_s \), workpiece feed rate \( v_w \) and wheel DOC \( d_p \). Output data is surface roughness \( R_d \). Hidden layer contains \( k \) units and \( k \) is determined by the quantity of inputting samples.

The learning process of three-layer neural network can be described as follows. For the \( p \)th \((p=1, 2, \ldots, P)\) input pattern, the output of the \( k \)th \((k=1, 2, \ldots, K)\) hidden layer unit is defined as \( h_{pk} \). The connection weight between output layer unit \( R_d \) and \( k \)th hidden layer unit is denoted as \( v_k \). The connection weight between \( k \)th hidden layer unit and \( n \)th \((n=1, 2, 3)\) input layer unit is denoted as \( w_{nk} \). For the \( p \)th input pattern, the \( n \)th input layer unit is \( x_{pn} \) and the expected output layer unit is \( o_{pd} \). So the output of the \( k \)th hidden layer unit \( h_{pk} \) can be calculated by [6]

\[
h_{pk} = f \sum_{n=1}^{3} w_{nk} x_{pn}
\] (1)
where \( f \) is the sigmoid function, namely \( f = (1 + e^{-v})^{-1} \). And, the output layer unit corresponding to the \( p \)th input pattern can be calculated using [6]

\[
o_p = f \sum_{k=1}^{K} v_k h_{pk}
\]

(2)

Here the energy error function \( E \) is expressed as [6]

\[
E = \frac{1}{2} \sum_{p=1}^{P} (o_{p0} - o_p)^2
\]

(3)

BP algorithm changes weights of \( w_{nk} \) and \( v_k \) through repeated iteration to minimize the energy error function \( E \). The iterative formula of the weight of every layer can be given as [6]

\[
\begin{align*}
v_i(n+1) &= v_i(n) - \eta \frac{\partial E}{\partial v} \\
w_{nk}(n+1) &= w_{nk}(n) - \eta \frac{\partial E}{\partial w}
\end{align*}
\]

(4)

The change of the weight of every iteration is defined as [6]

\[
\begin{align*}
\Delta v_i(n+1) &= \eta \sum_{p=1}^{P} \delta_p h_{pk} + \alpha \Delta v_i(n) \\
\Delta w_{nk}(n+1) &= \eta \sum_{p=1}^{P} d_{pk} x_{pm} + \alpha \Delta w_{nk}(n)
\end{align*}
\]

(5)

where, \( \eta \) and \( \alpha \) are the learning rate and the adjustment coefficient, respectively. And [6],

\[
\begin{align*}
\delta_p &= o_p (1 - o_p) (o_{p0} - o_p) \\
d_{pk} &= o_p (1 - o_p) \delta_p v_k
\end{align*}
\]

(6)

**Evolutionary neural network based on GA** [7] BP neural network has some characteristics, such as self-learning, self-adapting, robustness and fault tolerance. It is suitable for describing a complex nonlinear mapping relation among variables. But, it is easy to fall into the local minimum point caused by gradient descent algorithm of connection weight. The other disadvantages are slow convergence speed and weak global search capability. In this paper, GA is introduced into the learning process of traditional BP neural network and the evolutionary neural network is used. As shown in Fig. 2, its learning steps are described as follows.

1. **BP neural network Initializing.** The weight and threshold values take random values in the interval of \([-0.5, 0.5]\).
2. **Inputting a sample in the order of data.**
3. **Calculating the energy error function \( E(n) \) of \( n \)th iteration.**
4. **If \( E(n) \leq \varepsilon \) \( (\varepsilon > 0) \), the iteration will be stopped and learning process of BP neural network is completed.** Otherwise, the weight value will be adjusted by BP algorithm.
5. **Calculating the error gradient \( \Delta E \) [7].**

\[
\Delta E = \left[ E(n) - E(n - \tau) \right]/\tau
\]

(7)

where \( \tau \) is the window size of estimating error gradient. If \( \Delta E \) is less than the gradient threshold and \( E(n) > \varepsilon \), it indicates that neural network falls into the local minimum state and needs an evolutionary algorithm to optimize the connection weight of neural network.

6. **Chromosomes coding.** Initial population \( P = \{X_1, X_2, \ldots, X_N\} \) is generated randomly, where \( X_i \) \( (i=1, 2, \ldots, N) \) is corresponding to a weight distribution of the network. Chromosome \( X_i = [u_1, u_2, \ldots, u_M] \), \( u_k (k=1, 2, \cdots, M) \) represents the weight value between two nodes in network. The weight values are initialized and take random values in the interval of \([-0.5, 0.5]\).
(7) Chromosomes evaluation. Energy error function \( E(n) \) is used as fitness function and its judging standard is the same as that of step (4).

(8) Chromosomes selecting. The selecting probability of chromosomes is defined as \( f(X_i) = \beta(1-\beta)^{i-1}, \beta \in (0, 1), i=1, 2, \ldots, N \). For every chromosome \( X_i \), cumulative probability \( q_i = \sum_{i=1}^{\infty} f(X_i) \), \( i=1, 2, \ldots, N \).

A random number \( \gamma \) of uniform distribution is generated in \((0, q_N)\). If \( q_{i-1} \leq \gamma < q_i \), the \( i \)th chromosome \( X_i \) is selected. Above operations are repeated and the best chromosome is selected finally.

(9) Chromosomes intersection. According to the given crossover probability, the parents are selected and randomly divided into \((X'_i, X''_i) (i, j=1, 2, \ldots \) and \( i \neq j \)). After the crossover operation of the parents, the offspring \( x, y \) are generated [7].

\[
\begin{align*}
x &= \rho X'_i + (2-\rho) X''_i \\
y &= (2-\rho) X'_i + \rho X''_i
\end{align*}
\]  
(8)

where, \( \rho \) is a random value in \((0, 1)\).

(10) Chromosomes variation. For \( X_i = [u_1, u_2, \ldots, u_p] \), \( u_i' \) is randomly selected in \([-0.5, 0.5]\) to replace \( u_i \) and variant offspring \( X'_i = [u_1, u_2, \ldots, u_p] \) is generated. Neural network is reduced according to every variation result and performance evaluation is carried out. If offspring is better than parent, the variation will be stopped. Otherwise, the variation will be repeated until offspring superior to parent is found.

(11) New weight value is obtained through all the above steps. If the condition in step (4) is met, the variation will be stopped and the variation result is output. Otherwise, the algorithm will return to step (8) and a new round of intersection and variation will begin.

![BP neural network topology structure](image1)

![Evolutionary neural network based on GA](image2)

**Results and discussions**

**Ground surface integrity** Parametric grinding tests were conducted on an ultra-high speed surface grinder (Fig. 3). TC4 titanium alloy (Ti-6Al-4V) was selected as the work material and its material properties were shown in Table 1. A vitrified CBN wheel and a resin bond diamond wheel with 350mm in external diameter and water-based coolant were used. Before the tests, the wheels needed to be trued until the wheel run-out was less than 5\( \mu \)m. The effects of wheel speed \( v_s \), workpiece feed rate \( v_w \) and wheel depth of cut (DOC) \( a_p \) on ground surface performance were investigated respectively.
The ground surfaces were examined using a scanning electron microscope. Fig. 4 and Fig. 5 are typical SEM micrographs of the ground surfaces using the diamond and CBN wheels, respectively. The ground surfaces generated by the diamond wheel have typical spots and ploughing striations (Fig. 4(a)), while those ground using the CBN wheel consist of ploughing striations and slender cracks (Fig. 5(a)). It is visible that the numbers of spots and cracks decrease significantly when the wheel speed is increased (Fig. 4(b), 5(b)). Debris was also observed on the ground surfaces. It is difficult to quantitatively identify the influence of the grinding conditions on the surface characteristics via SEM, though it seems that the higher wheel speed can produce a smoother surface.

Ground surface roughness of the workpiece was measured using surface roughness tester (Hommelwerke T8000) and their values were plotted against different parameters. As shown in Fig. 6, it is seen that the roughness decreases with the increase in wheel speed and has tendency to increase with the increase in wheel DOC or workpiece feed rate. In most cases, the roughness value obtained using the diamond wheel is greater than that using the CBN wheel. But the change of the former is smaller than the latter. In addition, the roughness values obtained using the diamond and CBN wheels are 0.7~1.7μm and 0.4~1.3μm in Ra, respectively. It is much better than the values of 2.5~5μm achieved by conventional grinding. From the SEM micrographs (Fig. 4 and Fig. 5) and the measured roughness (Fig. 6), it can be concluded that the CBN wheel is a better selection for grinding titanium alloys under the high speed grinding conditions.
Fig. 6 Ground surface roughness contrast using different wheels under different conditions

Table 2 Surface roughness contrast between experiment and prediction

<table>
<thead>
<tr>
<th>v_s(m/s)</th>
<th>v_w(m/min)</th>
<th>a_p(mm)</th>
<th>R_a0(μm)</th>
<th>R_a1(μm)</th>
<th>(\Delta R_a(%)\times100)</th>
<th>R_a(μm)</th>
<th>(\Delta R_a(%)\times100)</th>
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<td>1.38</td>
<td>8.66</td>
<td>1.24</td>
<td>-2.36</td>
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</table>
Modeling results There are 23 groups of data samples were collected from the high speed grinding tests using the diamond wheel. The unit number of hidden layer was taken to be 50. Initial weight value was randomly generated in the interval of [-0.5, 0.5]. The learning rate and the adjustment coefficient used were 0.4 and 0.7, respectively. Table 2 shows the surface roughness comparison between the experiment and the prediction. In the table, \( R_{a0} \) is the experiment result. \( R_{a1} \) and \( R_{a2} \) are the prediction results using traditional BP neural network and evolutionary neural network respectively. \( A_1 \) and \( A_2 \) are relative errors under the above two conditions.

From Table 2, the relative error using traditional BP neural network is 4%~15% and the average relative error is 9.7%. The relative error using evolutionary neural network is 1%~5% and the average relative error is 3.24%. The average relative error and relative error fluctuation range of the former is larger than those of the latter. Fig. 7 shows the performance of convergence of two types of neural networks according to different random initial weight values. It is clearly seen that the evolutionary neural network based on GA can effectively avoid the easy-falling into a local minimum point, and improve the convergence speed and prediction precision.

Conclusions

In this paper, systematic high speed grinding tests of TC4 titanium alloy were performed. It was found that the spots and cracks on the ground surfaces decreased significantly when the wheel speed was increased from 60 to 150m/s. The ground surface roughness decreased with the increase in wheel speed and has a tendency to increase with the increase in wheel DOC or workpiece feed rate. A model based on the evolutionary neural network optimized by GA was established to predict surface roughness. The comparison results between the experiment and the modeling demonstrated that the evolutionary neural network developed can effectively overcome the problem of easy-falling into a local minimum point, and improve the convergence speed and the prediction precision.

Acknowledgements

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References

Experimental Research of Grinding Force and Specific Grinding Energy of TC4 Titanium Alloy in High Speed Deep Grinding

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Keywords: titanium alloy; high speed deep grinding; grinding force; specific grinding energy.

Abstract: Focusing on the characteristic of hard-to-grind for titanium alloy, experiments were conducted about grinding TC4 titanium alloy under high speed deep grinding (HSDG) condition. The changing of grinding force per unit area with maximum undeformed chip thickness \( h_{\text{max}} \) and equivalent cutting thickness \( a_{eq} \) are analyzed in this paper. The effect of maximum undeformed chip thickness \( h_{\text{max}} \) and specific material removal rate \( Z_w' \) on specific grinding energy \( e_s \), material removal mechanism and consumption of grinding power in HSDG process are also discussed. The experiment results reveal that application of HSDG can improve machining efficiency of grinding TC4.

Introduction

Recent years, because of excellent performance on corrosion resistance, thermal stability and fatigue strength, titanium alloy has been extensively used in engineering fields such as aviation, aerospace, navigation etc.[1, 2] But titanium alloy is a typical kind of difficult-to-machine material [3] and great efforts have been made to aim at grinding titanium alloy. Some experimental investigations developed new vitrified CBN grinding wheels and high efficiency grinding liquid [3], solid lubricant treatment technique was studied [4], abrasive belts were employed in literature [5], a cryogenic ELID grinding device combining with cryo-fabrication technology and ELID grinding technique was developed [6], and preliminary investigations of creep feed grinding of titanium alloy were conducted by using CBN wheels [7]. Although these works [2-7] have their own advantages, it is difficult to achieve high material removal rates and good surface integrity of workpiece simultaneously.

The development of high speed deep grinding (HSDG) technology provides an effective way to achieve high machining efficiency and good surface quality for titanium alloy. The higher wheel speed results in a decrease in the chip thickness and sectional area of the single grain on the premise of keeping material removal rates. So the grinding force of the active grains and wheel wear are reduced, and the wheel life is improved. On the other hand, if the chip thickness of the single grain keeps unchanged, the increase of wheel speed makes it possible to further raise the feed rate and the machining efficiency could be improved. Meanwhile, wheel detaches grinding zone rapidly with the increase of the feed rate and the majority of grinding thermal is transferred to coolant and grinding chips. It could decrease grinding temperature and grinding burn and improve workpiece surface quality [8-11].

In this paper, experimental investigations on HSDG of TC4 titanium alloy were carried out using vitrified CBN wheel and resin bond diamond wheel. Based on the analysis of the changing and characteristic of unit area grinding force with maximum undeformed chip thickness \( h_{\text{max}} \) and equivalent cutting thickness \( a_{eq} \), this paper discusses grinding force ratio \( N \) and specific grinding energy \( e_s \) varying with the change of corresponding parameters. The change of material removal mode and the consumption of grinding power on the grinding process are also researched.
Experimental details

**Experiment material.** TC4 titanium alloy (Ti-6Al-4V) was selected as the workpiece material and its properties are shown in Table 1. The workpieces are 60mm long, 15mm wide and 15mm thick.

**Experiment apparatus.** The grinding experiments were conducted on an ultra-high speed surface grinder. Grinding forces were measured using a three-phase piezoelectric dynamometer (KISTLER 9257BA). The measured grinding force includes tangential grinding force \( F_t \), normal grinding force \( F_n \) and axial grinding force \( F_a \). Actually, \( F_a \) is quite small and can be neglected. The micro-morphology of ground surfaces were examined by SEM (JSM-5610LV).

<table>
<thead>
<tr>
<th>Heat treatment method</th>
<th>Annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (HRC)</td>
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<tr>
<td>Tensile strength (MPa)</td>
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<tr>
<td>Yield strength (MPa)</td>
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<td>14</td>
</tr>
<tr>
<td>Reduction of area (%)</td>
<td>34</td>
</tr>
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</table>

As listed in Table 2, special vitrified CBN wheel and resin bond diamond wheel were used for experiment. The grinding wheel was trued until the radial runout of grinding wheel was less than 5μm, and then was dressed by alumina whetstone before experiment.

In the experiments, up-grinding and four groups of experimental scheme per wheel were used. The effects of wheel speed \( v_s \), workpiece feed rate \( v_w \) and wheel depth of cut (DOC) \( a_p \) on grinding performance were investigated respectively and specific material removal rate \( Z_w' \) were also calculated. Experimental conditions are listed in Table 3 and Table 4.

**Results and discussions**

**Characteristics and analysis of grinding force.** Usually, the maximum undeformed chip thickness \( h_{max} \) and the equivalent chip thickness \( a_{eq} \) are used to represent grinding characteristics, describe the effects of grinding conditions on grinding process and its output physical quantities, and research grinding mechanism. The \( h_{max} \) can be described as following expression [8].

\[
h_{max} = \left( \frac{3}{C \tan \theta} \right)^{1/2} \left( \frac{v_w}{v_s} \right)^{1/2} \left( \frac{a_p}{d_s} \right)^{1/4}
\]
where \( C \) is the density of the active cutting points, \( \theta \) is the semi-included angle for the undeformed chip cross section, \( d_s \) is the wheel diameter, \( v_w \) is the workpiece feed rate, \( v_s \) is the wheel speed and \( a_p \) is the wheel depth of cut.

Fig. 1 and Fig. 2 shows the effects of \( h_{\text{max}} \) on normal grinding force per unit area \( F'_{n} \) and tangential grinding force per unit area \( F'_{t} \). It is clearly seen that \( F'_{n} \) and \( F'_{t} \) have an obvious ascending trend with the increase in \( h_{\text{max}} \) and it becomes fast with the further increase in \( h_{\text{max}} \). The most part of the material is removed by chip formation when \( h_{\text{max}} \) is smaller. The proportion of chip formation in total material removal decreases quickly with the increase in \( h_{\text{max}} \), and the material is mostly removed by sliding and ploughing when \( h_{\text{max}} \) is larger. As shown in Fig. 3, the SEM micrographs that obtained from the ground surfaces with \( h_{\text{max}} \) of 2.5\( \mu \)m suggest that there are mainly plastic removal grooves and sliding traces on ground surfaces.

The experimental results reveal that \( F'_{n} \) and \( F'_{t} \) have a corresponding relationship with \( h_{\text{max}} \), and \( h_{\text{max}} \) is one of parameters to characterize effects of grinding conditions on grinding force per unit area.

\[
F'_{n} = \frac{v_w \cdot a_p}{v_s} \quad \text{(2)}
\]

Fig. 3 Illustration of SEM micrograph: 1 - plastic removal groove; 2 - sliding trace.

Fig. 4 and Fig. 5 shows the effects of \( a_{eq} \) on normal grinding force per unit area \( F'_{n} \) and tangential grinding force per unit area \( F'_{t} \). Similar to the former section, \( F'_{n} \) and \( F'_{t} \) have a rising trend with the increase in \( a_{eq} \), but \( F'_{n} \) and \( F'_{t} \) also increase slowly and then become fast.

Grinding force ratio \( N \) reflects difficult degree which abrasives press in ground surface. Specific material removal rate \( Z_{w} \) is defined as material removal volume per unit time and wheel width. The changing of \( N \) with \( Z_{w} \) also represents the variation of grinding ability of wheel under different grinding efficiency. As shown in Fig. 6, the increase of \( Z_{w} \) results in a regular reduction of grinding force ratio. It suggests that the chip thickness becomes thicker with rise of \( Z_{w} \) and enlargement of normal grinding force is always less than that of tangential grinding force. With further increase of \( Z_{w} \), abrasives are hard to press into ground surface and enlargement difference between normal grinding force and tangential grinding force becomes smaller.
From Fig. 7, it also can be seen that grinding force ratio has a great change on different wheel speed when $Z'_w$ maintains a certain value. Similar to Fig. 6, there is a downward trend of grinding force ratio with rise of $a_{eq}$ as shown in Fig. 7. Equivalent chip thickness $a_{eq}$ has great effect on grinding force ratio in the HSDG process. The larger the equivalent chip thickness, the smaller grinding force ratio. Abrasives become easier to force on ground surface. The material develops plastic deformation and it is mostly removed by sliding and ploughing.

**Characteristics and analysis of specific grinding energy.** The specific grinding energy $e_s$ is defined as \[ e_s = \frac{F_t v_s}{a_p w v_w} \]  
where $F_t$ is the tangential grinding force and $w$ is the grinding width. Fig. 8 shows effects of $h_{\text{max}}$ on specific grinding energy in two groups of the experiments. It is seen that there is a critical value (about 1.9μm) and the reduction in $e_s$ becomes slow and gentle when the value of $h_{\text{max}}$ is greater than this critical value. The application of HSDG could enlarge maximum undeformed chip thickness, improve cutting conditions of abrasives and decrease specific grinding energy in the grinding process.

As shown in Fig. 9, specific grinding energy in two groups of the experiments show downward trend with increase in $Z'_w$ and this trend becomes slow gradually. In the same specific material removal rate, smaller specific grinding energy is obtained under higher wheel DOC or workpiece feed rate. But the grinding depth and force of single grain is higher under above conditions. It also causes surface damage and higher roughness.
Fig. 8 Effect of $h_{\text{max}}$ on specific grinding energy $e_s$. Fig. 9 Effect of $Z'_w$ on specific grinding energy $e_s$.

From the former analysis, specific grinding energy reflects consumed energy of plastic sliding and ploughing in grinding process. Therefore, research of energy consumption in HSDG can combine with ploughing section area of grain and the $e_s$ can be described as [8]

$$e_s = \frac{P}{Q_w}$$

(4)

where $P$ is consumed grinding power and $Q_w$ is volume of removed material. Specific grinding energy is consumed grinding power of removing material in unit volume. Thus, concerned problem can be transformed into researching the relation between grinding power and ploughing section area.

The grinding power per unit width $P_m$ can be defined as

$$P_m = \frac{P}{B}$$

(5)

where $B$ is grinding width. While, the ploughing section area of grain per unit time and width $S_w$ can be defined as

$$S_w = C_0 \cdot v_s \cdot A_g = \frac{C_0 \cdot v_s \cdot h_{\text{max}} \cdot l_c}{\cos \theta}$$

(6)

where $C_0$ is the grain concentration of wheel surface, $l_c$ the contact length and $\theta$ the semi-included angle at the bottom of grinding chip.

Fig. 10 shows the relationship between the $P_m$ and the $S_w$. In two groups of the experiments, $P_m$ is increased with the increase in $S_w$, and they show some linear relationship.
Conclusions

By analysis of experiment data, the maximum undeformed chip thickness $h_{\text{max}}$, equivalent chip thickness $a_{\text{eq}}$ and specific material removal rate $Z_w'$ are key parameters in HSDG of TC4. This paper studies the effect of $h_{\text{max}}$, $a_{\text{eq}}$ on grinding force per unit area and the effect of $Z_w'$ on grinding force ratio $N$. It reveals that material removal mechanism changes from chip formation to sliding and ploughing at higher $h_{\text{max}}$ and $a_{\text{eq}}$. Specific grinding energy shows downward trend with increase in $h_{\text{max}}$ and $Z_w'$ and becomes slow gradually. It needs smaller specific grinding energy under higher wheel depth of cut or workpiece feed rate if the specific material removal rate keeps unchanged. HSDG is feasible method to machine titanium alloy with high efficiency.

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References

Abstract. With the help of the infrared camera temperature measurement technology, the systemic theoretical analysis and experimental research for temperature field and thermal error distribution in NC grinding machine is provided. Two different situations for temperature field and thermal error distribution are respectively measured while the free and loaded grinding by the new measurement method. The mathematical model of thermal error is built, and it shows that the actual error and the forecasted error from thermal error mathematical model have good comparability.

Introduction
The heat dynamic process in grinding represents that the thermal deformation is produced on the components of grinding machine because of the unstable phase of the heat balance from the internal and external heat source’s disturbance. The deformation can be brought on by the internal and the external heat source in certain machining conditions, which force the position of the components related to machining accuracy changed to lead the machining accuracy decreased [1-2]. The thermal deformation is unstable as time’s change, because the quantity of heat from all heat sources is different with the change of specific machining circumstance, machining time and the capacity of the machine, which resultes in the effect of time-delay in temperature rising.

The restricts from the wide application in industrial production are from Robust model and the optimal layout of the points used in temperature measurement, which obstructs the development of the measurement technology in temperature field and the thermal error distribution [3-4].

Designing and Choosing Experimental Plan
The Modal Analysis of Thermal Error in NC Grinding Machining. The thermal error in machine tool could be described by a superposition from a series of thermal error modals which holds the appropriate shape and time constant, but the process in the thermal deformation is slow and single direction which is known through measuring the displacement from the measured points [5]. But the measured points are difficult to be arranged, so the modal analysis of thermal error is dependent on heat source analysis, engineer judgments and experiment data to a large extent. The susceptive direction of machining error (X axial direction) includes the modal of machine body’s bend, machine body’s thermal expansion, X-axis screw thermal expansion and the thermal expansion of the spindle box’s thermal deformation error by researching and analyzing the mechanical structure of the NC grinding machine, working condition and thermal deformation.

Since the grinding machine body is used as a coolant storage tanks, the temperature rising of machine body isn’t consistent in upside and downside of it, because of change of the coolant’s temperature, which leads the bend of machine body, then makes the radial size of workpiece small compared with expected size [6]. The bend modal of machine body can be effectively estimated according to the differences of machine body because of the effect of heat transfer, the expanded machine body make the radial size of workpiece become big. Since the happen of bend modal is coinstantaneous basically with expansion modal, so the expansion modal of machine body could be effectively estimated according to the average temperature of it. Due to dragging table(X-axis)’s
movement, the rising temperature of screw leading nut’s back movement, which results in the radial size of workpiece become big. It is easily to acquire the temperature of dragging table by infrared camera, and the temperature of dragging table can be used in estimating thermal error instead of the temperature of screw. The heat produced by the rotation of spindle make the spindle box expanded toward vertical direction, the best appropriate measured point is closed to the spindle but locates in the spindle box for the thermal error modal.

The Selection of Instrument. The high-speed NC grinding machine-MKS1320 is chosen in the experiment, which holds the parameters as follows: the cutting speed - 50 m/s, the rotating speed of the spindle-80-800 rpm, the size of the wheel - \( \Phi 600 \times \Phi 203 \times (20-125) \) mm, the power of the machine - 19.5 kw. FLIR A40m infrared camera was adopted as measurement instrument, as shown in Fig.1. The infrared camera is connected with PC by IEEE-1394 to build up local area network. Through PC’s IE browser, they could come true that visiting the infrared camera as a server, browsing the images of temperature, setting various parameters and controlling the image camera, as shown in Fig. 2.

Measured Points to Determine. In traditional thermal error measurement system, the temperature measurement points are usually determined according to experiences to some extent and robust method to implement [7]. It is based on the engineer judgment firstly that a large of measured points are arranged in the different location of the machine. A few typical points can be used in building the model, which are chosen through statistical correlation analysis. Since not all the measured points are used in the building thermal error model at last, the method would cost a lot of time, which brings some shortcomings.

The following principles must be considered to determine the measured points: first, the main factor is choosing the measured points related to thermal error through analyzing the relation between measured temperature and thermal error data. Second, comparing the temperature from different measured points by irrelevant strategy, a fuzzy theory is used to study the temperature of measured points. Third, the key measured points are selected through considering the strategy of the greatest sensitivity and the most approximate linear strategy. At last, the key points selected by above steps are examined whether expressing thermal error to a certain precision according to observed strategy.

The Measured Experiment of Temperature in NC Grinding

The Measured Experiment of Temperature While Free Operation. The 11 points selected are arranged on the NC grinding machine, which are divided into 5 groups according to the position of single point. The specific divide method is as follows: number 0-1 to measure the temperature of the spindle box, number 2-3 to measure the temperature of the screw and the nut, number 4-5 to measure the temperature of the coolant, number 6 to measure the room temperature, number 7-10 to measure the temperature of the machine body.
The cycle test is carried out firstly to simulate the process of grinding when the spindle is running, the dragging table is moving and the coolant is flowing but no grinding, that is free operation. The temperature of the hydraulic oil cooler in the spindle box is set to 19°C, the distance between the infrared camera and the measured components is 1.5 m, the sample data from infrared camera are saved every 5 minutes and thermal imager could be acquired at the same time, the interval should be reduced properly for the key position according to the actual condition. The machine must run for 3.5 hours, then stop for 1 hour to get the accurate data. Repeat this process twice, the measurement results are showed in Fig.3 to Fig.6.

The Measured Experiment of Temperature While Loaded Operation. The law of temperature rising in loaded grinding is basically consistent with free grinding, but the difference is that a lot of grinding heat made the temperature rise obviously, especially the temperature of the spindle and the coolant.

The four key measured points $T_c$, $T_n$, $T_s$, $T_b$ represent the temperature of coolant, the screw and the nut in X-axial direction, the spindle, the machine body, respectively, the temperature rise of the points in the spindle is significantly faster than the other three measured points. Comparing with the temperature rise at the same measured position in free grinding, it is faster than the former because of the power consumption from the wheel spindle motor in grinding, part of mechanical energy is conversed into heat which was transferred to the spindle, and the other important heat source is grinding heat which can’t be neglected. The measurement results are showed in Fig.7 to Fig.10.

The Analysis of Thermal Error Distribution

The thermal error could be regarded as a function of temperature distribution, the thermal deformation of machine is affected by the temperature of machine that is influenced by the size of the