
Modelling of grinding mechanics: A review

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Abstract

Grinding can obtain the geometric shape of mechanical parts with high precision, so it has been widely used in the field of machining. In the grinding process, grinding force can effectively evaluate the performance of grinding process, and has great influence on machining accuracy, surface quality and dynamic performance. Therefore, the grinding force modeling method is very important for the optimization and control of grinding process. However, although there are many research papers on grinding force, there is no comprehensive review on the modeling of grinding force in recent years. The purpose of this paper is to provide the research and development of grinding force modeling. This work reviews and introduces the theoretical method and application of grinding force modeling in detail. Firstly, according to the cross-scale classification method, the development of macro and micro grinding force modeling is briefly reviewed. Then, the modeling processes of macro and micro grinding forces are described, respectively. Finally, the application prospect of grinding force model is discussed.

Keywords: Grinding force; Grinding force modeling; macro; micro; Application.

Nomenclatures

| | | | |
|----------------|--|----------|--|
| b | Grinding wheel's width | A | Amplitude |
| F | Grinding force | f_v | Frequency |
| F_t | Grinding force in tangential direction | R | Radius of the grinding wheel |
| F_n | Grinding force in normal direction | H | Material Hardness |
| F_d | Radial Grain Force in Ductile Mode | $C(z)$ | Grinding edge density |
| h | Uncut chip thickness | N | Number of active grains |
| θ | Wheel degree | F_b | Radial Grain Force in Brittle Mode |
| V_w or v_w | Work velocity | l | Grinding length |
| V_s or v_s | Wheel speed | a_p | Grinding depth |
| ρ | Abrasive Contact Density | ω | Angular velocity |
| I_v | Wear Rate | Φ_0 | Initial phase |
| h_{crit} | Critical Undeformed Chip Thickness | β | the Angle of Attack of the Particle |
| K_{IC} | the Material Fracture Toughness | $f(h)$ | Protrusion Height Distribution Function |
| E | Young's Modulus | K_w | Wear Percentage of Abrasive Grain |
| V_t | Total Volume on the Periphery of the Wheel | V_{sh} | Total Kinematic Shadow Volume of the Active Grinding Edges |
| ε | Feed Angle | | |

Abbreviations

| | |
|--------|---|
| AE | Acoustic Emission |
| AF-ESL | Nanofluid Air Flow Assisted Electrostatic Lubrication |
| CFRP | Carbon Fiber Reinforced Plastic |
| CG | Conventional Grinding |

| | |
|-------|---|
| ECG | Electrochemical Grinding |
| EGW | Engineered Grinding Wheels |
| FFT | Fast Fourier Transform |
| ICS | Internal Coolant Supply |
| IFFT | Fast Fourier Transform after the Spectrum Limit |
| IG | Intermittent Grinding |
| KSIM | Kinematic Simulation |
| LAG | Laser Assisted Grinding |
| LAMG | Laser-Assisted Micro grinding |
| LTSG | Laser Thermal Shock-Assisted Grinding |
| MQL | Minimal Quantity Lubrication |
| NF | Nanofluid |
| NMQL | Nanofluid Minimum Quantity Lubrication |
| NPs | Nanoparticles |
| RG | Rail Grinding |
| SGW | Segmented Grinding Wheels |
| SiC | Silicon Carbide |
| TD | The Dimension of Textures |
| TGW | Textured Grinding Wheel |
| UAECG | Ultrasonic Assisted Electrochemical Grinding |
| UAG | Ultrasonic Assisted Grinding |
| UMG | Ultramicro grinding |
| WT | Wavelet Transform |

1 Introduction

Grinding is one of the main manufacturing methods in the process of material removal because of its high machining efficiency and precision. In recent years, grinding research has focused on the basic mechanism of grinding process again [273]. As we all know, grinding force is an important index to evaluate wheel wear, dynamic

performance, surface quality and temperature. In order to realize the predictability of grinding process, the grinding force modeling has been developed rapidly, which can effectively reduce the time and cost of the experiment and realize the accurate pre-analysis, this is difficult to obtain in practice. Since 1990, the research on grinding force modeling has been developed rapidly, and the annual publication of related research papers has been increasing continuously (see Fig. 1).

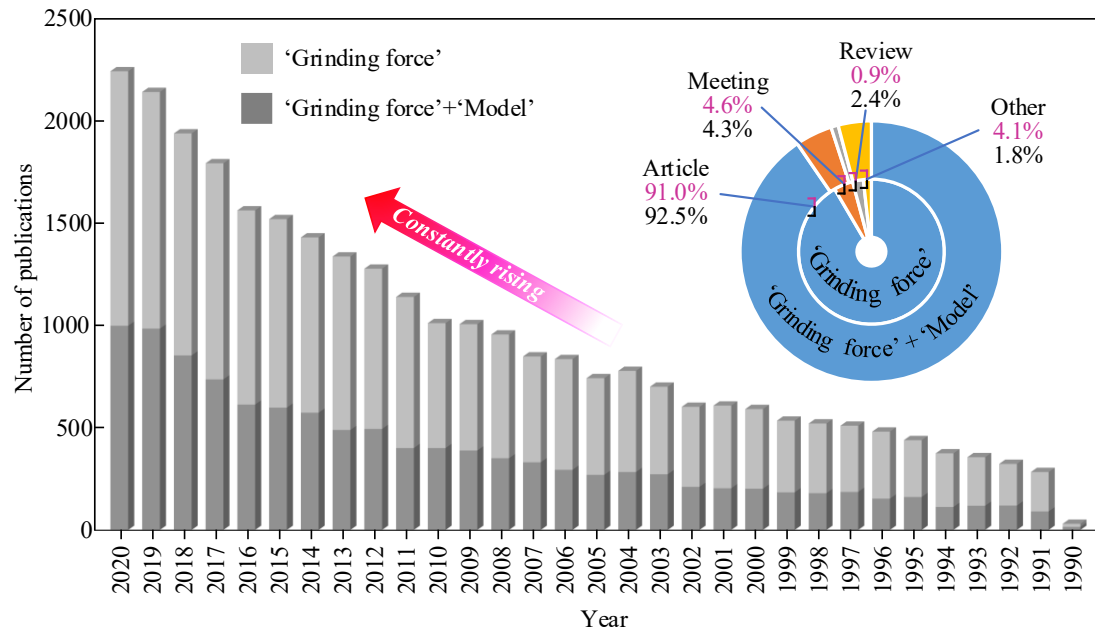


Fig. 1. Annual publication of the abrasive force and its models. (The statistical results are obtained by searching titles, abstracts and keywords related to grinding force in web of science core database, and all types of references are considered in the Science Citation Index Expanded (SCI-Expanded).)

However, so far, there is no review of systematic explanation of grinding force modeling. Therefore, in order to supplement the gap in the literature, the present progress of grinding force modeling is reviewed and discussed critically. From the research point of view, the interaction between abrasive particles and workpiece will affect the material removal mechanism, which makes the modeling process of grinding force more complicated. Therefore, the focus of this work is to classify the grinding force modeling according to the scale (macro scale and micro scale), that is, the whole grinding wheel-workpiece interaction is considered in Section 3, and the abrasive

particle-workpiece interaction is analyzed in Section 4. In addition, the application research of grinding force modeling is given in Section 5, and the conclusion and future trend of grinding force modeling are summarized in Section 6.

2 Classification of grinding force models

Selection of grinding parameters (such as material properties, grinding wheel speed, workpiece speed, cutting depth, etc.) determines the dynamic behavior of grinding wheel and workpiece (such as interaction between grinding wheel and workpiece, interference between abrasive particles and workpiece, etc.), which in turn determines the dynamic response in grinding process (such as grinding force and grinding power) [14]. Therefore, in order to further study the modeling method of grinding force, the dynamic behavior of grinding wheel and workpiece needs to be paid attention. From the perspective of modeling scale, grinding force modeling is divided into macro grinding force modeling and micro grinding force modeling according to whether the interference of abrasive is considered or not. In order to comprehensively introduce the modeling research of grinding force, as shown in Fig. 2, this paper summarizes the macro and micro grinding force modeling process, and arranges the main publications according to the time sequence.

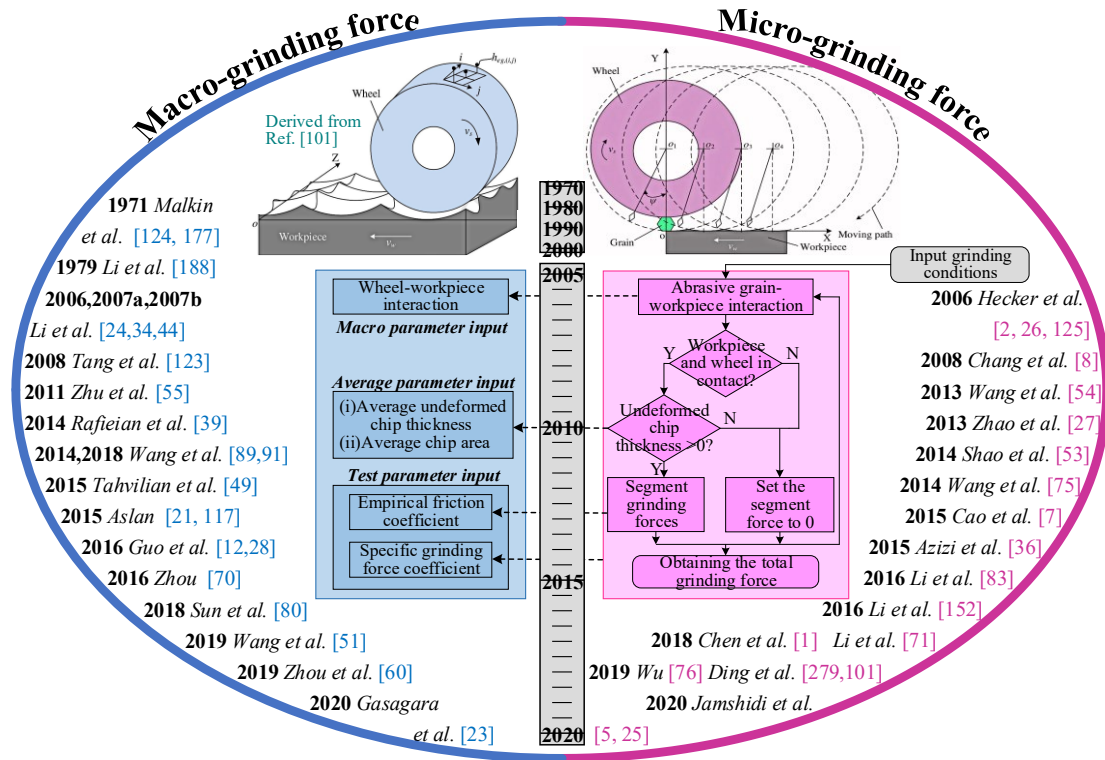


Fig. 2. Summary and comparison of macro grinding force models and micro grinding force models.

2.1 Macro grinding force model

Macro grinding force modeling (based on the interaction between the whole grinding wheel and workpiece) can be traced back to 1980s, that is, Werner [186] first proposed the expression of grinding force per unit wheel width, which were generated by two mechanisms (chip formation and friction). The macro grinding force modeling is based on the interaction between the whole grinding wheel and the workpiece, without considering the complex motion details of abrasive particles. Therefore, this method can reduce the amount of data calculation and get the results quickly. It is often used in production practice and phenomenon description, providing theoretical basis for machine tool deflection and realizing the stability control of machining process. Most of these macro grinding force models are based on macro parameters, average parameters and experimental parameters in grinding process, which usually require the coefficient calibration through experiments [25].

The first characteristic is the introduction of macro parameters, which is also the

most obvious characteristic. The macro grinding force model does not consider the precise modeling of abrasive grains, but focuses on the interaction between grinding wheel and workpiece. The accuracy of the macro grinding force model is improved by analyzing the important macro intervention parameters such as grinding wheel speed, workpiece speed, grinding depth [12, 28] and spindle vibration [14].

Another characteristic is the input of average parameters, which is generally reflected in the establishment of average undeformed chip thickness. The average undeformed chip thickness can be used to calculate the relationship between grinding force and vibration, surface profile and chatter [24, 34, 44]. Similarly, in most grinding finite element models, the introduction of the average thickness of undeformed chips can link the grinding force with the volume of the grinding wheel grid [15]. The input of average parameters is based on macro parameters, which is obviously helpful to improve the operation speed. However, the randomness of the distribution of abrasive particles on the grinding wheel is not considered, and the size and quantity of abrasive particles can only exist in an average way. This has been divorced from the facts, and it is impossible to analyze the influence of abrasive wear, crushing and other behaviors on mechanical properties from a microscopic point of view.

The last characteristic of macro grinding force modeling is that it depends on experimental coefficients. Malkin et al. [124,177] first summarize the expression of grinding force composed of rubbing and cutting components from the experiment. He thinks that the mechanism of grinding process is due to the existence of negative rake angle. However, it is obvious that he does not consider the irregularity of negative rake angle caused by the randomness of abrasive grains. In addition to this problem, it is necessary to consider the friction coefficient which depends most on the experimental calibration. The friction coefficient can be obtained by friction binomial theorem [123], which considers the coefficients related to the physical and mechanical characteristics of the contact interface, but does not consider the influence of the contact arc length. Based on this consideration, through long-term calibration experiments, the equation of

sliding friction coefficient can be obtained [39], which can be used to supplement the contact length, so as to calculate the grinding force [21, 117]. The relevant constants in the above models all depend on experimental data, which will reduce the universality of the model.

In the above models, some engineering conditions are regarded as macro coefficients. Average parameters are added in the modeling process, and the coefficients are calibrated by experimental means. Under specific working conditions, this kind of model has the characteristics of high efficiency and strong engineering, and is an effective way to express grinding force. However, it is necessary to carry out exploratory tests for different processing materials to determine the best macro grinding force coefficient under any given processing conditions, and a large number of repetitive verifications may be needed to improve the accuracy of the model. It should be noted that, due to the lack of consideration of abrasive particles, the expression of macro grinding force still cannot analyze the randomness and complexity of micro grinding process.

2.2 Micro grinding force model

At the end of the 20th century, with the vigorous development of grinding kinematics simulation (KSIM), and with the demand of miniaturization and micromachining of products, micro grinding force modeling based on abrasive grain level has become a research hotspot. Generally, this kind of model does not consider any macro parameters, test parameters and average parameters, so it has high accuracy. Many scholars found that in the actual grinding process, the change of grinding force was mainly caused by the dynamic behaviors such as the chip load of single abrasive grain, the change of inlet and outlet angle and direction [8]. Therefore, in order to achieve accurate modeling of grinding force, the interference between abrasive particles and workpieces is widely used in scientific research. This micro grinding force modeling based on single abrasive grain with dynamic component can quantitatively describe the amplitude-frequency characteristics of grinding force and directly reflect

the dynamic performance of grinding vibration and grinding process.

In micro grinding force modeling, it is necessary to effectively combine the effects of abrasive kinematics and grinding dynamics. The micro grinding force can be obtained by judging the distribution of dynamic grinding edges and the instantaneous undeformed chip thickness caused by abrasive grain kinematics. Therefore, an accurate micro grinding force model needs to study parameter input from macro and micro levels. The macro dynamic factors, such as parallel runout of grinding wheel [5], tool deflection [76], grinding wheel vibration [25] have been proved to have significant influence on grinding force. On the micro level, the dynamic characteristics of abrasive particles, such as kinematic hidden particles [2], local particle skew [26] and abrasive wear [205] affect the grinding force per unit abrasive particle. However, due to the complexity of grinding system, this multi-scale grinding force modeling method has rarely been comprehensively analyzed, or become the development direction of future research.

This modeling technology needs to couple the micro and macro characteristics of grinding process, and the future research may aim to establish a more comprehensive analysis model and the relationship between abrasive particles. Besides, for grinding wheels with multi-layer abrasive grain structure, it may be a challenging task to count the distribution of abrasive grains.

3 Modeling process of macro grinding force

The modeling process of macro grinding force can be summarized as in Fig. 3. The macro grinding force model regards the contact surface as a continuous and uniform material. It is necessary to consider the interaction between grinding wheel and workpiece (Section 3.1) in different grinding modes (Section 3.4). The macro grinding force (Section 3.3) in different grinding stages can be obtained by calculating the instantaneous undeformed chip thickness (Section 3.2).

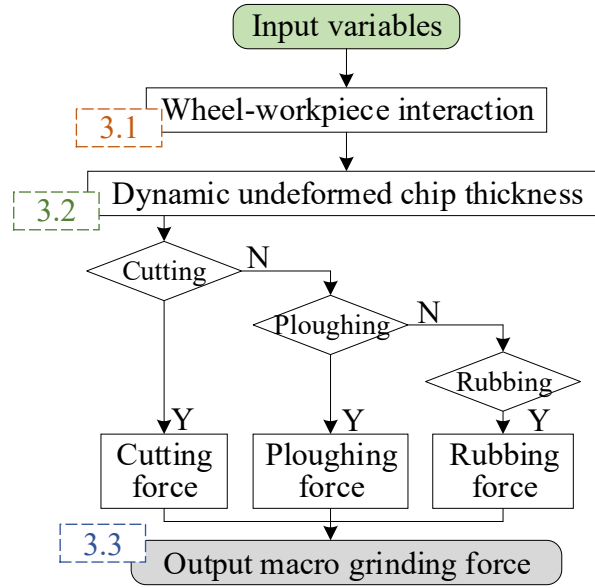


Fig. 3. Modeling method of macro grinding force.

3.1 Modeling of the wheel-workpiece interaction

On the macro scale, it is the key to determine the macro grinding force to calculate the movement between the grinding wheel envelope surface and the workpiece. Fig. 4 shows the kinematic equations mainly applicable to grinding processing.

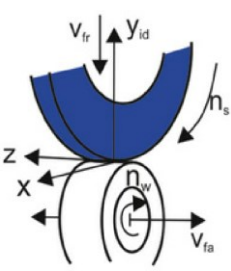
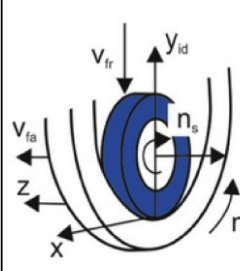
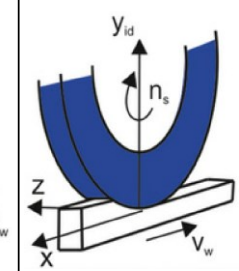
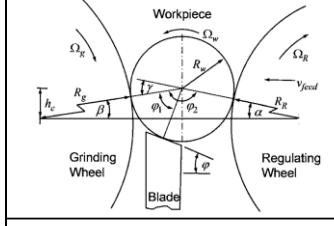
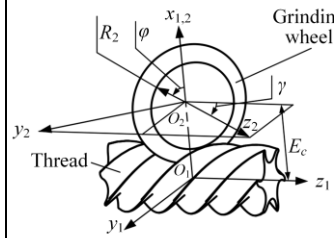
| External grinding [271] | Internal grinding [271] | Surface grinding [271] | Centerless grinding [34] |
|--|---|---|---|
|  |  |  |  |
| $y(x, z) = \frac{q^2 - a_1 \frac{r_s}{r_w} (1 + 2a_2 q)}{2r_s (1 + a_2 q)^2} x^2 - \frac{v_{fr}}{v_s + a_2 v_w} x$ $z = z_0 + \frac{v_{fa}}{v_s + a_2 v_w} x$ <p> $a_1 = 1$: External grinding $a_2 = 1$: Up-grinding $a_1 = -1$: Internal grinding $a_2 = -1$: Down-grinding $a_1 = 0$: Surface grinding $q = \frac{v_s}{v_w}$: Speed ratio </p> | | | $\begin{bmatrix} x'_w \\ y'_w \end{bmatrix} = \begin{bmatrix} \cos \theta' & \sin \theta' \\ -\sin \theta' & \cos \theta' \end{bmatrix} \begin{bmatrix} x_w - x_g \\ y_w - y_g \end{bmatrix}$ |
| <p>Thread grinding [54, 272]</p>  | | | $x = \frac{d_s}{2} \sin \theta + \frac{d_s v_w}{2 v_s} \theta, \quad y = \frac{d_s}{2} (1 - \cos \theta)$ |

Fig. 4. Kinematics of mainly used grinding processes.

Three common grinding processes (such as external, internal and surface grinding) are possible to obtain a general system of equations, through transformation and

introduction of factors describing the application of grinding technology [271]. As the research work on the trajectory of workpieces under conventional grinding methods becomes more and more mature, the interaction problems under some complex grinding methods need to attract more attention, such as centerless grinding and thread grinding. Centerless grinding needs to expand its trajectory based on process model [34]. The force characteristics of thread grinding also need to consider three-dimensional motion parameters such as thread angle [196]. Of course, it should be clear that although the above equations model the real engagement conditions in the contact area between grinding wheel and workpiece, it simplifies the inevitable kinematic errors in the machining process.

Considering the kinematic differences brought by different grinding methods, it is necessary to consider some dynamic factors of grinding wheels according to actual machining conditions: one of the main problems is grinding stiffness. For grinding tools with weak rigidity, special attention should be paid to the grinding force vibration caused by the change of material removal amount [264]. Especially for the internal grinding of deep holes, the kinematic changes caused by the deflection [62], deformation [153] and assisted method [274] of grinding wheels are considered in macro grinding force modeling. However, the relationship between grinding force and workpiece surface quality has not been well explained for extreme parts such as special-shaped surface and workpiece with large length-diameter ratio. This seems to be a good future research direction, and it is an inevitable demand to explain the mechanism of precision grinding from the angle of grinding force. Another major problem is the eccentricity and runout of grinding wheels. In order to explain the influence of dynamic change of cutting depth on grinding force modeling, it is an important means to introduce temporary center to explain the circular law of grinding wheel excircle. However, there is still a lack of consideration for the comparison of unbalance between workpiece spindle and grinding wheel spindle, which will bring serious problems of theoretical and practical deviation. Kinematics analysis of macro grinding force mainly

focuses on macro contact area. Compared with micro scale, macro grinding force model still has irreparable defects in fine modeling.

3.2 Dynamic undeformed chip thickness

The influence of the dynamic undeformed chip thickness on the grinding force is a key step in the process of grinding force modeling. The initial expression of the maximum chip thickness can refer to the following equation [177]:

$$h = \left[\frac{4}{Cr} \left(\frac{v_w}{v_s} \right) \left(\frac{a_e}{d_{eq}} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}} \quad (1)$$

where C is the number of active grits per unit area, r is the chip width-to-thickness ratio, v_w is the workpiece speed, v_s is the contact wheel speed, a_e is the work engagement, and d_{eq} is the equivalent wheel diameter.

This model provides a basis for chip thickness at macro scale, but it does not consider the difficulty of measuring r value caused by the complexity of real chip shape. Moreover, due to the equivalent treatment of grinding wheel diameter, the dynamic change of grinding process is not considered. Therefore, the undeformed chip thickness at macro scale needs to consider some practical processing conditions: one of the main problems is the introduction of dynamic factors. As shown in Fig. 5, the chip thickness is filled with a solid color, grinding wheels are used as edge grinding tools. The contribution of orthogonal vibration is similar to the cross-coupling term in the cutting process model, and the expression of undeformed chip thickness considering the dynamic velocity in two directions can be listed as [24]:

$$h = 2\pi \frac{v_t}{v_s N_r} \sin \theta + 2\pi \frac{v_n}{v_s N_r} \cos \theta \quad (2)$$

where N_r is the number of active grits per revolution. The model is based on the double regenerative chatter model and it provides a time-domain analytical expression of the undeformed chip thickness. However, in the actual grinding process, due to the unbalanced rotation of the rotor, the direction of chip thickness change caused by

chatter is often difficult to predict, which still requires a lot of statistical work to get close to the truth.

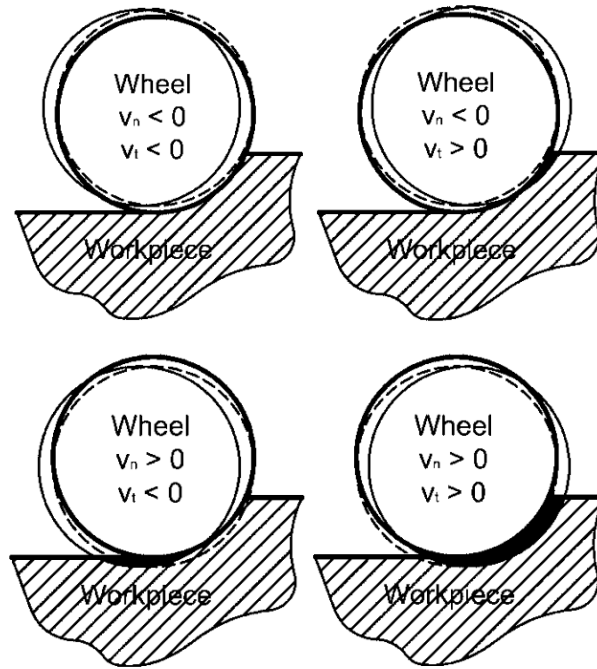


Fig. 5. Uncut chip thickness variation due to vibration [24].

On the other hand, the influence of contact deformation should be considered, especially with the diversified development of workpiece materials. For the workpieces with high elastic modulus, it is necessary to consider the linear relationship between chip thickness h and elastic modulus ratio ($h \propto E_{\text{workpiece}} / E_{\text{wheel}}$) [286]. However, there is not much research in this field. Therefore, it is still an important task to deeply understand the influence of dynamic interference between grinding wheel and workpiece on undeformed chip thickness, which should be included in the refinement of Eq. (1).

3.3 Determination of macro grinding force

By analyzing the interaction between tool and workpiece under different machining conditions, the instantaneous variation law of grinding thickness and grinding coefficient can be obtained [55]. Because there are few researches on modeling process of macro grinding force of brittle materials, some research results are shown in Table 1 mainly according to the perfection degree of ductile grinding stage. With the

development of the model and the increase of considering elements, the equations become more complex. It can also be seen from the equations that, compared with ideal kinematic grinding, most coefficients such as v_w , v_s and N_r remain unchanged, so it has little influence on dynamic grinding force. For Drew's model [13], this is only applicable to grinding tests with short duration. This modeling technology should consider more comprehensive grinding process, such as the contact and removal process between materials and grinding wheels, and the force oscillation caused by variable speed grinding. The relationship between macro grinding force modeling and actual parameters of grinding process is a problem to be further studied. Considering these problems, the time-varying stiffness [126], regeneration effect [55] and chatter boundary [24, 44] in the dynamic grinding system are introduced, so that the dynamic properties of the macro grinding force model are more in line with the actual machining process. However, in these models, the grinding force component is not considered. With the development of macro grinding force refinement technology, rubbing [23] and ploughing [19,12,28] component expressions are put forward, and mechanical expressions become more and more complicated and refined. However, we need to note that many coefficients need to be determined by experiments, only considering the average value of grinding force, and there are still some limitations and errors.

Table 1

Macro grinding force models

| Authors and references | Models | Grinding stages |
|------------------------------|--|--------------------|
| Drew et al. [13] | $\begin{cases} F_n = \frac{u_{ch} b \delta V_w}{V_g} \\ F_t = k_1 F_z \end{cases}$ | Cutting |
| Lnasaki et al. [126] | $F_n(t) = k_g a(t) + c_g \dot{x}(t)$ | Cutting |

| | | |
|--------------------------|--|----------------------------------|
| Zhu et al. [55] | $F = \mp(K_c + K_o)h_w b[x(t) - \mu(t) - T]$ | Cutting |
| Li and Shin [24, 44] | $\begin{cases} F_n = K_r \frac{2\pi}{v_s N_r} (v_t \sin \theta + v_n \cos \theta) N_a A \\ F_t = K_t \frac{2\pi}{v_s N_r} (v_t \sin \theta + v_n \cos \theta) N_a A \end{cases}$ | Cutting |
| Gasagara et al. [23] | $\begin{cases} F_n = (\Phi_1 K_1 + \Phi_2 K_2 \ln \frac{V_c^{1.5}}{a^{0.25} V_w^{0.5}}) \frac{V_w a}{V_c} b + (\frac{4bA p_0 V_w}{V_c}) (\frac{a}{D_e})^{1/2} \\ F_t = (K_1 + K_2 \ln \frac{V_c^{1.5}}{a^{0.25} V_w^{0.5}}) \frac{V_w a}{V_c} b + bA(\beta + \frac{4\alpha p_0 V_w}{D_e V_c}) (D_e a)^{1/2} \end{cases}$ | Cutting, Rubbing |
| Guo et al. [19,12,28] | $\begin{cases} F_n = K(V_w / V_s) a_p + K_1(V_w / V_s) d_e^{-0.5} a_p^{0.5} + \\ K_4(V_w / V_s)^a d_g^b C_s d_e^{0.5} a_p^{0.5+c} \\ F_t = K'(V_w / V_s) a_p + (K_2 + K_3 V_w / V_s d_e) d_e^{0.5} a_p^{0.5} + \\ K_5(V_w / V_s)^a d_g^b C_s d_e^{0.5} a_p^{0.5+c} \end{cases}$ | Cutting, Ploughing Rubbing |

3.4 Influence of unconventional grinding on macro grinding force model

Assisted grinding technology refers to the combination of grinding technology and other processes/machines, which improves the grinding force properties of conventional grinding by changing kinematics and material properties [266]. According to whether there is any assisted technology that interferes with grinding force, the summary of the models can be seen in Fig. 6. Generally speaking, ultrasonic assisted technology and robotic assisted technology can change the movement trajectory of grinding wheel, thus changing the grinding force. This is also a research hotspot at present and has been widely used. The purpose of electrochemical assisted technology and laser assisted technology is to change the material properties of grinding wheels and workpieces. Relevant scholars have analyzed the reasons for the change of grinding force from the material modification mechanism. However, we need to pay attention to the fact that exploring the change mechanism of undeformed chip thickness and grinding force from the grinding wheel/abrasive cutting effect has not been deeply studied.

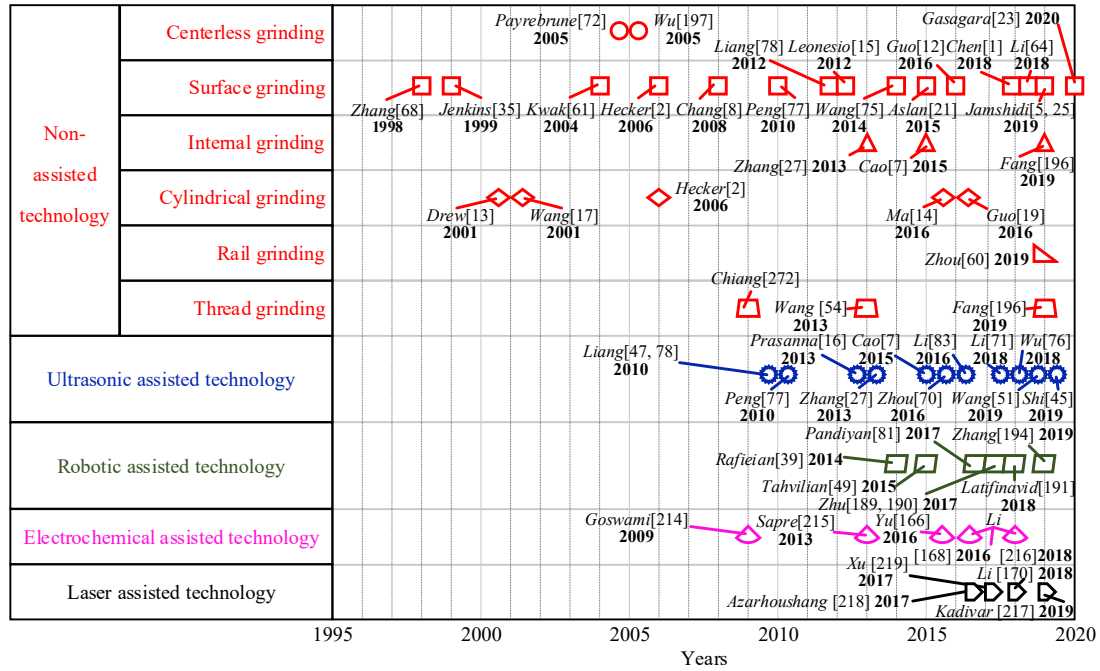


Fig. 6. Classification and development of grinding methods.

The addition of ultrasonic is a typical example to change the kinematics of abrasive grains. The working principle is to control the ultrasonic power [71] by adjusting the ultrasonic generator, thus generating high-frequency vibration [77]. As shown in Fig. 7, the grinding force under ultrasonic effect is proved to be significantly lower than that under conventional grinding (CG) [100, 167].

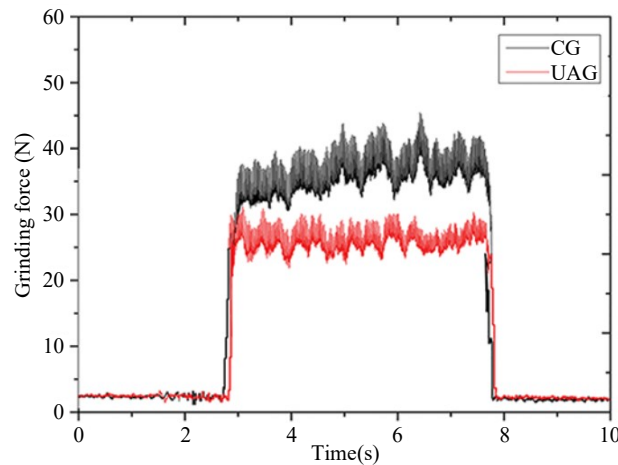


Fig. 7. Comparison of grinding forces for UAG and CG [69].

The action mechanism of ultrasonic assisted grinding (UAG) can be summarized into two parts. Firstly, the periodic cutting motion of abrasive particles is mainly caused by ultrasonic vibration, which reduces the chip thickness in the grinding area, thus

reducing the effective grinding force on each abrasive grain [213]. In addition, the grinding force curve of UAG fluctuates smoothly, which is because the high frequency ultrasonic vibration will cause more short fibers in the microstructure after processing, which can effectively improve the material removal effect and improve the stability of grinding force [69]. The second main reason is that, under the excitation of ultrasonic vibration, the abrasive particles make sinusoidal curvilinear motion. The grinding length $l_{kc} \approx (v_s \pm v_w)T$ of CG can be derived from the particle trajectory, and the grinding length range $(l_{ku} \leq (v_s \pm v_w)T + 4A)$ assisted by ultrasonic can be estimated. Therefore, the different grinding contact length leads to lower grinding force under ultrasonic condition. However, the force modeling research of UAG has not developed into a complete system. In the existing research work, ultrasonic as a new assisted machining method is still in the application verification stage, and most models realize multi-factor force performance analysis by coupling ultrasonic parameters and grinding parameters. In the future research, more complex analytical models between grinding force, tool wear and surface roughness need to be developed.

Similar to the ultrasonic effect, robotic grinding also makes the grinding wheel break away from the grinding area at any time, resulting in intermittent movement, so as to improve the grinding force. However, due to the low stiffness of the robot, it is necessary to consider the impact dynamics on the grinding force [49]. From Fig. 8, we can see the location and frequency of tool impact. In the unsteady region, the impact force is randomly distributed in different angular positions. While in the steady-state stage, the impact force is distributed at the same angle and the impact of each turn occurred in the angular position. At present, robotic grinding mainly focuses on the research of constant force control. Therefore, the existing model simplifies the notch formed during each impact, and does not consider the influence of impact instability on grinding force modeling. In addition, angular velocity, as the acceptable boundary of force coefficient in grinding force model, needs to consider the practical problems of

testing outside the laboratory. How to distinguish the speed drop caused by impact from the background noise in the signal is also a part of the broader efforts of robotic grinding force modeling.

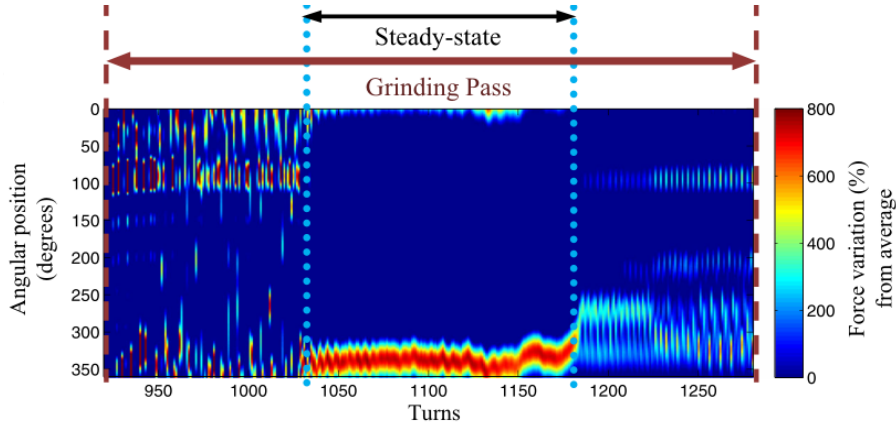


Fig. 8. Impact grinding diagram of robotic grinding [49].

In addition to improving the force characteristics by changing the dynamics, adjusting the properties of the material and structuring the grinding wheel are also commonly used methods. For laser-assisted grinding, there are two main ways to improve grinding force. The first way is to modify the material. The action of laser radiation will soften the workpiece, making the grinding force ratio F_n / F_t less than CG [170]. Larger laser energy density will increase the amount of material removed, and will cause cracks to occur and expand at the laser ablation. Both phenomena will cause a significant reduction in grinding force [218]. The second way is to combine the concept of laser and grinding wheel/workpiece microstructure. It is reported that obtaining different types of surface textures or creating new grinding edges on abrasive surfaces by laser technology will also significantly affect the grinding force [236]. However, the influence of microstructure grinding wheel on grinding force is mainly focuses on experimental verification at present, and further research is needed to explain the influence mechanism of microstructure parameters (such as microstructure width, structuring rate, pattern shape, etc.) on grinding force (especially the components of ploughing and rubbing) from the perspective of simulation and experimental mechanism. In addition, hybrid technologies based on laser-assisted technology such

as laser thermal shock-assisted grinding (LTSG) [219] have been developed, which can effectively overcome the limitations of high grinding forces.

According to our statistics, the popular laser-assisted mixing technology is laser-electrochemical-assisted grinding, that is, the coaxial injection of laser beam and etching solution can increase local chemical reaction and improve the force characteristics during grinding. ECG dissolves the surface of the workpiece through the electrolyte flow, which is conducive to the removal of the grinding wheel, thereby reducing the grinding force [215], so the grinding force is effectively reduced and is affected by the concentration and flow rate of electrolyte [215]. The extremely low Vickers microhardness of the workpiece surface makes the grinding force lower than any of the ultrasonic and electrochemical assisted methods [216]. However, the influence of electrochemistry, grinding wheel and electrolyte erosion on grinding force has not been systematically and qualitatively analyzed.

4 Modeling process of micro grinding force

As we all know, macro grinding force is the sum of micro grinding forces on all active abrasive grains. In order to make up for the shortcomings mentioned above in the macro-scale grinding force modeling, the micro grinding force model is developed, which is based on the formation process of micro-chips. The process of modeling considers the complexity of grinding process and the mechanical properties of materials (Section 4.1), which can reflect the material removal process of abrasive particles-workpiece.

The general modeling process of micro grinding force can be summarized as in Fig. 9. On the basis of considering the interaction between the abrasive grains and the workpiece in the grinding contact area (Section 4.2), combined with the kinematics and dynamics phenomena, the microstructure of the abrasive grains composed of height (Section 4.3) and number (Section 4.4) is determined. Segment force is obtained by calculating the instantaneous undeformed chip thickness (section 4.5), which is necessary to judge the deformation state of the contact stage. Finally, according to the

superposition principle, the total grinding force (Section 4.7) can be obtained from the grinding force on each grain (Section 4.6).

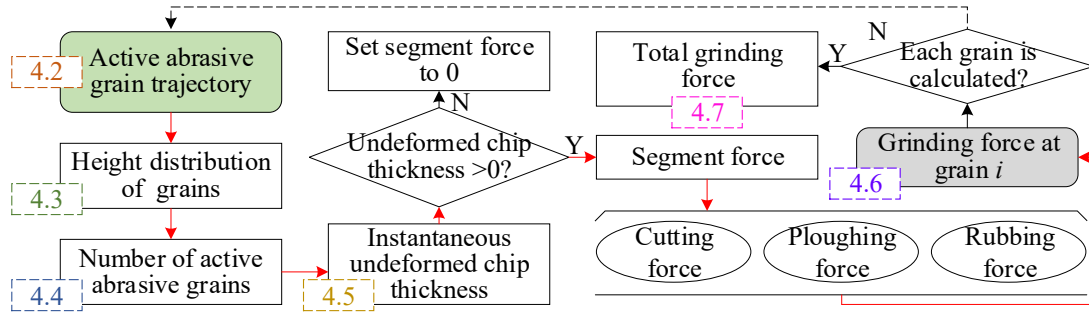


Fig. 9. General modeling process of micro grinding force.

4.1 Foundation of micro grinding force modeling

The research of micro grinding force modeling is based on the material removal state of workpiece by abrasive particles [204]. Material removal methods can be divided into ductile material removal and brittle material removal according to material properties, which is helpful to refine the grinding force model. The removal process of ductile materials includes rubbing, ploughing and cutting [197]. As for brittle materials, brittle fracture occurs when the thickness of undeformed chips exceeds the critical value [206]. Therefore, the ductile-brittle transition in grinding force modeling of brittle materials has been widely concerned by scholars.

For ductile materials, the understanding of chip formation mechanism is helpful to optimize the grinding process, as shown in Fig. 10. When the force of a single abrasive is kept small, the abrasive particles will stay in the outermost rubbing area, and the elastic deformation occurs at this stage. With the increase of grinding depth, extra force will be generated to balance the ploughing effect, and the interaction between particles and workpiece will be transformed into elastic and plastic deformation. When the abrasive particles enter the center position with strong force, the cutting force can make the grinding process have the ability of complete plastic deformation and chip formation. It can be seen that rubbing force is always the largest part in grinding force modeling, followed by ploughing force and cutting force. Therefore, we can conclude that the relationship among grinding depth [203], force

components [19] and deformation state [205] should be considered in the process of grinding force modeling. However, the existing models mainly focus on simplifying the scratching of single abrasive particles. In the future, the model can be improved by combining more abrasive grain shape characteristics, abrasive grain tip angles, abrasive grain protrusion heights and other factors (such as elastic deformation, cooling and lubrication conditions of single abrasive grain). On the basis of statistical analysis of random abrasive grains, a single grinding force will be extended to the whole grinding tool. In addition, in the real grinding process, it is necessary to consider the influence of time-related variables and changing cutting angle on micro grinding force. The grinding force model of ductile materials can also be extended to brittle materials, that is, crack propagation and particle breakage will replace the chip formation area.

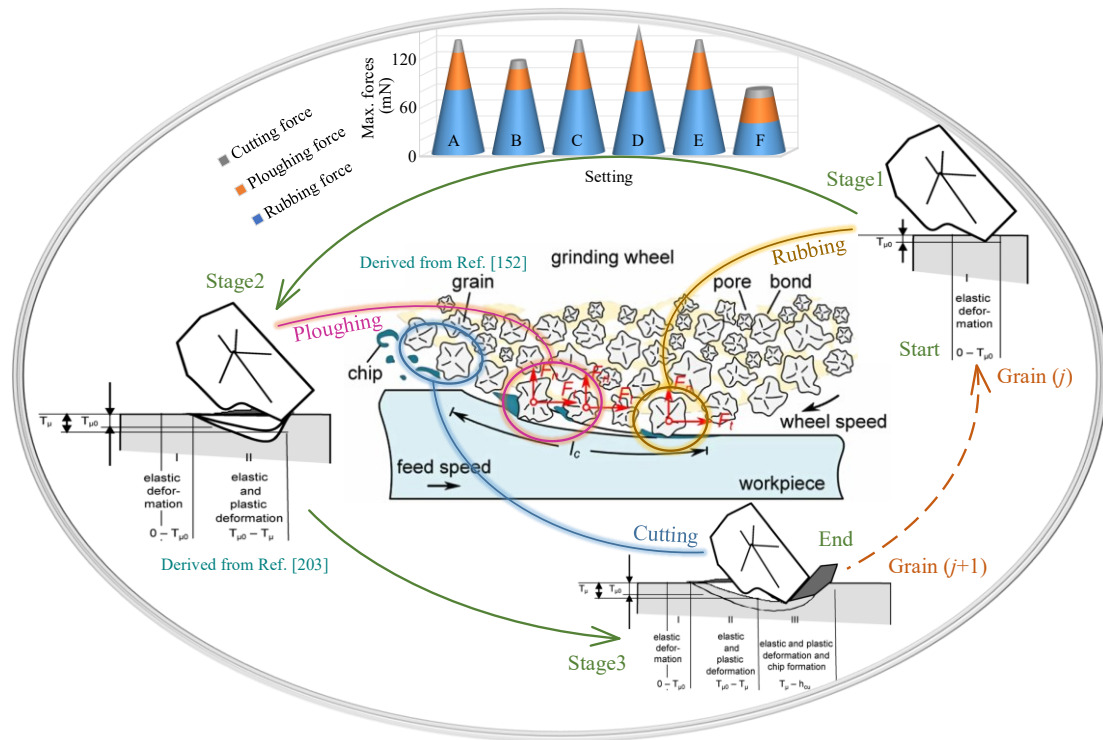


Fig. 10 Ductile material removal process considered in force modeling process

In recent years, scholars have done a lot of research on different material removal mechanisms of hard and brittle materials (such as CFRP [280], SiC [281], BK-7 glass, etc.) during grinding. Because of the difference of fracture mechanism between brittle and ductile removal modes, it is of great significance to study the critical state of

ductile-brittle transition for micro grinding force modeling. The general modeling method takes the material removal volume at this stage as a bridge, and establishes the theoretical model of grinding force through the close relationship between the final material removal volume and the number of active abrasive particles [282]. As shown in Fig. 11, according to the deepening of scratch depth, the grinding force can be determined as three different states: ductile, ductile-brittle transition and brittle. Under low grinding force, abrasive grains plow out of grooves, and materials are taken away by plastic flow, resulting in plastic deformation of materials and ductile grinding grooves in the subsurface region [274]. With the increasing grinding force, central cracks and lateral cracks will be formed under abrasive grains. After brittle fracture, the grinding force begins to fluctuate obviously, and the fluctuation of thrust force F_t is more serious than that of cutting force F_c , which indicates that the surface damage is more serious [265]. Although there are many researches on hard and brittle materials, new materials such as YAG and spinel have not been deeply studied because of their different crystal properties. For ultrahard materials such as sapphire, the relationship between the under-surface precision and the micro grinding force during ductile-brittle transition has not been explained. In addition, as an important evaluation index of micro grinding force modeling, material removal will lead to higher grinding force ratio. However, in the actual grinding process, only a small amount of materials need to be removed. Therefore, in the future work, more meaningful high efficiency indicators and other measurement standards will be introduced, such as determining the surface quality and subsurface damage of hard and brittle materials. How to determine the qualitative relationship between these efficiency indicators and grinding force may be a more urgent problem to be solved. In addition to the above problems, the qualitative analysis of fracture of hard and brittle materials has always been a challenging task in mechanics and computational science, and the relationship between grinding force caused by a single scratch and multiple contacts in grinding brittle materials has not been solved well.

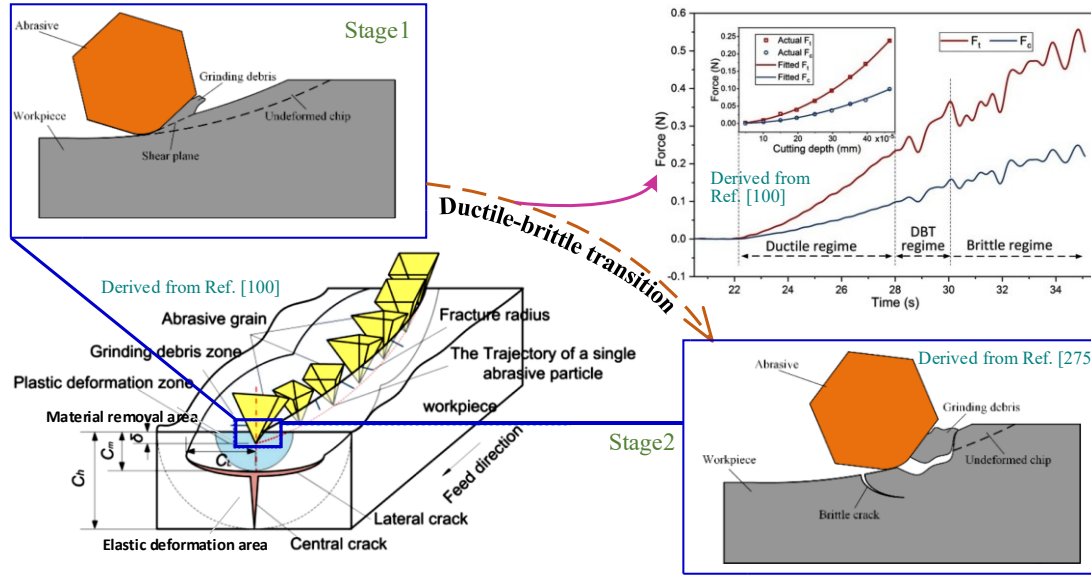


Fig. 11 Brittle material removal process considered in force modeling process

In addition to the removal characteristics of workpiece materials, some scholars also consider the wear condition of the grinding wheel in the grinding force modeling, which makes the force model more consistent with the actual grinding process. It can be seen from Fig. 12 that the wear of abrasive particles will affect the magnitude of grinding force and the composition of each component, which can be explained from the following angle. One reason is that the initial abrasive grains are complete and sharp, the critical transition depth from ploughing to cutting stage is very low, and most abrasive grains are in cutting state. However, for worn abrasive particles, the passivation of abrasive particles makes the force react to ploughing and rubbing, and reduces the number of abrasive particles in cutting state. Wear will bring ploughing force and friction to the worn surface. Another reason is that the change of the contact area between the workpiece and the top of abrasive particles caused by wear will also change the number of effective grains, thus affecting the grinding force. In some grinding processes (such as flexible grinding, abrasive belt grinding, etc.), small abrasive grain stiffness is easy to cause wear. Considering the progressive abrasive wear [205], the concept of abrasive wear rate k_w can be introduced to modify the hardness of abrasive particles, so as to obtain the critical depth and establish the logical relationship among wear-depth-force. The angle of attack of the particle β , corrosion height

distribution function $f(h)$ and abrasive contact density ρ are used to characterize the force ratio coefficient ($i = F_t / F_n$), which all represent the wear state [276]. However, these models still mainly serve the online detection of abrasive wear. For the height and shape distribution of abrasive particles after wear, the general treatment method is to analyze single abrasive particles, and it is considered that the properties of different abrasive particles are uniform, which is obviously unreasonable. In the future, more data statistics and signal processing work need to be carried out to establish a more comprehensive micro grinding force model considering abrasive wear.

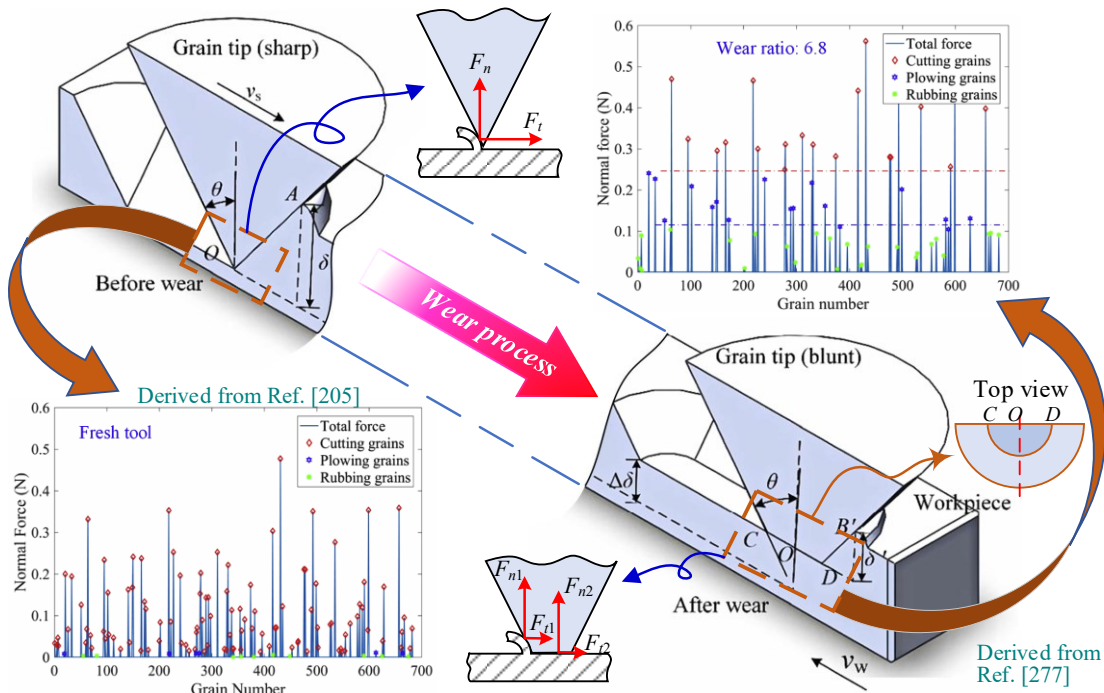


Fig. 12 Abrasive wear process considered in force modeling process

4.2 Active abrasive grain trajectory

On the micro-nano scale, any slight movement of the grinding wheel will affect the trajectory of abrasive grains [90], and the trajectory of each active abrasive grain will affect the undeformed chip thickness and the final surface of the workpiece profile [21]. At present, the common methods to change the kinematics of abrasive particles are self-excited vibration [4] and forced vibration [21]. In self-excited vibration, the relative vibration between grinding wheel and workpiece is usually regarded as sine wave. In forced vibration, such as ultrasonic vibration, it is considered as the

combination of the circular movement of the grinding wheel and the ultrasonic vibration curve [83], as shown in Fig. 13.

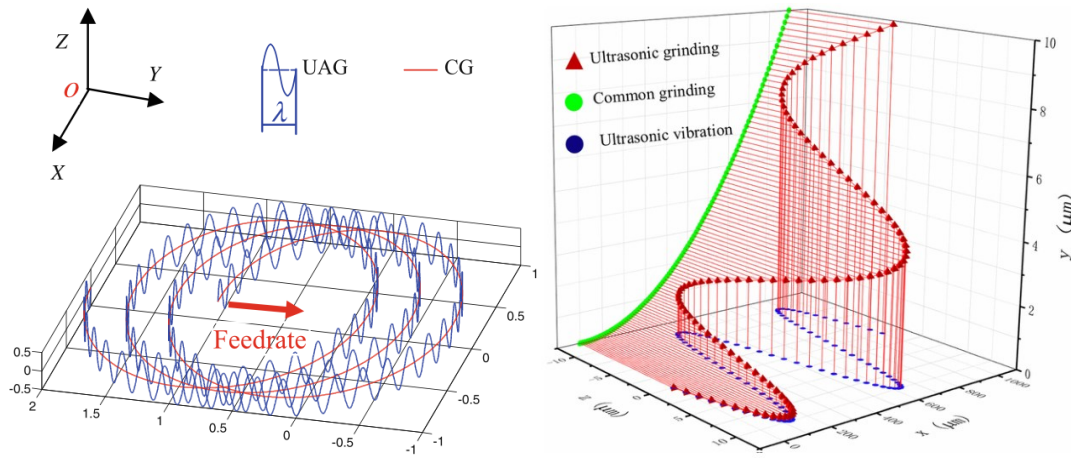


Fig. 13. Three-dimensional motion trajectory of single grain in CG and UAG [42, 71].

Table 2 Trajectory expressions of each abrasive grain

| Authors and references | The trajectory of each abrasive grain | Grinding method | Dynamic factors |
|---|--|-----------------|-----------------|
| Budak et al. [5,25] | $\begin{cases} x_i = [R_i + R_0 \sin(\theta_i / 2)] \sin(\theta_i) + ft \\ y_i = [R_i + R_0 \sin(\theta_i / 2)] (1 - \cos(\theta_i)) \end{cases}$ | CG | Deflection |
| Zhou et al. [60] | $\begin{cases} x_i = r \sin(\omega t) \\ y_i = v_\omega t + r \cos(\omega t) \end{cases}$ | RG | Swing |
| Zhou et al. [70] Sun et al. [80] Li et al. [71] | $\begin{cases} x_i = v_w t + d_s \sin(2\pi n_s t) / 2 \\ y_i = d_s (1 - \cos(2\pi n_s t)) / 2 a \\ z_i = A \sin(2\pi f t) \end{cases}$ | UAG | Vibration |
| Wu et al. [76] | $\begin{cases} x_i = f_v t + R \sin(\omega t - 2\pi m / M) + r \sin(\omega t + \alpha_0) + \\ F_x (L - a_F)^2 (2L + a_F - 3z) / (6EI) \\ y_i = R \cos(\omega t - 2\pi m / M) + r \cos(\omega t + \alpha_0) + \\ F_y (L - a_F)^2 (2L + a_F - 3z) / (6EI) \end{cases}$ | UMG | Run-out |

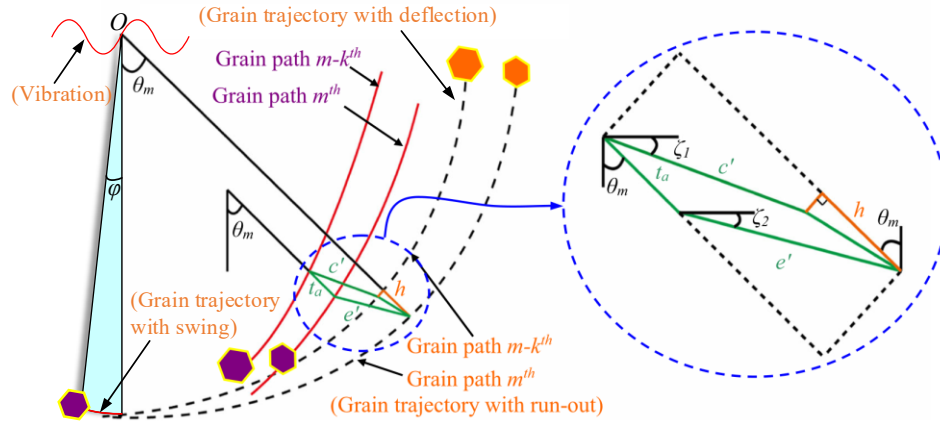


Fig. 14. Grain path with dynamic factors [76].

The expressions of abrasive trajectory under different grinding methods and the common influencing factors of the trajectory are listed in Table 2. In order to be closer to the actual machining process, dynamic factors such as (eccentricity [5, 25], swing [60], vibration [70], run-out [76], etc.) is an inevitable topic, as shown in Fig. 14. In order to explain the action mechanism of these macro movements on micro grinding force, Budak model considers the actual grinding wheel eccentricity condition and develops deterministic kinematic equations. However, the assumption that the distance between all adjacent grits along the periphery of the wheel surface is the same is obviously contrary to the real grinding wheel topography. In the future research, if we want to study the transient response of grinding force, we should not neglect the real modeling of grinding wheel for the sake of idealization and convenience of modeling. In Zhou model, the movement process of a single abrasive grain under different swing angles is established, but the impact of corrugation, spalling and vibration caused by swing on the grinding force modeling is ignored. This problem is also reflected in the modeling process of grinding wheel vibration and run-out. Therefore, we can realize that there is no systematic study to fully explain the relationship between these dynamic factors and grinding force characteristics, and more influencing factors representing motion trajectory errors need to be further elaborated.

4.3 Determination of the height distribution of active abrasive grains

The height of abrasive particles determines the shape of grinding wheel, which has

a profound impact on grinding force [60]. The schematic diagram of particle protrusion height is shown in Fig. 15.

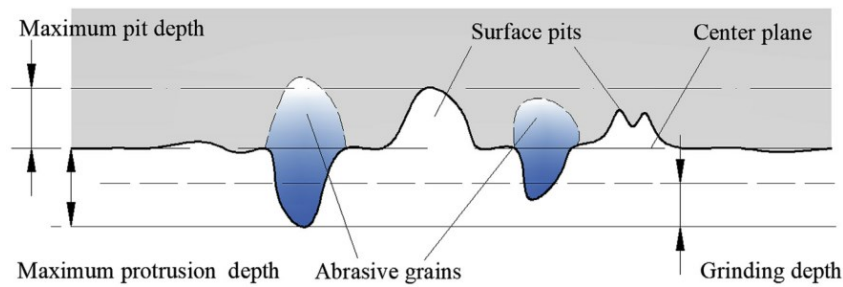


Fig. 15. Schematic diagram of protrusion heights of grains [60].

The critical height of dynamic abrasive particles should be given according to working conditions [21, 36]. It is generally considered that the protrusion height distribution of common grinding wheels such as metal/resin bonded diamond grinding wheels before and after grinding follows the normal distribution law [102-104]. However, in some studies, it is considered that the distribution of protrusion height will change from exponential to uniform [102]. The result of this difference may be due to the degree of abrasive particle loss caused by abrasive breakage and/or movement during dressing, but the dynamic failure mechanism of abrasive particles has not been paid attention to. The focus of future research may be to establish a more comprehensive functional relationship between critical failure conditions and height distribution of multilayer abrasive particles. With the development of the modeling, the Kolmogorov Smirnov and Shapiro Wilk tests show that the normal distribution can well fit the surface morphology of new wheels well, but it cannot represent worn wheels correctly [287]. This may be because the grinding wheel wear will keep the height of inactive abrasive grains unchanged, while the active abrasive grains with high height will lose their peak value. Considering this phenomenon, extreme value distribution fitting method [108] and generalized extreme value function [5] can be used for this negative skewness phenomenon. However, for any grinding wheel, it is still a work to be explored to determine the appropriate probability distribution function.

For worn abrasive grains, the grain shape will change constantly, thus affecting

the grinding force on the single grain tip. Therefore, the wear rate ($I_V = dV / dS$) is introduced, and the wear model of the whole grinding process is established from the point of view of single grain cutting [277]. Through the established grinding force model, the quantitative relationship between scratch distance and wear height is obtained. In the normal detection test [105], data sample size [106] and accuracy [107] are considered as important parameters for evaluating the distribution law of wear particles. For the height of abrasive particles before and after wear, if it does not conform to the normal distribution, specific mathematical methods can be used, such as Johnson transform [101]. The data of normal distribution can be modified by modifying function, and its accuracy has been confirmed by relevant research. However, the beneficial effect of modifying technology on grinding force expression needs to be further verified.

4.4 Determination of the number of active abrasive grains

In the grinding process, the number of dynamic abrasive grains is one of the most important grinding parameters [22], which can directly affect the total grinding force. Generally speaking, before calculating the number of dynamic abrasive grains, it is necessary to determine the distribution density of dynamic abrasive grains [91] on the grinding wheel surface:

$$N = C_{ds} b v_s \quad (3)$$

Dynamic density of abrasive grains is obtained by static density of abrasive grains and dynamic effects such as local abrasive grain deflection and dynamic hiding of abrasive grains. Therefore, the dynamic density of abrasive grains is always lower than the static density [7,131], as shown in Fig. 16. The law can be explained by the following equation. In the precise calculation of grinding force, compared with the statistics of static abrasive grains, the dynamic abrasive grain density is the best condition to judge the force performance. Among them, the density of abrasive grains can be solved from many schemes: one is fitting by measurement ($C_s(z) = Az^k$ [2]). Although the statistical technique has been widely used and has high accuracy, it is only

applicable to the static index of abrasive density, and the influence of dynamic deflection cannot be evaluated. Considering this problem, another method is characterizing by removing the volume from the material $\{C_s(z) = C_s(z')(1 - V_{sh}/V_t) [26]\}$. The model considers that the dynamic effects of each abrasive particle will bring about the change of the number of abrasive particles, thus removing the space materials in the dynamic range. This method verifies the change of dynamic abrasive particle number from the angle of volume removal rate, and the idea is feasible. However, the difficulty is that the specific expression of the number of abrasive particles cannot be determined from the removal volume, so this method has not formed a systematic qualitative study. In the future research, it is an important subject to establish a more comprehensive analytical model based on active abrasive density, and this influence should be included in the refinement of equation (4).

$$C_d(z) = \frac{C_s(z)}{1 + \frac{2}{3} \frac{C_s(z)}{z} \frac{\tan(\theta)}{\tan(\varepsilon)} E(h^3)} \quad (4)$$

where z is the radial distance measured into the wheel, and the adjusted parameters A and k depend on the wheel type and dressing conditions. $C_s(z)$ is the static abrasive particle density. V_t is the total volume on the periphery of the wheel that is engaged in the workpiece and V_{sh} is the total kinematic shadow volume generated by the active grinding edges

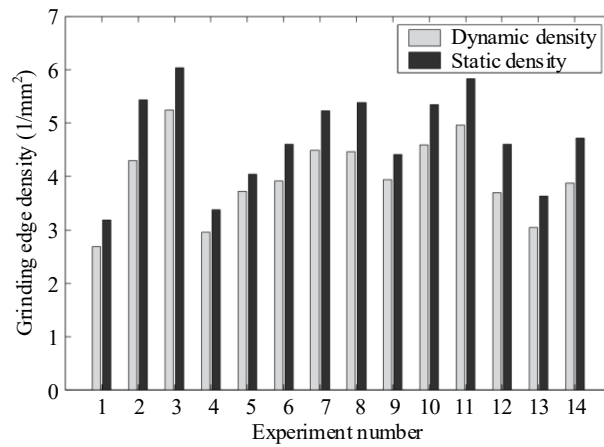


Fig. 16. Simulation: static and dynamic grinding edge density [2].

After obtaining the number of abrasive particles in the fixed area, the dynamic

number of abrasive particles in the required feed angle ε can be obtained through calculation: $N_\varepsilon = N(\tan\varepsilon)^m$ [124]. However, with the strict requirement of model precision, it will be a very meaningful work to determine the number of dynamic grains in any tiny feed angle [125]. For different machining methods, the number of abrasive grains per unit width can be coupled with machining characteristic parameters, such as electrolysis time t [27] under electrolysis condition, ultrasonic amplitude A and frequency f [71] under UAG. However, the influence of effective abrasive grain number on the machining process, such as the maximum undeformed chip thickness and grinding force, has not been deeply studied. The same problem lies in the analysis of the comprehensive influence of dynamic error on the number of dynamic abrasive particles. At present, most models of abrasive grain number mainly focus on the verification of static or uniform abrasive grain number. The complete verification of effective abrasive grain number needs to be further clarified.

4.5 Calculation of instantaneous undeformed chip thickness

The grinding chip formation parameters can be calculated in terms of grinding kinematic and directly affect the process behavior and finished surface precision [109, 110, 111]. There are three modeling schemes for undeformed chip thickness: average modeling, probability distribution modeling and statistical modeling of abrasive height difference. The first is the average modeling scheme. As shown in Eqs. (5-1) ~ (5-4) in Table 3, many scholars have developed different models of undeformed chip thickness in the early days, but only consider the average value without considering its inhomogeneity, which reduces the prediction accuracy [101]. This average consideration is embodied in the characterization of the number N of abrasive particles. In Agarwal model [183, 184] and earlier models [180-182], the change of active abrasive particles in real grinding wheels caused by static and dynamic interference is not counted. The fraction f of particles actively cut in grinding in the equation ($N=4f / \{d_g^2(4\pi / 3v)^{2/3}\}$ [183, 184]) obviously exposes this defect. Based on this idea, reviewing the previous models, the key coefficient λ in Pahlitzsch model [180] also

reduces the credibility of the model.

Secondly, probability distribution modeling. Random distribution models such as uniform distribution, Gaussian distribution [Eq. (5-5) [287]] or Rayleigh distribution [Eq. (5-6) [2]] are used. Gaussian distribution and Rayleigh distribution are the probabilistic characterization models which are most commonly used. The former has centralization, symmetry and uniform variability, while the latter has the advantage of being uniquely defined by one parameter (σ). It has been proved that Rayleigh distribution in hard and brittle materials [287, 80], alloy materials [2], metal materials [196], etc. have high accuracy. The distribution and error comparison of the two distribution can refer to Fig. 17. However, most of the above probability models of chip thickness distribution are based on assumptions, and more work is needed to verify the unknown materials by experiments. At the same time, compared with ductile materials, the coexistence of ductile-brittle of brittle materials makes it difficult to verify the chip thickness, which is still a problem to be further clarified.

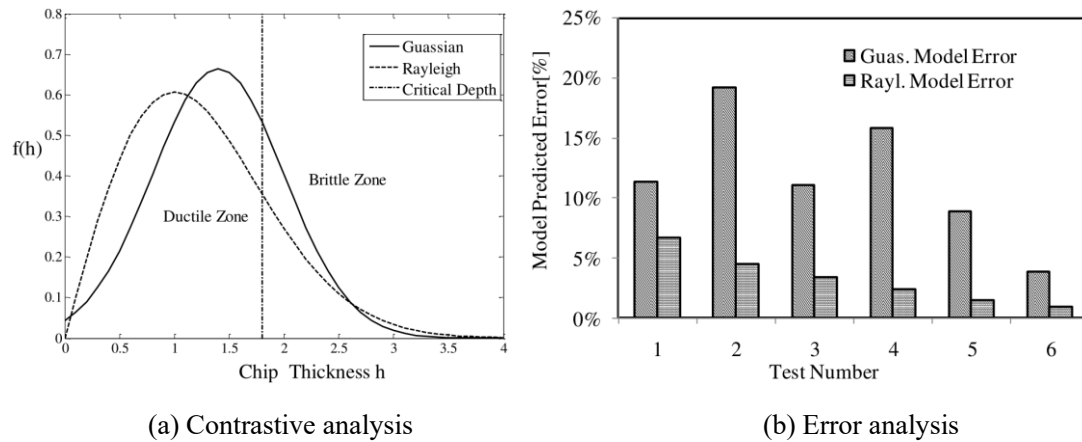


Fig. 17. Comparison of Gaussian and Rayleigh probability distribution [287].

In order to establish an instantaneous undeformed chip thickness model which is more in line with the actual structure, the last scheme is statistical modeling of abrasive height difference. The biggest feature of instantaneous undeformed chip thickness at micro scale is that the dynamic difference of adjacent abrasive grain heights is considered. As shown in Fig. 18, it is a schematic diagram of undeformed chip thickness of single grain. How to make scientific statistics and characterization is a research

difficulty. The undeformed chip thickness model based on grain height characteristics and active grain spacing can be expressed as Eq. (5-7) [124]. However, it has been found that the Malkin model is considered under the condition that the wheels are stationary. It describes the difference of grain protrusion height without considering the influence of dynamics. On this basis, such as Eqs. (5-8) [25] and (5-9) [101], the introduction of motion parameters such as dynamic height difference [25] and tangential angle position [101] in the actual grinding process is very critical. Although the statistical model provides a better understanding of the grinding process, it may be a time-consuming task to experimentally extract the statistical characteristics of abrasive particles as one of the input parameters [288]. The difficulty of the above models is mainly reflected in the measurement and filtering processing. White light interferometer may be a better choice for abrasive particles with small particle size. However, the error of grinding wheel shape accuracy will distort the results of one-dimensional filtering (such as high-pass, low-pass and band-pass technologies, etc.), resulting in bad image noise. Two-dimensional filtering can smooth the height of abrasive particles and bring errors. For larger abrasive particles, camera focusing may be a feasible method. However, the range of focal length will bring errors in the height of abrasive particles, and this method is time-consuming and labor-intensive. For scanning electron microscope, ultra-depth-of-field optical microscope, etc., gray-scale image processing technology is an ongoing research. In the future, in order to use the model more conveniently, it is still an important subject to improve and modify the measurement and statistical techniques.

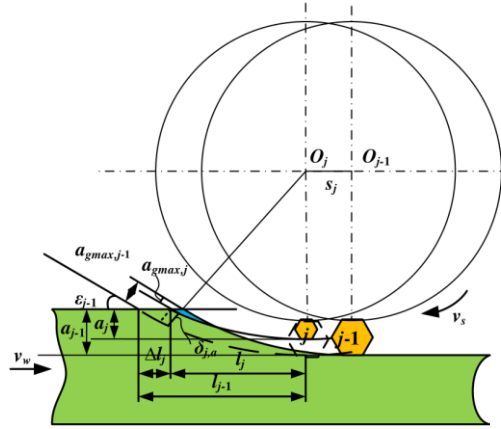


Fig. 18. Schematic illustration of the undeformed chip thickness of single grain. [101].

Table 3

Several developed models to calculate the undeformed chip thickness.

| Authors and references | Equations | Number |
|------------------------|---|--------|
| Pahlitzsc [180] | $h = 2\lambda \frac{v_w}{v_s} \sqrt{\frac{a_p}{d_s}}$ | (5-1) |
| Shaw [181] | $h = \left[\frac{4v_w}{v_s N_d c} \sqrt{a_p / d_s} \right]^{1/2}$ | (5-2) |
| Werner [182] | $h = \frac{1}{A} \left(\frac{2}{N_{st}} \right)^{1/\alpha+1} \left(\frac{v_w}{v_s} \right)^{1/\alpha+1} \left(\frac{a_p}{s_s} \right)^{1/2(\alpha+1)}$ | (5-3) |
| Agarwal [183, 184] | $h = \sqrt{\frac{a_e v_w}{N r v_s} \frac{1}{l_c}}$ | (5-4) |
| Wu [287] | $f(h) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_g} e^{-\frac{(h-\bar{h})^2}{2\sigma_g^2}} & h \geq 0 \\ 0 & h < 0 \end{cases}$ | (5-5) |
| Hecker [2] | $f(h) = \begin{cases} (h / \sigma^2) e^{-h^2/2\sigma^2} & h \geq 0 \\ 0 & h < 0 \end{cases}$ | (5-6) |
| Malkin [124] | $h = 2s \left(\frac{a_{j-1}}{d_s} \right)^{1/2} - \delta_j$ | (5-7) |
| Budak [25] | $h = R_{n,j} - R_{m,j} + (n-m)f_t \sin(\theta_{i,j}) + n_{i,j}$ | (5-8) |

Ding [101]
$$h = 2\lambda_j \frac{v_w}{v_s} \left(\frac{a_{j-1}}{d_s} \right)^{1/2} - 2 \frac{v_w}{v_s} \left(1 + \frac{v_w}{v_s} \right) \left[a_{j-1} - (a_j a_{j-1})^{1/2} \right] \quad (5-9)$$

The above-mentioned instantaneous undeformed chip thickness is based on the ideal kinematic law, however, some inevitable dynamic factors need to be considered in the grinding process: the regenerative vibration caused by the circumferential eccentricity [3], runout [5], deflection [76] and other errors of the grinding wheel profile. The influence of tool runout and tool deflection on undeformed chip thickness is shown in Fig. 19. Therefore, the instantaneous chip thickness of a single abrasive grain cross section is composed of three factors: (a) motional static undeformed chip thickness, (b) dynamic chip thickness and (c) dynamic chip thickness deviation [1]. This model has fully explained the dynamic influence of various dynamic errors on the undeformed chip thickness of single abrasive grain. In the future work, more attention should be paid to the problem of multiple coupling between dynamic error and different active abrasive grains, and the undeformed chip thickness modeling technology of single abrasive grain should be applied to multiple abrasive grains on the whole surface of grinding wheel.

$$\begin{aligned} h &= \pm h_{cu,0} + \Delta h_{cu,i} + \delta h_{cu,i}(\phi_i) \\ &= \pm f_i \sin(\phi_i) + [(H_{is}(t-T) - H_{is}(t)) - H_{iw}(t-T) - H_{iw}(t)] + R_i'(\phi_i') - R_{i-1}'(\phi_i') \end{aligned} \quad (6)$$

where $h_{cu,0}$ is static chip thickness, $\Delta h_{cu,i}$ is dynamic chip thickness in radial direction derived from regenerative vibration. $\delta h_{cu,i}(\phi_i)$ is named as dynamic chip thickness deviation excited by eccentrically rotational behaviour of grinding wheel or machine tool spindle.

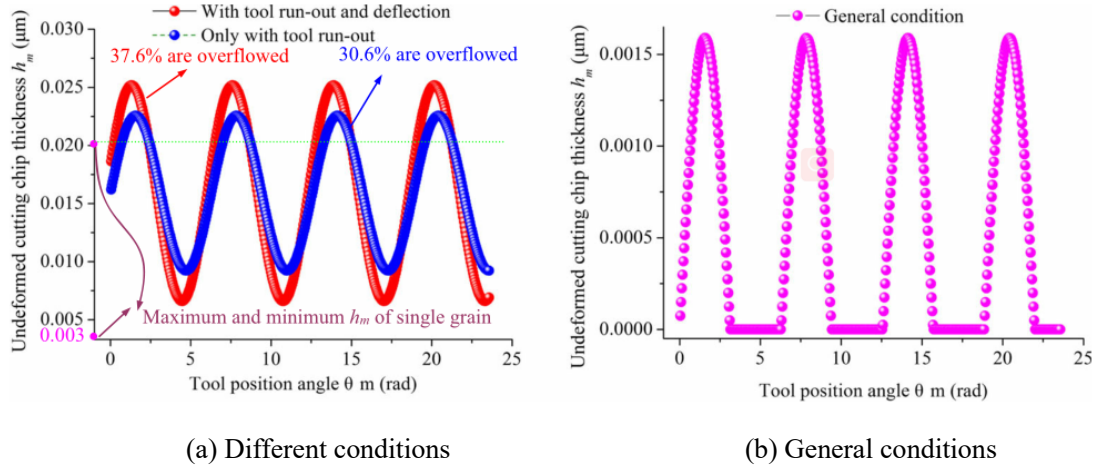


Fig. 19. Undeformed cutting chip thickness in different conditions [76].

4.6 Determination of micro grinding force

In order to determine the grinding force on a single abrasive grain, the properties of workpiece materials should be determined firstly. Different materials consist of different force components, which has been mentioned in Section 4.1. In the process of establishing these expressions, the grinding force components on a single abrasive grain are usually identified at a specific time in a certain grinding stage [130], and the total grinding force is the sum of the grinding force components in each stage. Part of micro grinding force models for removing ductile or brittle materials are listed in Table 4. It can be seen from the equations that the modeling results are generally composed of structural parameters (such as grinding wheel diameter [2], abrasive properties [27]), motion parameters (grinding wheel speed [1], workpiece speed [282], motion displacement [152]), material parameters (hardness [26], elastic modulus [280]), process parameters (deformation [280], contact arc length [279], grinding depth [19], wear [205]). These four types of parameters influence each other, and the refinement of micro grinding force modeling has always been a research hotspot. For ductile materials, at first, Hecker model [2, 26] has done a lot of work on the number of active abrasive particles. However, the structural parameters are still simplified, and the geometric shapes of abrasive particles are not counted and analyzed. The same problem is also reflected in Chen model [1] and Budak model [5, 25]. Although these models deeply

discuss the influence of main excitation sources on dynamic grinding force, it is not desirable to simplify the distance between abrasive particles. Considering the above problems, Li model [152] considers the numerical analysis of the shape, size and position of abrasive particles, but the influence of dynamic effect on the time delay of grinding force is a problem to be clarified. Therefore, it can be concluded that the key of micro grinding force modeling of ductile materials is to establish a multi-factor coupling model that meets the actual machining process and future research may aim at establishing a more comprehensive grinding force model. As for brittle materials, it has not been well studied as in ductile materials. It can also be seen from Wang model [280] and Zhang model [282] that there are still experimental coefficients in the force expression. This is because for hard and brittle materials, the current research work mainly focuses on the process exploration of machining accuracy. In the future, with the improvement of understanding of material removal mechanism of brittle materials, micro grinding force modeling technology will also develop rapidly.

Table 4

Micro grinding force models

| Authors and references | Models considering different Grinding stage | Material property |
|------------------------------|--|----------------------|
| Hecker et al. [2,26] | $\begin{cases} F_t = d_f \frac{HB\pi D}{2} (D - (D^2 - d^2)^{1/2}) (\sin \alpha + f \cos \alpha) \\ F_n = d_f \frac{HB\pi D}{2} (D - (D^2 - d^2)^{1/2}) (\cos \alpha - f \sin \alpha) \end{cases}$ Cutting | Ductile |
| Chen et al. [1] | $\begin{cases} F_t = K_s [\nu_w / \nu_s]^{2\epsilon-1} [d_s]^{1-\epsilon} h_{cu,i}(\phi_i) d\phi \\ F_n = c_s F_t \end{cases}$ Cutting | Ductile |
| Budak et al. [5, 25] | $\begin{cases} F_n = K_{nc} w_c h_{i,j}(\theta_{i,j}) + K_{ne} w_c \\ F_t = K_{tc} w_c h_{i,j}(\theta_{i,j}) + K_{te} w_c \end{cases}$ Cutting, Ploughing | Ductile |
| Li et al. [152] | $\begin{cases} F_n = F_{nr,np,nc}^{(i)} \cos \left[\arctan \frac{z_{global}^{(i)} - z_{wheel}^{(i)}}{x_{global}^{(i)} - x_{wheel}^{(i)}} \right] + F_{tr,tp,tc}^{(i)} \sin \left[\arctan \frac{z_{global}^{(i)} - z_{wheel}^{(i)}}{x_{global}^{(i)} - x_{wheel}^{(i)}} \right] \\ F_t = F_{tr,tp,tc}^{(i)} \sin \left[\arctan \frac{z_{global}^{(i)} - z_{wheel}^{(i)}}{x_{global}^{(i)} - x_{wheel}^{(i)}} \right] - F_{nr,np,nc}^{(i)} \cos \left[\arctan \frac{z_{global}^{(i)} - z_{wheel}^{(i)}}{x_{global}^{(i)} - x_{wheel}^{(i)}} \right] \end{cases}$ | Ductile |

Cutting, Ploughing, Rubbing

| | | | |
|--------------------|--|-----------------|---------|
| Wang et al. [280] | $\begin{cases} F_d = \frac{8E(d\delta_d - \delta_d^2)^{\frac{3}{2}}}{3d(1-\nu^2)} \\ F_b = \frac{1}{3}E(8d)^{\frac{1}{2}}\delta_b^{\frac{3}{2}} / (1-\nu^2) \end{cases}$ | Ductile Brittle | Brittle |
| Zhang et al. [282] | $F_{ctg} = \left(\frac{d_{gc}^2 (15l_d + 16l_c) \cot^4 \theta H^{\frac{1}{2}} K_{IC}^{\frac{1}{2}} (1-\nu^2)^{\frac{1}{4}}}{192E^{\frac{7}{8}} \eta^2 l_c} \right)^{\frac{8}{9}}$ | | Brittle |

Ductile-to-brittle transition

4.7 Superposition principle of micro grinding force

Vector superposition of grinding forces on all effective abrasive grains on the grinding wheel is a necessary way to transform micro grinding forces into total grinding forces, and an important means to verify and apply the grinding force model. Related scholars have done a lot of research on superposition principle. At first, in order to obtain the result of grinding force quickly and conveniently, the grinding force can be homogenized. The total grinding force on the whole grinding wheel can be expressed as the product of the number of particles in the grinding area and the micro grinding force of a single abrasive particle [83,64,2,54], i.e., $F=NF_g=C(z)lF_g$. However, this method cannot accurately obtain the exact analytical solution of the total grinding force, so a more optimized model is proposed. Combined time-domain model method and grinding mechanism, the dynamic grinding force can be regarded as the sum of segmented forces along the contact length of the wheel in the whole processing time [14]. As shown in the following equation, the grinding force on a certain contact length is accurately calculated by the segmented force model, which improves the accuracy of the model to a certain extent.

$$F = \int_{\theta_s - \Delta\theta}^{\theta_s} F(t_i) d\theta_s(t_i) \quad (7)$$

With the increasing demand for grinding force model, more refined superposition models are proposed. The normal and tangential grinding forces [1, 25] in the grinding process are obtained by superimposing the force of each moving particle independently,

and the equation is as follows:

$$\begin{bmatrix} F_x \\ F_z \end{bmatrix} = \sum_{i,j} \left(\begin{bmatrix} -\cos \theta_{i,j} & -\sin \theta_{i,j} \\ \sin \theta_{i,j} & -\cos \theta_{i,j} \end{bmatrix} \times \begin{bmatrix} Ft_{i,j} \\ Fn_{i,j} \end{bmatrix} \right) \quad (8)$$

However, when considering the material removal mechanism of abrasive particles, the grinding forces in the required grinding stage should be superimposed, so that the total grinding forces are closer to the actual machining situation, where ($N_c + N_p = N$):

$$\begin{cases} F_t = \sum_1^{N_c} [F_{tc}(a_{gn}) + F_{tcf}(a_{gn})] + \sum_1^{N_p} [F_{tp}(a_{gm}) + F_{tpf}(a_{gm})] + f_t \\ F_n = \sum_1^{N_c} [F_{nc}(a_{gn}) + F_{ncf}(a_{gn})] + \sum_1^{N_p} [F_{np}(a_{gm}) + F_{npf}(a_{gm})] + f_n \end{cases} \quad (9)$$

From the development of superposition model, it can be seen that the complication of superposition principle will lead to a fine micro grinding force model. Therefore, it is an important research content to deeply understand the influence of superposition principle on grinding force results, which should be included in the refinement of Eq. (7).

5 Applications of grinding force model

With the development of grinding force modeling technology, the grinding process has been evaluated more accurately. The grinding force model can accurately predict the grinding results, optimize the grinding conditions and control the grinding process. In the following chapters, we will review the beneficial application of grinding force model in chatter suppression, force control technology and other grinding process simulation.

5.1 Chatter suppression

It is demonstrated that the instability of dynamic grinding force might be traced back to frictional chatter [113], mode coupling [114], thermo-mechanical instability [115], and other complex effects due to system non-linearities [116]. Due to the unstable grinding force, it usually leads to production loss and high rejection rate of products [142], so it is necessary to analyze and suppress the chatter properties from the perspective of grinding force. Although the grinding force is applied to the above

vibration models, the expressions of the grinding force still have obvious average characteristics, and the composition of dynamic components is not considered. Based on this problem, in Guo's model [19,68], the expression of grinding force is established from the perspective of dynamic frequency domain, and applied to the nonlinear analysis of machine tool system. Even so, we should realize that although the theoretical modeling of grinding force has gained rapid attention and development in recent years, the expression of $F(t)$ has not been updated in the dynamics of machine tools, especially rotor systems [289]. In the future, based on the existing grinding force modeling technology, we should further study the influence of machine tool dynamic parameters, micro-morphology of abrasive particles and dynamic errors. This is of great value for improving the finite element meshing technology of machine tool system, rotor rub-impact fault analysis and other applications.

$$\begin{cases} F_x(t) = m_x \ddot{x}(t) + c_x \dot{x}(t) + k_x x(t) \\ F_y(t) = m_y \ddot{y}(t) + c_y \dot{y}(t) + k_y y(t) \end{cases} \quad (10)$$

The main purpose of grinding force in machine tool system dynamics is to provide theoretical basis for the prediction of chatter boundary [24]. Under the interaction of grinding force and regenerative vibration, a closed-loop feedback system is formed, which makes the grinding dynamic result closer to the actual value. As shown in Fig. 21, the stability analysis can be traced back to the characteristics of the grinding force field, and it can be clearly observed from the naked eye that the unstable grinding force will bring a lot of ripples to the surface. Therefore, maintaining the stability of grinding force can prevent unnecessary dynamic displacement and chatter in the contact area. However, the prediction of stability limit has not been fully verified by the above models, and it is necessary to take alternative ways to change dynamic parameters such as stiffness and mode. Moreover, a more complete analytical model needs to be deeply studied in order to fully understand the possible relationship between grinding force and chatter theoretically. We can judge that the research on chatter is still mainly focused on machine tool design, process technology, monitoring system and signal

processing. In the next few years, as the grinding force model becomes more and more complex and accurate, it will provide strategies to solve the chatter problem from the perspective of the nonlinear system of machine tool-tool rest-tool-workpiece.

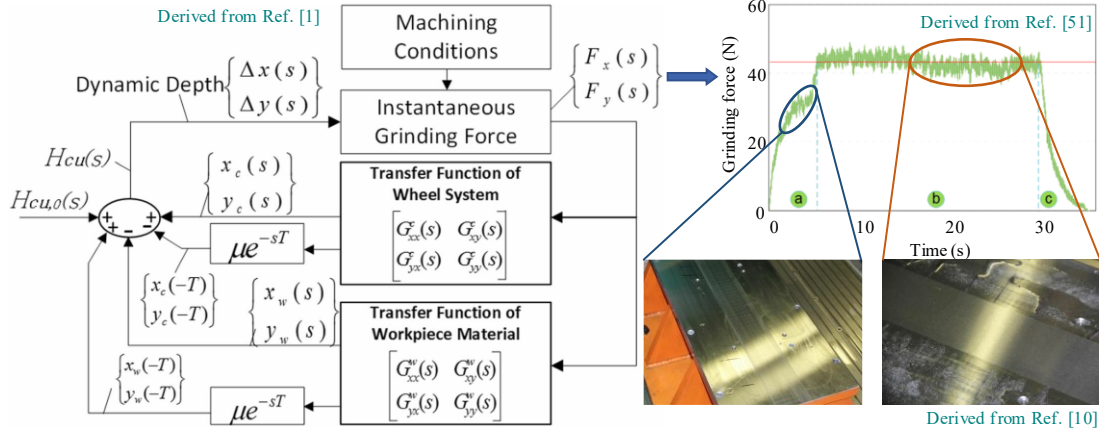


Fig. 20. Close-loop control system of grinding force

5.2 Force-control technique

Unexpected grinding force could lead to unnecessary defects and damage of workpiece and wear of grinding wheel. The deflection and material removal rate of the machine tool can be adjusted accurately by combining the grinding process model with the force control during the grinding process, which can improve the repeatability of the shape and finishing of the resulting parts [155]. Therefore, in order to increase productivity and improve the quality of the ground surface, it is necessary to control the grinding force [32].

Hahn [153] is the first person to propose the idea of controlled-force grinding, but this method is only suitable for short-stroke grinding operation. For the conventional grinding process, the passivation of grinding wheel will also change the grinding force signal constantly. In order to reduce the workload of selecting grinding parameters and maintain the stability of grinding process, many force-control grinding strategies have been proposed, such as feedback control system [199] and adaptive control system [200].

The feedback control system is generally a closed-loop control technology, which can maintain a constant grinding force. The feedback control system of grinding force

is shown in Fig. 21. Excessive machining forces can result in brittle fracture of the machined surface. In contrast, when the feedback control loop is enabled, the grinding force curve becomes relatively flat and better grinding results are obtained [11]. At present, the grinding force controller is usually established according to the relationship between the difference between the grinding detection force and the average cumulative force and the predetermined benchmark, as shown in the following equation. However, this method still has drawbacks. At the initial stage of grinding, due to the fluctuation of signal, it is a difficult problem to accurately obtain the average value of grinding force as an evaluation standard. Moreover, the current force feedback control technology is mainly reflected in the force boundary control. For some ultra-precision grinding [290], it may be a breakthrough technology in the future to monitor and adjust all the force signal.

$$F_m - \frac{\Sigma F_t}{A_t} \geq F_s \quad (11)$$

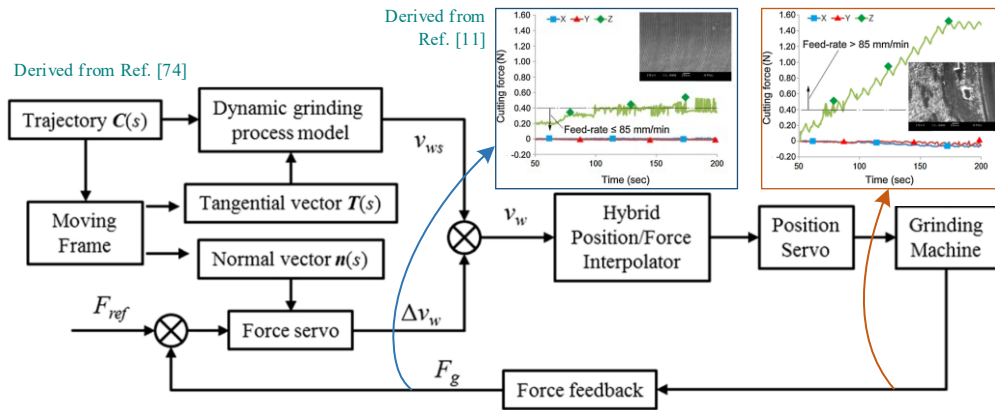


Fig. 21. Feedback control system of grinding force

Although the feedback control strategy can control the grinding force by adjusting the feed rate, the dynamic response of the controller is often required during the grinding process. Since the force-adaptive grinding strategy can make a strong response to any changes in the control variables, and can achieve the necessary process optimization [67], it has attracted the attention of many scholars. Nonlinear adaptive control law can realize the stability of uncertain nonlinear systems [40] and has the

characteristics of fast dynamic response, small overshoot, and high steady-state accuracy [197]. However, its relationship with force signals needs further explanation, and it may be a daunting task to determine reasonable evaluation parameters for materials that are not caused by human beings. The system block diagram is shown in Fig. 26. The difference between the average current and the predetermined current is also used as an effective parameter for the induction grinding force feedback [85]. The working principle of the feedback system is: $I_{avg} = \sum_1^{A_t} I_n / A_t$, $I_{avg} > I_{set} (MFO -4\%)$, $I_{avg} \leq I_{set} (MFO +2\%)$. In the above technology, "vibration assisted mode" is used, which is a very interesting method. In the future, more modes should be considered and applied to the adaptive feedback control system, such as "laser in-situ assisted mode", "electrochemical assisted mode" or "multifunctional coupling mode".

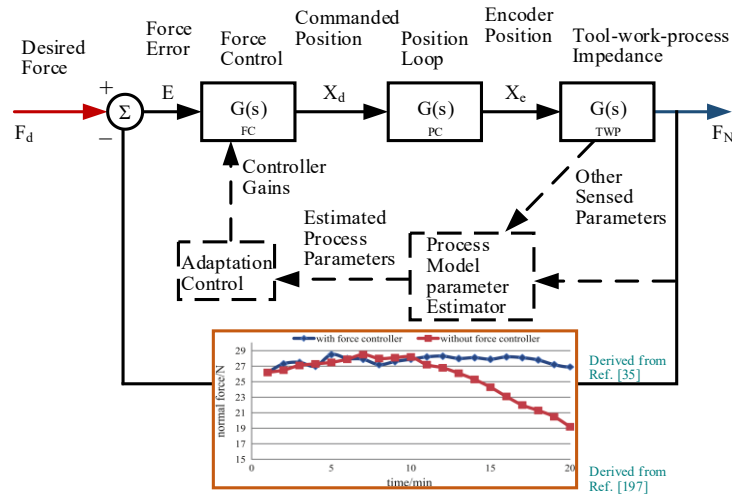


Fig. 22. Adaptive control system of grinding force.

The grinding resistance can be effectively reduced by the above grinding force control method, the stability of grinding process is controlled and the surface finish of workpiece is improved. However, some important parameters need to be considered in future research, such as capacitance shunt of piezoelectric ports.

5.3 Grinding process simulation

As an important parameter to evaluate the grinding performance, grinding force is also widely used in the grinding simulation.

The grinding force directly affects the mechanical energy generated in the grinding

process, and most of the mechanical energy is converted into heat [37]. The heat convection on the workpiece surface in the grinding area is shown in Fig. 23, so the heat flux density curve of the whole grinding contact length can be established by grinding force [93]. However, it should be noted that F_t does not reflect the dynamic action of grinding force. Based on the real-time change of grinding force, it is an important subject to deeply understand the influence of abrasive grain characteristics on micro-scale heat transfer performance.

$$q_l = \frac{F_t v_s}{b \Delta l} R_w \quad (12)$$

where R_w is the heat partition ratio to the workpiece.

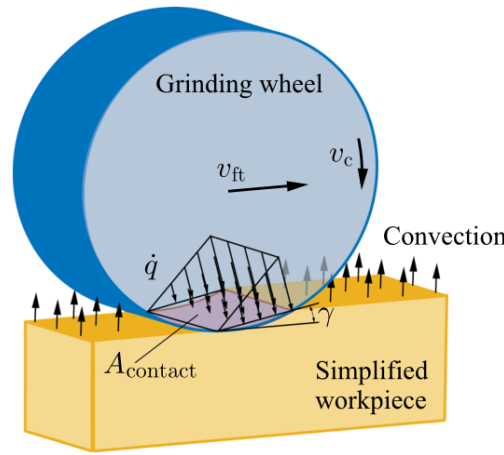


Fig. 23. Heat model for grinding [73].

The same problems also appear in the characterization of specific grinding energy G $\{G = (F_v v_s)/(b a_p v_w)$ [57] $\}$, which is used to evaluate the energy efficiency of grinding process [60]. In addition to the above indexes, grinding force model is also the key to solve the theoretical problems of contact deformation, stress field distribution and surface defects. The local deformation required by force balance can be solved by iterative method [34] and Laplace transfer function [74], thus realizing the control of grinding force on contact deformation. For the stress field distribution, the residual stress distribution over the whole grinding length can be obtained by using the grinding force in the finite element model [93]. The relationship between grinding force, grinding chip morphology and grinding potential energy can be realized by using

molecular dynamics method, which provides a theoretical basis for the analysis of subsurface defects. In addition to the simulation application of grinding force, the grinding force model is also an important index in automatic detection. It is reported that the ripple attenuation rate of abrasive particles can be predicted by the frequency characteristics of grinding force [72]. And the wear condition of the grinding wheel can be monitored by measuring the grinding force, so that the grinding wheel can be repaired or replaced in time [284]. As a kind of random signal, grinding force signal has rich connotation and can reflect the performance of grinding process in real time. How to make good use of the information brought by the grinding force signal, so as to better formulate the grinding process and reduce the grinding cost, this is a problem that needs to be seriously considered.

6 Conclusions

Grinding force modeling is an important method to study the vibration phenomenon, grinding wheel wear and machine tool deformation caused by grinding process, which has been widely concerned by many scholars. Most of the theoretical methods and techniques have been proposed and developed in the past 20-25 years. The macro and micro models of grinding force are classified and summarized, and the mechanism of material removal and wear is considered. From a simple macro grinding force model to a micro grinding force model considering the characteristics of abrasive particles, it aims to explain the dynamic mechanism of the grinding process. The key technologies involved in grinding force model are summarized, such as chatter suppression, force-control technology and other applications. To sum up, we can get conclusions and research directions:

- More and more studies have proved that grinding force modeling is promising. Grinding force modeling can quantitatively describe the dynamic process of relative vibration, which helps to evaluate the dynamic interaction in grinding process.
- Macro grinding force modeling is mainly used for ductile grinding. With the trend

of miniaturization, micromachining and difficult machining, these modeling methods need to be improved to be more suitable for small grinding tools and grinding methods of hard and brittle materials.

- In the past 5-10 years, models related to micro grinding force have been greatly developed. However, all the models put forward so far have made some assumptions, ignoring some time variables that may have great influence on micro grinding force. Micro grinding force model still needs more attention and improvement to solve the complexity and uncertainty brought by dynamic behaviors.
- In the current grinding force model, evaluation indexes such as material removal amount are still the first choice, but there are low efficiency, waste and pollution. Therefore, in the future work, it is necessary to introduce more meaningful indicators of high efficiency and environmental protection.
- The influence of dynamic factors (such as workpiece run-out, deflection, wheel imbalance, eccentricity) on grinding force modeling has been widely analyzed. In the future, more processing factors need to be considered in order to obtain more accurate prediction, such as thermal performance, dynamic stiffness, tool deformation, friction conditions, material flow characteristics. The study of multi factor coupling model is of great significance.
- As an important parameter to judge the grinding quality, the modeling method of grinding force signal has been widely developed and applied. However, the advanced theoretical modeling technology of grinding force has not been applied to the evaluation of grinding process in time (such as chatter suppression, force-control technology and other grinding process simulation). In the future, it is necessary to further study the relationship between key dynamic parameters in grinding force modeling and machine parameters.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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