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Modeling of a virtual grinding wheel based on random distribution of multi-grains and simulation of machine-process interaction*

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Abstract: The interaction of the machine-process in grinding frequently brings unpredictable results to the quality of the products and processing stability. This paper presents a multi-grains grinding model to simulate the precision grinding process of cemented carbide inserts. The interaction between the grinding process and machine tool is then investigated based on the proposed grinding model. First, the real topography of the grinding wheel is simulated. Based on the assumption of spacing distribution of multi-grains and the virtual grid method, the hexahedron abrasive grains are randomly distributed on the surface of the virtual grinding wheel and the postures of abrasive grains are randomly allocated. Second, the grinding model is built by importing the virtual grinding wheel model into Deform-3D software, and the grinding force values are obtained by simulation. The validity of the proposed grinding model is verified by experiments. Then, the interaction coupling simulation of the machine tool structure and grinding process is built to investigate the interaction mechanism. The simulations reveal that remarkable interactive effects exist between the deformation of the grinding wheel of the machine tool and grinding force. The finite element method (FEM) coupling simulation method proposed in this paper can be used to predict the machine-process interaction.

Key words: Virtual grinding wheel, Random distribution, Interaction process, Precision grinding, Coupling simulation
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1 Introduction

A cemented carbide cutting tool, made as a kind of hard and brittle material, plays an important role in the aerospace industry, and its operational performance is closely related with the grinding manufacturing processes. A diamond wheel is widely used to grind a cemented carbide cutting tool. However, the product precision and surface quality of the cemented carbide cutting tool is instable, since cemented carbide material has high hardness and brittleness. Brecher *et al.* (2009) pointed out that these problems are mainly caused not by the unreasonable parameters or mechanical structure design but the additional effect of the interaction between the machine tool and the process. The traditional processing has paid less attention to the interaction between the machine tool and process. However, this kind of interaction can induce unpredictable results in the quality of products and processing stability when the hard and brittle materials are precisely grinded because of their special physical and mechanical properties, the higher accuracy requirements, and the harsher conditions. Therefore, the effects of the dynamic interaction between the machine and the process should be

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further considered to achieve precision or ultra-precision machining of the hard and brittle materials.

The research of grinding mechanism mainly include two aspects. On the one hand, the complex grinding process can be simplified to a single abrasive grinding so that other abrasive's affection could be excluded and the grinding mechanism of a single abrasive grinding could be explored. On the other hand, the grinding process can be seen as a co-work completed by the uneven, irregular abrasive grains which are on the surface of the grinding tools. The observation and analysis of the grinding process become difficult due to abrasive grains' large quantity, irregular shape, high grinding speed, and small grinding depth. Therefore, many researchers began their research with the single abrasive grain and built the finite element models to analyze grinding mechanism (Wang *et al.*, 2009; Anderson *et al.*, 2011). Su *et al.* (2008; 2013) and Duan *et al.* (2013) finished the microscopic mechanical simulation of the single abrasive grain with the finite element method (FEM) and smoothed particle hydrodynamics (SPH), and Yan *et al.* (2012) used AdvantEdge software to simulate the cutting process of the single abrasive grain under different technologic parameters. They analyzed the influence of cutting speed and cutting depth on the critical cutting depth, cutting force, cutting temperature, and material removal rate. Cheng *et al.* (2011) researched the single abrasive chip forming process of titanium alloys TC4 by using the finite element simulation technology. All the studies above mainly centered on single abrasive grain grinding, and ignored the complicated interaction among multi-grains. Chen and Rowe (1996) presented a method to build a 2D grinding wheel model based on circular abrasive grains of the same diameter, which are randomly distributed, and Hegeman (2000) built a 3D grinding wheel model through oval abrasive grains. Warnecke and Barth (1999) presented a simulation method by importing the grinding wheel and workpiece into the finite element model to carry out research on the influence of grinding wheel vibration on material removal. The above studies on virtual grinding wheels with multi-grains have not considered the microscopic mechanical phenomena.

There have been extensive studies on the grinding process modeling and simulation. Most of them just focused on the study of the local contact area interaction between the grinding wheel and workpiece, but the interaction between the machine structure and the grinding process has relatively few studies (Nguyen and Butler, 2005; Brinksmeier *et al.*, 2006; Doman *et al.*, 2009). Since it is difficult to predict the dynamic interaction between the machine tool and process systems, complex simulations have been usually done. That is why there exists a necessity of establishing the models of the machine model and the grinding process model. Altintas *et al.* (2005) pointed out that only the accurate simulation of the interaction among the machine tool, workpiece, and cutting process can get better analysis and optimize the process. Brecher and Witt (2006) proposed a coupled simulation method and built a manufacture simulation model concluding the interaction between the grinding machine and grinding process. Herzenstiel *et al.* (2007) studied the interaction of the high-performance grinding machine-process based on the finite element and grinding wheel kinematics simulation. Weinert *et al.* (2007) adopted a geometric-motion simulation and finite element simulation to optimize the forming grinding process. Aurich and Kirsch (2012) studied the interaction of the high-performance grinding machine-process based on the kinematics simulation. However, present interaction theoretical studies are still insufficient (Brecher *et al.*, 2009), especially in the field of grinding hard and brittle materials. This paper targets the cemented carbide materials grinding process: first, the virtual wheel grinding model with multi-grains is built, then a coupling simulation model of the interaction between the machine structure and the grinding process is established based on the grinding simulation model and the finite element model of the machine tool, so as to further investigate the interaction mechanism between the machine structure and the grinding process when precision grinding hard and brittle materials.

2 Virtual wheel model

2.1 Average spacing of abrasive grains

First, the super depth of the field microscope is used to measure the topographies of a diamond wheel (230#–270#) to get the number of grains per mm^2, as shown in Fig. 1. The abrasive density is then calculated as 127 mm^{-2}, which is used to estimate the average spacing between the grains. Assuming that nine abrasive grains are equally distributed on the square surface of which the side length is l, as shown in Fig. 2, the equivalent abrasive grain number is 4. According to the abrasive density, the average spacing of abrasive grains could be calculated. As for the 230#–270# diamond wheel, the average spacing of abrasive grains on the surface is 0.089 mm.

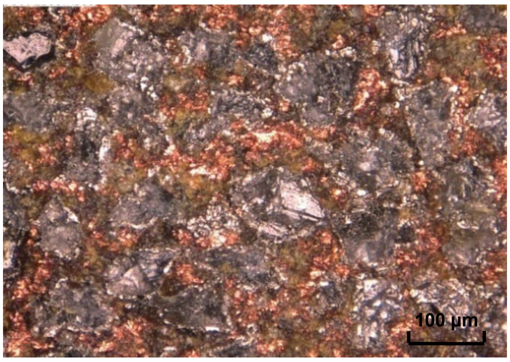

Fig. 1 Diamond grinding wheel microscopic magnification

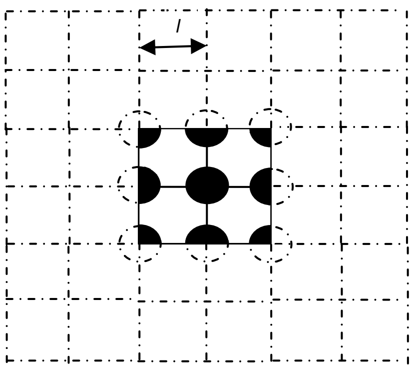

Fig. 2 Sketch diagram of particle average spacing

2.2 Random distribution of virtual wheel abrasive grains

On the surface of the actual grinding wheel, the abrasive grains are randomly distributed and their projection heights are different from each other. That is why this type of characteristics of random distribution should be taken into account when creating a virtual wheel. In the usual study of the grinding process, the shape of the abrasive which is distributed on the surface of the wheel is normally idealized. Barge *et al.* (2005) simplified the abrasive shape as prismatic, Gong *et al.* (2002) deemed it as spherical, some others simplified it as conical or flat conical with the sphere radius on the tip (Wang and Li, 2002; Wang and Ding, 2005). Seen from the sharpness of the abrasive cutting, the prismatic abrasive shape is better, which is also close to the true shape, that is why this paper adopts the hexahedral structure as the basic form of the abrasive shape. The position of the abrasive is presented by the coordinates of the center part. By controlling the center coordinate of the abrasive, it is achievable to distribute the abrasive in the binder and revolve the abrasive round center randomly to change its posture.

To avoid the overlap between the abrasive grains, the method of using a virtual grid is adopted to model the grinding wheel. That is, every abrasive grain is restrained in an imagined grid and their exact positions in the grid are controlled by random transform coordinates. This kind of modeling method is not only avoiding the overlap between the abrasive grains, but also letting the abrasive grains conform to the characteristics of random distribution. The random position of the abrasive is shown in Fig. 3. The size of the virtual grid A is dependent on the wheel's abrasive density. In Fig. 3, D represents the size of the abrasive particle and the coordination of the abrasive position is randomly distributed in each small square grid of l×l.

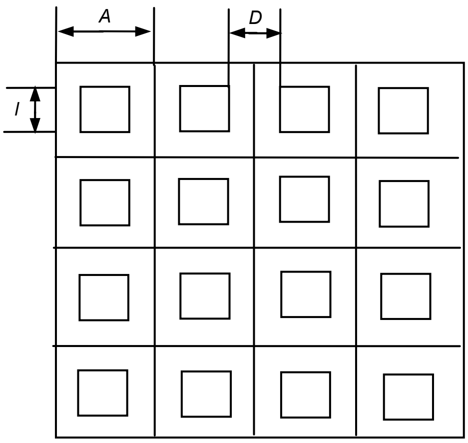

Fig. 3 Grinding grain of a random position distribution diagram

2.3 Modeling of virtual wheel

The grinding wheel surface topography is mainly composed of a binder and abrasive grains. In the grinding process, the binder is not in direct touch with the surface of the workpiece, but holds the abrasive grains to enable them to grind the workpiece. To facilitate the grinding simulation, the interference process between the abrasive grains and the workpiece is just considered. The shape of the binder is simplified when creating the virtual wheel model. The wheel structure model with randomly distributed multi-grains on the rectangular binder is established.

Take the surface area of the diamond wheel abrasive as the prototype of the virtual wheel, whose particle size is 230#–270#, the abrasive density is 127 mm^{-2}, and the nominal size is about 50–70 μm. The model shape is hexahedral with the edge length of 50 μm and resin bond is chosen with the shape of the cuboid. This study intends to randomly distribute the virtual abrasive grains which are 4×4×1 in a rectangular binder to create a virtual wheel structure model. Specific steps are shown as follows:

1. Generate the position and orientation. Use the RND random function in VB programming language to generate the random position coordinate and random posture angle of the abrasive grains, as shown in Fig. 4.

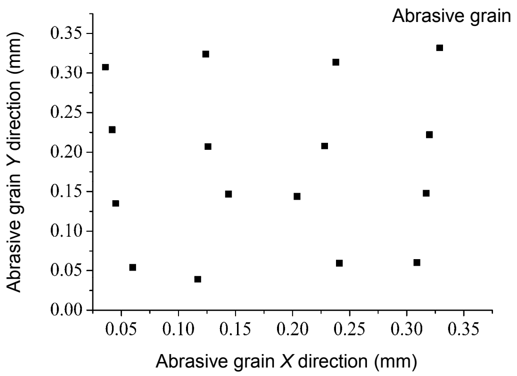

Fig. 4 Random distribution of the abrasive particle coordinates

2. Use the AUTOLISP language in CAD software to import the random position coordinate which is formed in the previous step to obtain the random distributed abrasive grains. Then import the random posture angle to make the posture randomly distributed as well.

3. Combine the binder and multi-grains. First, the cubic binder model is created. Then establish the virtual wheel model by binding the binder and multi-grains. As shown in Fig. 5, the multi-grains on the virtual wheel surface are randomly distributed, so the established virtual wheel model has similar structure characteristics with the actual wheel.

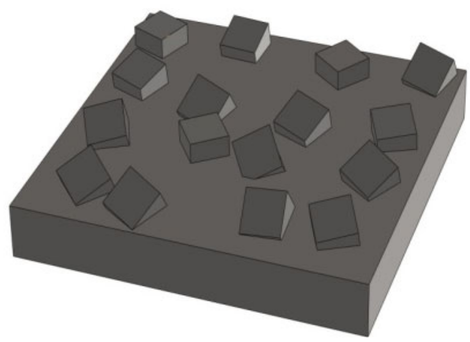

Fig. 5 3D view of virtual grinding wheel

3 Grinding model

3.1 Virtual wheel grinding model

WC is adopted as the material of the workpiece, a diamond is adopted as the abrasive material. The material properties are shown in Table 1.

Table 1 Material properties of the workpiece and the tool

Material	Elastic modulus (GPa)	Poisson's ratio	Heat conductivity (W/(m·K))	Hot melting (J/K)
Diamond	900	0.2	2000	1.654
WC	650	0.25	29	15

The development of the material model means to gain a material stress-strain curve (constitutive relation) to define the response behavior under loads. The flow stress is affected by temperature, strain, and strain rate. That is why one of the keys to the simulation is building a material constitutive model which can accurately reflect the cutting process under high temperature, large strain, and high strain rate. There are many material constitutive models to describe thermal viscoplastic deformation behavior of materials under high strain rate. The most common one is the Johnson-Cook model (Zheng *et al.*, 2012). This model takes into account that materials under a high strain rate characterized by strain hardening, strain rate hardening, and thermal softening effect, which is expressed as

$$\sigma=(A+B\varepsilon^n)\left[1+C\ln\left(\frac{\varepsilon}{\varepsilon_0}\right)\right]\left[1-\left(\frac{T-T_{\text{room}}}{T_{\text{melt}}-T_{\text{room}}}\right)^m\right], \quad (1)$$

where A, B, n, C, m are constants determined by the material itself, T_{melt} is the hot melting, T_{room} is the indoor temperature, ε is the strain rate, and ε_0 is the reference strain rate. For the carbide workpiece WC, A=1506 MPa, B=177 MPa, n=0.12, C=0.016, and m=1. Import these parameters, the flow stress curves under different temperatures are shown in Fig. 6.

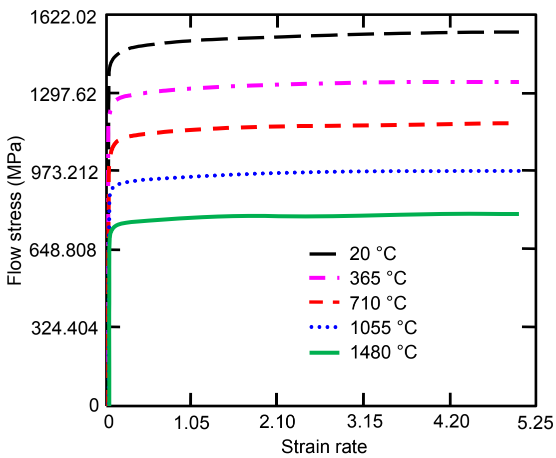

Fig. 6 Flow strain curves under different temperatures

To make the grinding simulation with multi-grains work effectively and reduce the computation, this study selected only a quarter of the previous created virtual wheel as the simulation object. Because the abrasive grains on the grinding wheel are on the principle of random distribution, the generated quarter of the model also does not change the essence of the virtual grinding wheel. Importing a quarter of the virtual grinding wheel model into Deform-3D software, the carbide workpiece is generated directly in the preprocessor of the software. Fig. 7 shows the finite element grinding model of virtual grinding wheel and the workpiece. The simulation selected four-node tetrahedral elements, and divided the grinding area of the virtual grinding wheel and the workpiece into local grids. Chip separation used the adaptive re-meshing techniques to simulate the deformation of the chip via the Lagrange method.

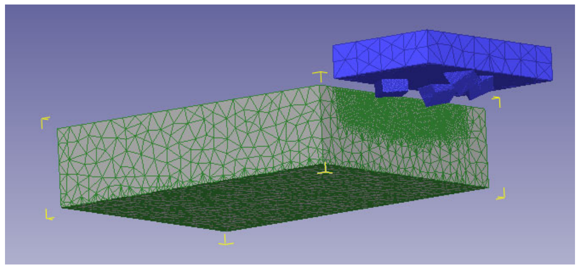

Fig. 7 Finite element model of the virtual grinding wheel and workpiece

Based on the finite element grinding simulation model, the maximum normal and tangential grinding forces of the multi-grains (F_{mn} and F_{mt}) could be obtained. The forces divide respectively by the grain number in the simulation model, and the average grinding force values of a single grain are obtained. Then the grinding forces could be calculated through the single average grinding forces multiplied by the effective grain number. The corresponding prediction mathematical model is as follows:

$$\begin{cases} F_{\text{mt}}=\dfrac{1}{4}NF_{\text{ft}}, \\ F_{\text{mn}}=\dfrac{1}{4}NF_{\text{fn}}, \end{cases} \quad (2)$$

where N is the effective grain number, and F_{fn} and F_{ft} are the maximum normal and tangential grinding forces, respectively, obtained from the finite element grinding simulation model.

3.2 Case study

The previous virtual grinding simulation model is used to predict the grinding force in the machine-process interaction coupling simulation, so the model must be able to accurately predict the grinding force. Therefore, the accuracy of the model needs to be proved by experiment. Grinding experiments are conducted on a five-axis computer numerical control (CNC) tool grinding machine, the workpiece is an equilateral triangle indexable inserts, the diameter of the inscribed circle is 12.7 mm, the thickness is 4.8 mm, and the material is cemented carbide. The grinding wheel is a bowl-shaped wheel with a diameter of 400 mm and a width of 10 mm, and the abrasive material is a diamond. The grinding wheel spindle feeds in the negative X-axis of the machine tool, and the Y-axis of the machine tool swings back and forth at 1 Hz frequency. The grinding force is measured by a 9272 type KISTLER dynamometer, and the maximum peak value is used to contrast in this study. Coolant is filled during the experiment. In consideration of the influence on the grinding force caused by three factors, i.e., the wheel speed, wheel feeding speed, and grinding depth, three levels are designed for each factor in L_9 (3^3) orthogonal experimental scheme as shown in Table 2. Experiment with the nine groups of test programs is in the orthogonal table, and the test field is shown in Fig. 8.

Table 2 Prediction values of grinding force

Test No.	Grinding depth (mm)	Grinding wheel feed speed (mm/min)	Spindle speed (r/min)	Prediction force (N)
1	0.02	100	1500	27
2	0.02	300	2000	31.9
3	0.02	500	2500	25.3
4	0.04	300	1500	42.8
5	0.04	500	2000	47.3
6	0.04	100	2500	38.5
7	0.06	500	1500	63
8	0.06	100	2000	66
9	0.06	300	2500	58.3

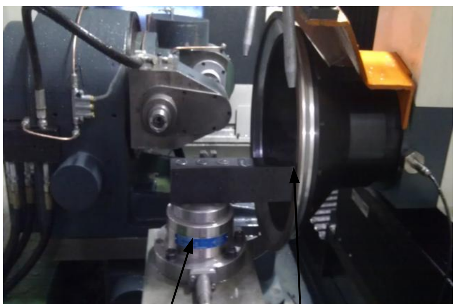

Fig. 8 Grinding force test site

Comparing the largest normal grinding force under the experimental conditions and the largest normal grinding force obtained from the virtual grinding simulation model, the results are shown in Fig. 9. That the errors between the predicted data and measured data are controlled within 10%, which shows the grinding simulation model of the virtual grinding wheel of multi-grains could be used to predict the grinding force.

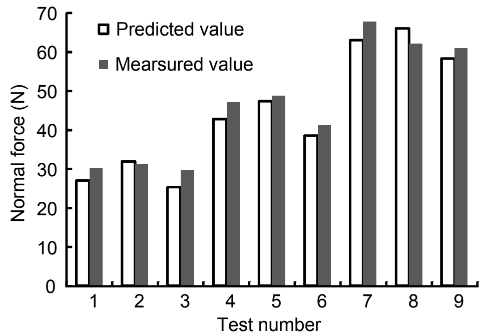

Fig. 9 Contrast of predicted values and experimental values

4 Modeling of the machine structure

FEM is commonly used in the analysis of static and dynamic characteristics of the machine tool structure, especially in the analysis of time-variation and coupled processes. The machine tool is a complicated structure composed of multiple parts, and the analysis on individual parts is not enough to elaborate the performance of the overall machine. Therefore, it is necessary to analyze the machine tool as a whole.

When modeling a machine tool, some necessary simplification should be considered otherwise the finite element analysis will be difficult or unable to complete. The simplification follows the rules below: deleting the model holes, small face, chamfer, etc., whose structure would produce large numbers of finite elements, ignoring the effects of temperature stress, simplifying rounded corners and screwed holes to prevent uneven density of elements, simplifying shield, replacing the gravity of the motor with an equal mass, ignoring stress and deformation caused by the gravity of the ball screw, cooling pipe and exerting full constraints on the fixed position at the bottom of the grinder, and applying glue Boolean operation to the inner structure of the components (Zhang *et al.*, 2013). The simplified 3D machine tool model is shown in Fig. 10.

The contact stiffness of machine tool joints has a significant impact on the dynamic performance of the machine tool. In the machine tool model, the displacement of grinding wheel under grinding force action is mainly considered, and the research belongs to static analysis, so the accuracy of the machine tool static stiffness should be ensured. Therefore, the tensile experiment was carried out. The experiment results were compared with the simulation results of the static stiffness of the machine tool, as shown in Table 3. The experimental and simulation results are basically identical, so the model of the machine tool can be used in the mechanical analysis of the machine tool.

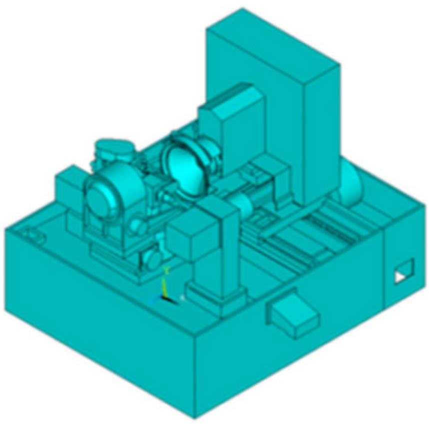

Fig. 10 Simplified model of machine tool structure

Table 3 Displacement and static rigidity extracted from the results of the experiment and simulation

Tension (N)	Static rigidity (N/μm)		Difference (%)
	Experiment	Simulation	
50	6.41	6.65	3.61
100	6.42	6.61	2.87
150	6.30	6.63	4.98

The spindle-wheel plays a critical role in the grinding process. Since the formation of the workpiece is directly related to the end face of the grinding wheel, more emphasis should be put on the dynamic structural deformation of the rotating part. The grinding wheel is defined as a flexible part, while the spindle is defined as a rigid body. The finite element model of the wheel-spindle part is established with the bowl-shaped grinding wheel and abrasive as a whole, setting material as 40Cr. This study excludes the flexibility of the workpiece, and assumes it as a rigid body. In addition, the contact between the grinding wheel and the workpiece is further simplified as a single point contact, as shown in Fig. 11.

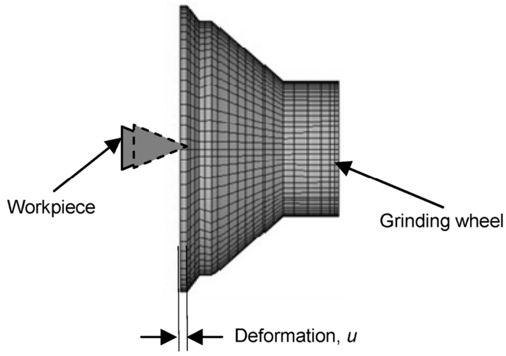

Fig. 11 Point contact between the grinding wheel and the workpiece

5 Machine-process interaction

5.1 Modeling of machine-process interaction

Most current studies on a grinding mechanism deal with the single abrasive grain model, which simplifies the abrasive to a simple geometric shape to study the grinding force (Anderson *et al.*, 2011). According to Syoji (2007), the theory formula of a grinding force of a single abrasive grain can be obtained as follows:

$$\begin{cases} F_{\mathrm{st}} = C_p \dfrac{v\Delta b}{V} + \mu F_{\mathrm{sn}}, \\ F_{\mathrm{sn}} = C_p \dfrac{\pi v\Delta b}{2V} \tan\alpha, \end{cases} \tag{3}$$

where F_{st} and F_{sn} are the tangential and normal grinding forces of a single abrasive grain, μ is the friction coefficient, C is the coefficient of the undeformed chip section area, subscript p means the contact surface pressure, v is the feed speed, Δ is the grinding depth, b is the grinding width, V is the line speed of the wheel, and α is half of the front vertex angle. Since the axial grinding force F_{sa} is small, it is generally ignored (Syoji, 2007).

Because of the grinding force, the machine tool especially the end face of the bowl-shaped wheel will produce a certain deformation u_i. Due to the deformation, the grinding depth Δ_{i+1} will be changed, and its value calculation is shown as follows:

$$\Delta_{i+1} = \Delta_i + u_i. \tag{4}$$

Putting the new grinding depth into Eq. (3), a new grinding force is obtained. After many times of cycle computing, the grinding force value will stabilize. In the machine-process interaction model, the grinding forces of a single grain F_{st} and F_{sn} are instead by F_{mn} and F_{mt} which are obtained from Eq. (2), and the change of the grinding depth is obtained from the finite element model of a machine tool applied to grinding force loads.

5.2 Machine-process interaction coupling simulation

The interaction of the machine-process coupled simulation is realized through the exchange interaction of the simulation data between the machine tool structure model and the virtual wheel grinding model: the grinding forces are obtained by the virtual wheel grinding model simulation, and the force data is put into the finite element model in ANSYS as a load. Then, the data of the machine deformation is transferred as the input data to the grinding model, as shown in Fig. 12.

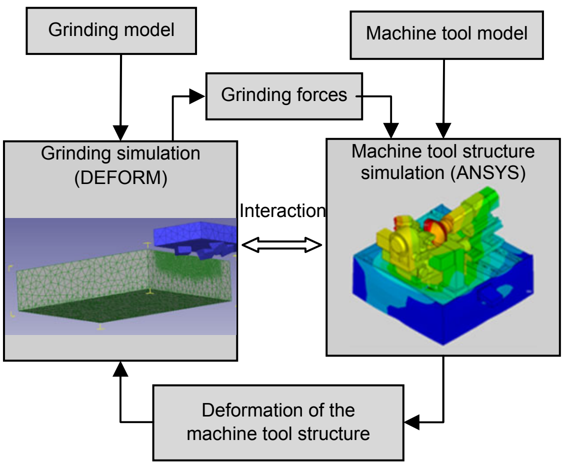

Fig. 12 Coupling modeling and simulation of machine-process interaction

A bowl-shaped diamond grinding wheel in the actual grinding process could produce a small deformation u in the axial direction because of the effect of the dynamic force, as shown in Fig. 11. Considering the deformation of the grinding wheel, the grinding depth Δ_0 is no longer a constant, but is $\Delta_1=\Delta_0+u$. When the grinding depth changes, the normal grinding force F_0 of the virtual wheel grinding simulation model will also changes to F_1. The grinding wheel will generate new variants u_1 under F_1. Therefore, the interaction between the machine and the process is an iterative process. An iterative process is repeated, so there is a need to determine the convergence of the iteration: if one of the two consecutive iteration steps in the force or displacement has reached the convergence condition, the iterative process stops. The iterative process is shown in Fig. 13.

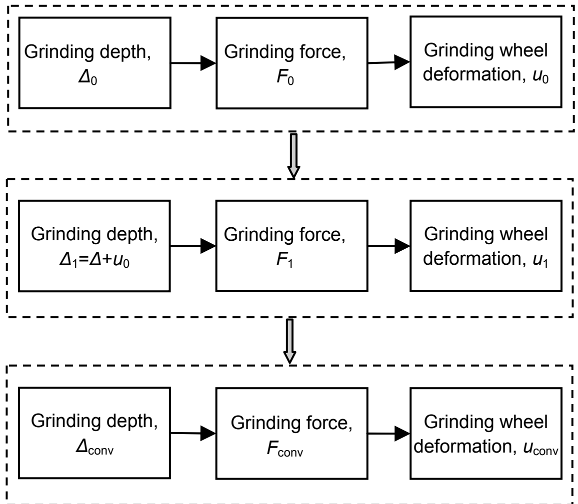

Fig. 13 Coupling iteration process of grinding force and grinding wheel deformation

Δ_{conv}, F_{conv}, and u_{conv} are the convergences of grinding depth, grinding force, and grinding wheel deformation, respectively

5.3 Results and discussion of coupling simulation

Based on the test conditions of No. 2 which is shown in Table 2, the coupling of the interaction between the machine tool and the process has been simulated by the iterative method proposed above, and the simulation results are summarized in Fig. 14.

Fig. 14 indicates that the normal grinding force value decreases from 31.9 N to 25.7 N after the coupling iteration. The grinding forces and the deformation are smaller than the values corresponding to the uncoupled solution. Besides that, the grinding force and the deformation become stable after several iterations.

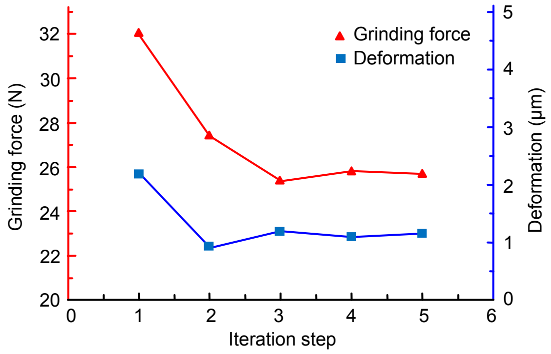

Fig. 14 Iteration of the coupling simulation

The force signals are substituted by a set of harmonic functions of the grinding depths and the generated harmonic loads are able to excite the grinding wheel. The force and the deformation are normalized so that they can be represented in the same diagram. All forces shown are normalized by dividing the amplitudes of the initial force value. All deformations are normalized by dividing the maximum value. Considering the force and deformation in one wheel revolution, the coupling simulations between the grinding wheel and the process are performed in a set of harmonic grinding depths with a fixed amplitude of 20 μm and a fixed frequency of 200 Hz. From Fig. 15 we can see that the effective forces acting on the grinding wheel are smaller than the values corresponding to the uncoupled solution, and the effective force is 90% of the initial force in the first cycle which is most likely due to the deformation of the grinding wheel.

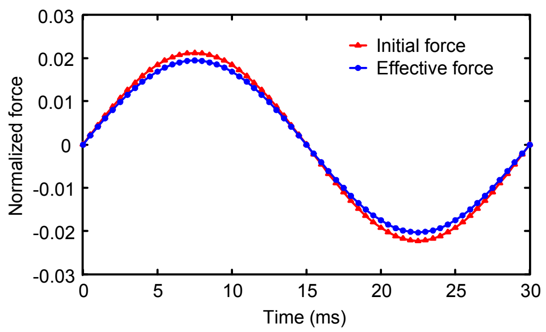

Fig. 15 Coupled iteration of the effective force compared with the initial force

To be supplemented, Fig. 16 shows that, in the coupling system of the grinding simulation model and machine tool model, the grinding forces and the deformations of the grinding wheel are interactive action. The deformations of the grinding wheel are generated by the harmonic loads, and the deformation in turn causes the variation of the grinding force.

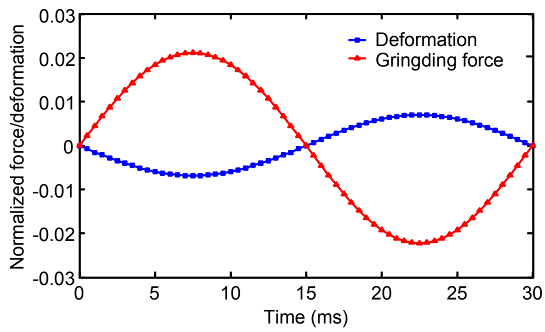

Fig. 16 Coupled iteration of the grinding force and deformation

6 Conclusions

1. Based on the virtual grid method, the virtual grinding wheel with random distribution of multi-grains is built. The position of each abrasive in the grid can be controlled by randomly transforming the coordinates, and its posture can be changed by a random function. In this way, the random position and posture of the multi-grains on the wheel surface have been achieved.

2. The 3D model of the virtual grinding wheel is imported into Deform-3D software, the virtual wheel grinding model of multi-grains grinding carbide material has been constructed, and the model has been experimentally validated.

3. The machine tool structure model has been constructed by FEM. Based on the ANSYS and the DEFORM software, the integrated model of the machine tool structure and grinding process is constructed. The coupling simulation method of the integrated model has been taken to study the interaction between the machine tool and the grinding force. The coupling simulation result shows that there is a remarkable interaction influence between them.

4. The structure of the machine tool and the grinding process are interconnected and interactional. Only by integrating them into a dynamical interaction machining system can we explain the complex physical phenomenon during the grinding process and predict the surface quality of the production, the wear of the wheel, and the process ability of the machine tool.

5. The coupling simulation method that this paper proposed could be used on the prediction of interaction between the machine tool and grinding process. Similarly, the method could also be used on the research of interaction between a machine tool and other cutting processes.

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中文概要

题　目：基于多颗磨粒随机分布的虚拟砂轮建模及机床-工艺交互仿真

目　的：以硬质合金材料的精密磨削加工为对象，探索机床-工艺之间的交互作用，构建多颗磨粒磨削模型和机床模型，通过两个模型之间参数传递与交互耦合仿真，实现对机床-工艺交互作用的预测。

方　法：1. 根据金刚石砂轮形貌构建磨粒位姿随机分布的虚拟砂轮，建立多颗磨粒磨削模型，对新模型的磨削力预测进行实验验证；2. 建立机床模型，特别是主轴-砂轮模型，并通过刚度试验；3. 将磨削模型的磨削力与机床模型的砂轮变形作为交互参数实现机床-工艺之间的交互作用仿真。

结　论：1. 构建的多颗磨粒模型可以实现磨削力预测；2. 构建的机床模型可以模拟机床结构刚度；3. 机床产生的变形与磨削力之间存在显著的交互作用，文中提出的有限元耦合仿真法可以实现预测机床-工艺的交互作用。

关键词：虚拟砂轮；随机分布；交互作用；精密磨削；耦合仿真