

Investigation into Engineering Ceramics Grinding Mechanism and the Influential Factors of the Grinding Force

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Abstract

The grinding force is a key parameter in the grinding process, which is closely associated with the grinding mechanism of engineering ceramics, microstructure and properties of ceramic materials, and the selection of grinding parameters. Meanwhile, it is also a key indicator to assess the grindability of a material. The grinding force is a crucial parameter to reflect the grinding process, which is closely related with microstructure and properties of the grounded material, grinding parameters, grinding wheel characteristics and material removal mechanism. In this paper, from the perspective of material removal mechanism in ceramic grinding model and the grinding process of engineering ceramics, the ceramics grinding process was analyzed and the formation of grinding force was explored. With the analysis of characteristics of the grinding force, from the aspect of influential factors of the grinding force, impacts of the performance of ceramic materials, grinding direction, grinding wheel velocity, workpiece velocity, grinding depth, particle size of grinding wheel, grinding wheel wearing, the grinding fluid, the rigidity of machine tool and process system and other factors on the grinding force were analyzed, thus providing further knowledge and development of ceramics grinding.

Keywords: *Engineering ceramic; Grinding, Material removal mechanism; Brittle fracture; Plastic removal; Grinding force; Grinding parameters; Grinding wheel characteristics*

1. Introduction

With the development of science and technology, especially energy and space technology, engineering ceramics have been widely highlighted by the unique molecular composition, superior physical, chemical and mechanical performance, such as high strength, low expansion rate, wear resistance and chemical stability [1-12]. This material has a broad prospect in fields like aerospace, chemistry, military, machinery and electronics and so on. The material of engineering ceramics is formed through high-temperature agglomeration after the molding of the raw material in the form of powder. As a typical hard and brittle material, the engineering ceramics is hard to be processed, which constrains its further application. According the properties and uses, engineering ceramics can be divided into two categories, namely, structural ceramics and functional ceramics. As a structural material, structural ceramics are often used in the manufacture of structural components and parts, thus having high demands of mechanical properties, such as strength, fracture toughness, hardness, modulus of elasticity, wear resistance and high temperature performance. As a functional material, functional ceramics can be mainly made into functional components by the excellent physical and chemical properties of inorganic material, such as electromagnetism, thermal properties, optical properties and biological performance, etc. So far, diamond grinding wheel

is an effective way in the precision machining of engineering ceramics. Grinding wheel squeezes material surface by the high-speed revolution wheel, and generates debris through plastic deformation or brittle fracture and forms a new surface [13-20]. Using multi-blade microfabrication, it supports long-term processing and acquires high precision and accurate geometric dimensions. It is a key modern manufacturing machine for precision machining and ultraprecision machining. However, the grinding mechanism and grinding process of engineering ceramics are different from metal and other materials. The grinding force originates from elastic and plastic deformation after the contact between workpiece and wheel. Chip formation and the friction among abrasive particles, binding agents and the workpiece surface are closely associated with the property and microscopic structure of the grounded material, grinding parameters, grinding wheel characteristics and material removal mechanism. The grinding force is a key factor that influences deformation of the grinding system and generates grinding heat as well as grinding vibration. It directly influences the ultimate surface quality and dimensional accuracy of the workpiece. The grinding force demonstrates the basic features of grinding process. The grinding force is almost related with all grinding parameters and is a key indicator to assess the grinding performance of a material.

Scholars [21-27] have conducted systematically theoretical analysis and experimental research on the grinding force. Deng Chaohui and other scholars from Hunan University explored into the material removal mechanism of ceramics grinding. Lin Bin and other scholars from Tianjin University studied on the ductile regime removal grinding mechanism of ceramic materials. Tian Xinli [28-30]. and others from College of Armoured Force Engineering of PLA applied indentation fracture mechanics to analyze the grinding machinability and surface residual stress of ceramic materials. Wang Changqiong et al conducted detailed experimental study of the grinding force of engineering ceramics in diamond wheel grinding process. The impact of different factors on the grinding force and the grinding effects was analyzed and the empirical equation of the grinding force of ceramics was established. From the empirical equations, it can be known that the grinding force is most greatly influenced by the transverse feed volume of the wheel, followed by the grinding depth of wheel. Reciprocating rubbing speed of the workpiece does not impose significant impact of the grinding force. Meanwhile, ceramic materials are not suitable for the creep-feed and deep-cut high efficiency deep grinding. Yang Hai and other researched on the grinding formation mechanism of the ceramics grinding, and established grinding model of engineering ceramics based on the formation and development of cracks [31-34]. Their study pointed out that transverse crack is a major factor of material damaging, and derived that the relational expression between the grinding force of ceramics grinding and the material removal rate. Yao Chunyan et al [35-37] investigated on the regression analysis of artificial neural network and its application in the forecast of the grinding force. They introduced simple regression and multiple regression analysis methods based on artificial neural networks. With the examples of the sine function and the grinding force equation, they compared these with traditional regression analysis. The experiment demonstrated that regression analysis methods based on artificial neural networks were superior to conventional ones in the aspect of regression accuracy. Kuang-Hua Fuh, Shuh-Bin Wang and others [38-43] applied an improved BP neural network for modeling and predicted the grinding force in creep feed grinding. Their research results showed remarkable convergence, showing a learning error of about 3%. Shandong University [44-46] established a processing performance prediction and processing parameter simulation system of engineering ceramics, and created a processing performance prediction model of engineering ceramics. This prediction model not only applies for processing parameters in stable and instable processing. The model had a rate of

prediction errors of 8.6% in engineering ceramics performance, and technical parameters selected by the optimization model were used in the technical verification, showing that the overall performance of engineering ceramics processing was improved. Chisato Tsutsumi and I.Inasaki and others [47-56] probed into high efficiency deep grinding mechanism of ceramic materials. S.Malkin and others analyzed the grinding force from the grinding of ceramic materials. B.R.Lawn and others [57-66] established a regional indentation fracture model for ceramic materials. Many scholars started to highlight the ceramics grinding, showing its importance in the field of the machining and the processing.

2. Ceramic Grinding Model

The engineering ceramics are chemical compounds comprising metal and non-metal atoms bonded in the forms of ionic bond or a covalent bond, having excellent hardness and chemical stability but low toughness. It is a special hard and brittle material. The fracture removal runs through the entire process, especially in the early stage. There are two kinds of fractures in engineering ceramics grinding process: one happens in the early stage of fracture. As the workpiece surface is rough while the wheel surface has significant punches with sharp abrasive particles, the fracture will happen from colliding (Figure 1(a)); the second happens in the middle and late stage of grinding, when a platform-shaped contact appears on the abrasive particles and workpiece surface, can be shown in Figure 1(b). The model variation is shown in Figure 1.

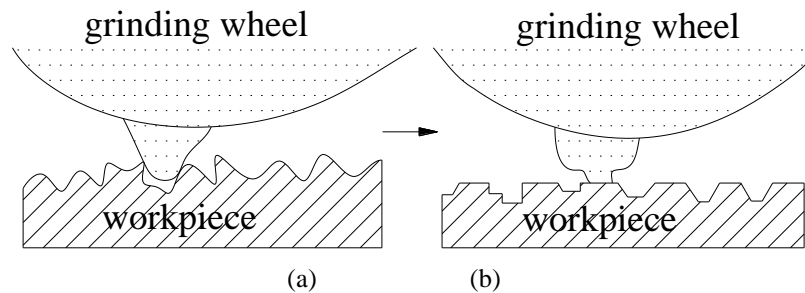


Figure 1. The fracture model

As for fracture removal in the middle and late grinding process, it should give the consideration to the model of indentation fracture mechanics [67-70]. The modeling of indentation fracture mechanics was based on the approximate small-range indentation on abrasive particles and workpiece surface in ceramics grinding. It generally includes fixed and mobile indenter models. Figure 2 shows a fixed indenter model. Right under the indenter, there is a small plastic deformation area. From this area, two major fracture systems are formed, namely, radial crack and transverse crack. Generally, radial crack will reduce the material strength, even microscopic damages on the surface or sub-surface. Meanwhile, transverse crack mainly leads to the removal of materials and influences the surface roughness after the processing.

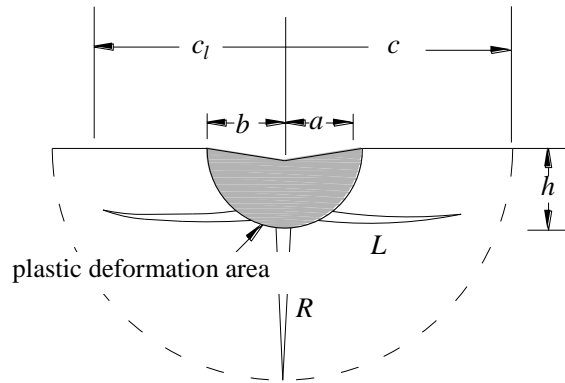


Figure 2. The impression fracture mechanics model

3. Engineering Ceramics Grinding Mechanism

The material removal mechanisms in the engineering ceramics grinding process mainly include brittle fracture, pulverized removal and ductile regime removal.

3.1 Brittle fracture removal mechanism

The brittle fracture removal in ceramics grinding can be fulfilled by the following ways: particle removal, material peeling, brittle fracture, micro-cracking of particle boundary, etc. In particle removal, the material removal is achieved by the peeling of an entire particle from the workpiece surface, accompanied by peeling. This is a crucial removal mechanism in the grinding process of ceramic materials. The material removal is realized in the form of locally peeled blocks due to transverse and radial cracks generated from grinding process. The fracture expansion with this way greatly reduces the mechanical strength of the workpiece. In addition to transverse crack, brittle fracture removal is also influenced by fracture. The front and lower fracture of abrasive particles is generated by various damages from circumferential stress and shear stress distribution.

3.2 Pulverized removal mechanism

The pulverized removal refers to the possible pulverization of materials when no fragmentation and fracture mechanism occur in a grinding depth at the sub-micron level. The pulverization mechanism is a result of particle boundary or intergranular micro-crushing generated by local shear stress field surrounded by hydrostatic pressure from abrasive particles in the grinding process. Due to pulverized removal, ceramic particles are further crushed in finer crystals and form the pulverization area. The research discovers that this arises from micro-grinding in the complex stress state so that the grinded materials are more loosely bonded relative to main parts of the material. To apply hydrostatic pressure stress at the contact between abrasive particles and the workpiece in the contact zone, the grinded parts can be re-compacted. When the depth of cutting is smaller than the critical value, ceramic materials only have grinding rather than macroscopic fracture. In single-blade grinding, the material has rolled horizontally and piles. The smaller depth of cutting is, the greater the stockpile coefficient is.

3.3 Ductile regime removal mechanism

Ductile regime removal is similar to the chip formation in the metal grinding, involving rubbing, ploughing and chip formation processes of abrasive particles. The material is removed by shear deformation. In certain processing conditions, brittle materials are able to be removed by plastic flow. The model of indentation fracture mechanics predicts the critical load of transverse crack. Under processing conditions lower than the critical load, the removal will focus on ductile regime removal. T.GBifano and others reached the same conclusion from the perspective of energy.

4. Mechanism and Characteristics of the Grinding Force

4.1 Generation of the grinding force

Grinding is a complex process. People make attempts to use a basic parameter to characterize the grinding characteristics, and to describe the impact of grinding conditions on grinding process and the output physical volumes. In this way, the grinding mechanism can be analyzed. Under certain grinding conditions, when the wheel interferes with the workpiece, the abrasive particles are pressed in the workpiece surface, forming normal force. The size of normal force and material features decide the removal ways of the workpiece: ductile regime removal mechanism or brittle fracture removal. The removal approach identifies the reasons to form the grinding force and to influence the size of the grinding force. Abrasive particles cut the material in the range of interfering and form a tangential force, which is influenced by the material removal approach. In addition, abrasive particles generate substantial rubbing and ploughing reactions on the workpiece surface, which are components of the tangential force, even the most important part. Hence, it includes the force generated from the process that abrasive particles remove the workpiece and the friction of rubbing and ploughing on workpiece surface. During the grinding process, when abrasive particles generate rubbing effects, abrasive particles are influenced by material deformation and friction; when abrasive particles generate cutting action, the separated debris generate resistance to deformation to abrasive particles due to intensive deformation. The rubbing between machined surface and debris on the abrasive particles and the workpiece also generates friction. Binding agents in the contact zone also rub with the workpiece. Hence, the grinding force mainly comprises of the cutting force and friction.

Most of empirical equations of the grinding force are expressed by exponential functions of grinding parameters as shown in Equation (1). Different empirical equations have slightly different indicator values of parameters.

$$F_t = C_F v_w^\alpha v_a^\beta a_p^\gamma \quad (1)$$

Where C_F is a constant of ratio, v_w is wheel velocity, v_a is feeding velocity and a_p is depth of cutting.

Equations of the grinding force can mainly be divided into four categories: first, the equations of the grinding force established based on Mainz analytical method; Second, empirical equations of the grinding force based on experimental data; Third, the universal equations of the grinding force based on Mainz analytical method and experimentation research; Fourth, modeling based on artificial neural network.

4.2 Characteristics of the grinding force of engineering ceramics

With the grinding wheel velocity $v_s=14.06\text{m/s}$, the swing velocity $v_w=1032\text{mm/min}$, grinding depth $a_p=30\mu\text{m}$, the grinding force in the grinding of Si_3N_4 -based and Al_2O_3 -based ceramics is shown in Figure 3, which present the following characteristics.

4.2.1 The grinding force F_n , F_t

It is generally considered that ceramics have a high hardness. The normal grinding force and the tangible grinding force should be large. But our experiment showed that the normal grinding force of ceramics was not very large and the tangible grinding force was small, as shown in Figure 3. Among them, the unit normal grinding force of Si_3N_4 -based ceramics with larger fracture toughness was 8.33N/mm and the unit normal grinding force of Al_2O_3 -based ceramics with larger hardness and poor tenacity was 1.73N/mm , indicating that the size of the normal grinding force of engineering ceramics is not only related with the hardness of grinded materials but also dependent on the fracture toughness and grinding characteristics of the grounded material.

4.2.2 The grinding force ratio F_n/F_t

The grinding force and the grinding force ratio are two important indicators to evaluate the grindability of the material. Compared with the metal grinding process, a remarkable characteristic of the grinding force of ceramics is the large grinding force ratio, that is, the normal grinding force is significantly larger than the tangible grinding force, indicating that the diamond grinding material is hard to cut into the surface of ceramics. It also verifies that during the grinding, ceramics mainly realizes the goal of removal by brittle fracture with a very small shearing effect. It can be seen from Fig.3 that the tangible grinding force of Si_3N_4 -based ceramics and Al_2O_3 -based ceramics is very small, respectively as 0.67N/mm and 0.5N/mm . Hence, the grinding force ratio of two ceramics materials is large. Among them, the grinding force ratio of Si_3N_4 -based ceramics is relatively large, reaching 12.5. This is because Si_3N_4 -based ceramics grinding material generates a phenomenon similar to indentation hardening under the effect of abrasive particles. the grinding force ratio of Al_2O_3 -based ceramics is relatively small, reaching 3.45. The large grinding force ratio of ceramics is common in ceramics grinding, indicating that the ceramics grinding process mainly involves the friction ploughing with the indentation feature and the chip deformation rarely happens.

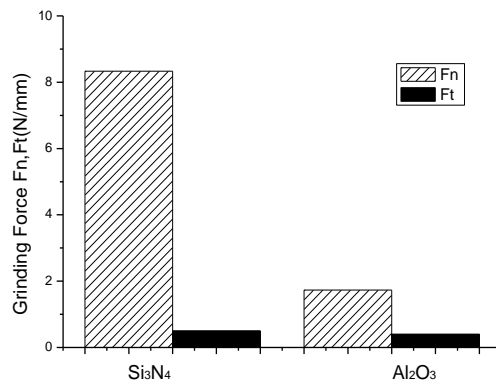


Figure 3. The comparison of specific grinding force of Engineering Ceramics

4.2.3 Specific Grinding Energy μ

The specific grinding energy is a key concept in grinding theories, which is closely related to the tangible grinding force. The value can be calculated with the following equation:

$$u = \frac{F_t V_s}{V_w a_a b_s} \quad (2)$$

a_a -actual depth F_t -the tangible grinding force b_s -grinding width V_s -grinding wheel velocity V_w - workpiece velocity.

In the engineering ceramics grinding, the grinding energy mainly includes two parts: one is shear energy from plastic deformation of the workpiece. Two is the frictional work between abrasive particles and debris in the formation of debris. The grinding energy needed by the rubbing and ploughing changes with the variation of grinding parameters while chip formation can basically remain stable [71-73]. According to Eq. (2), the specific grinding energy of ceramics can be calculated. For example, the specific energy of Si_3N_4 is $77.85\text{J}/\text{mm}^3$ and that of Al_2O_3 is $136\text{J}/\text{mm}^3$. It can be seen that the specific grinding energy of Si_3N_4 -based ceramics and Al_2O_3 -based ceramics is not large.

5. Influential Factors of the Grinding Force

5.1 Impact of the performance of ceramic materials on the grinding force

The research of Dr. Wang Xibin presented that under the same grinding conditions, different ceramic materials will have different grinding forces, force ratios and specific energies. This is because the plastic shearing grinding process of metal materials is different from the brittle fracture grinding process of hard and brittle material. The grinding process of structural ceramics can be divided into the process focusing on microscopic plastic deformation and the process focusing on brittle shedding. It is considered that the characteristic type of the grinding process depends on the micro-hardness of a material and the relative size of critical grinding thickness of abrasive particles a_{gc} determined by fracture toughness and the maximum grinding thickness of abrasive particles a_{gm} determined by grinding parameters. When $a_{gc} > a_{gm}$, the grinding process mainly concentrates on microscopic plastic deformation. When $a_{gc} < a_{gm}$, the grinding process mainly concentrates on brittle shedding. After the identification of grinding parameters, the properties of a material will determine the characteristics of the grinding process. It is generally acknowledged that under the same grinding conditions, different ceramic materials have different grinding forces and the grinding force ratios. The higher the strength of ceramic materials has, the larger the fracture toughness is. With smaller particle size, the microstructure will have better compactness and larger normal grinding force. However, the tangential force is not sensitive to the particle size so that the changes of the tangential force are insignificant and the force ratio is increasing.

5.2 The impact of grinding direction on the grinding force

In the plane grinding process, there are two modes, namely, down grinding and up grinding. Through the literature review, it was found that studies on down grinding and up grinding are limited but some conclusions have been reached. Among them, Lin Zhengbai and others from Fuzhou University conducted experiments and summed up the following conclusions [75-77].

- (1) The grinding force of down grinding is always larger than up grinding. Generally speaking, for the tangible grinding force F_t , down grinding is larger than up grinding by 8% on average and this gap can be up to 20%. For the normal grinding force F_n , down grinding is larger than up grinding by 7% on average and this gap can also be up to 20%.
- (2) The temperature in the grinding zone during down grinding is higher than up grinding. Generally speaking, the temperature in the grinding zone during down grinding is higher than up grinding by 13% on average and this gap can even reach 30%.
- (3) Down grinding is very different from up grinding from the entire chip formation mechanism. The grinding process of up grinding generally goes through rubbing, ploughing and cutting. However, these three processes are not necessarily experienced in down grinding. Down grinding generally experiences ploughing and cutting and some even start the cutting once abrasive particles enter the grinding zone.
- (4) In order to ensure a premium processing quality, up grinding can be used for the advanced plane grinding. Through experiments, it was found that the surface roughness of up grinding was significantly reduced. During up grinding, the grinding force was larger than down grinding by about 13.87%, indicating that up grinding presents better grinding effects.

5.3 Impact of peripheral velocity of wheel on the grinding force

In 2000, K. W. Lee [78] found through experiments that with the increase of peripheral velocity of wheel, the normal grinding force and the tangible grinding force were reduced but with a mild tendency. By analyzing the average grinding force at different revolving speeds, they identified whether peripheral velocity of wheel influences the grinding force, as shown in Figure 4.

Experiment results show that in the processing, with the increase of peripheral velocity of wheel, the grinding force was gradually reduced. It reduces the actual cutting thickness of abrasive particles as well as the grinding force of abrasive particles. On the other hand, it generates high temperature and improves the fracture toughness of ceramic materials and plastic deformation. Hence, the proper increase of peripheral velocity of wheel can enhance the self sharpness of the grinding wheel and acquire a high rate of removal. Meanwhile, it can enhance plastic deformation and improve the surface quality of the workpiece. However, an overly large peripheral velocity of wheel will enlarge the thermal wear of the wheel and the rate of processing error, leading to the shedding of bonded particles of the wheel and the vibration of the grinding system; an overly small peripheral velocity of wheel increases the depth of cutting of each cutting blade, leading to the fragmentation and shedding of abrasive particles.

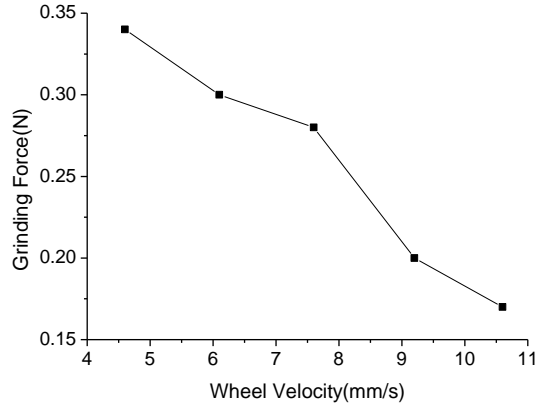


Figure 4. The grinding force vs wheel velocity

5.4 Impact of workpiece velocity on the grinding force

With the increase of feeding velocity of the operating platform, the normal grinding force and the tangible grinding force were increased correspondingly. This conclusion was also verified by I.Inasaki and K.Li through experiments. I.Inasaki and K.Li and other scholars [79] conducted Al_2O_3 and Si_3N_4 grinding experiments, and concluded that with the increase of workpiece velocity, the normal grinding force and the tangible grinding force were increased but the increase tendency was gradually slowed down. With a fairly large workpiece velocity, the total increase range of the grinding force was small, and the force ratio and specific grinding energy were reduced but the rigidity of specific grinding. In the processing of Al_2O_3 and Si_3N_4 under certain conditions, as workpiece velocity increased, the grinding force was also significant enlarged. When the workpiece velocity was continuously increased, the grinding force was reduced as the actual cutting thickness of abrasive particles and the brittle shedding was increased, as shown in Figure 5.

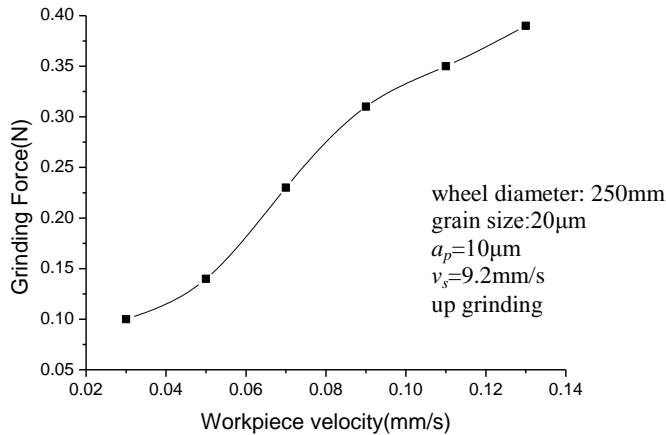


Figure 5. The grinding force vs workpiece velocity

5.5 Impact of grinding depth a_p on the grinding force

Studies showed that the normal grinding force has the following relationship with the actual depth of grinding wheel:

$$F_n = F_0 + C_a a_a \quad (3)$$

Where C_a is a constant decided by the grinding condition. F_0 is the value when a_a is zero. a_a is the actual depth.

From equation (3), it can be seen that when increasing the grinding depth, the grinding force and force ratio were enlarged. When the grinding depth was very small, as ceramics had micro plastic deformation, the grinding force was very small. When increasing grinding depth, the effective abrasive particles that participate in the grinding were increased. Meanwhile, the length of contact arc was increased and the grinding force would present the peripheral increase. When reaching the critical depth of cutting and brittle fracture, the grinding force declined to a certain degree and fluctuated. This indicated that the removal of most ceramic materials originated from brittle fracture, while the grinding force was increased with plastic deformation. Therefore, to obtain high precision grinding parts, we should choose a smaller depth of cutting so that it can be smaller than the critical depth of cutting and ceramics can be removed mainly by plastic deformation.

5.6 Impact of particle size of grinding wheel on the grinding force

As the grinding wheel is directly involved in grinding, the particle size of the grinding wheel and the bonding type has a significant impact on the grinding process. Experiments of K.W.Lee and others verified that under the same grinding conditions, with the increase of the size of abrasive particles, the density of the grinding blade and the normal grinding force was decreased. Meanwhile, the surface roughness of the grinding workpiece was enlarged. Based on the analysis of the average grinding force with different particle sizes in the processing, it was analyzed that whether the particle size of grinding wheel influences the grinding force. CrO_2 , Si_3N_4 and Al_2O_3 were used in the experiments, as shown in Figure 6.

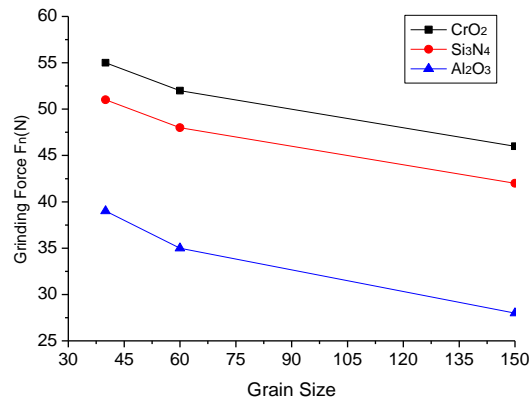


Figure 6. The grinding force vs grain size

Through the analysis of experiment results, it was found that when the particle size was increased, the grinding force was reduced. It can be concluded that the smaller the particle size of grinding wheel, the lower the grinding efficiency and the larger the grinding force in grinding process. Bi Zhang and other [80] pointed out that with the same size of abrasive particles and other conditions, the diamond grinding wheel using metal bonding presented smaller grinding force and higher rate of removal relative to the diamond grinding wheel using ceramics bonding.

5.7 Impact of grinding wheel wearing on the grinding force

Studies outside China presented that in the initial stage of grinding wheel wearing, abrasive particles are difficult to cut into the surface of ceramics, showing remarkable rubbing effects on abrasive particles and the workpiece surface. This led to the sharp increase of the grinding force with the wheel wearing. As the normal grinding force ratio and the tangible grinding force was greatly increased, the force ratio was also enlarged. Meanwhile, as more materials are removed by plastic flow, the specific grinding energy was enlarged when the mechanical strength of the grinding parts should be obviously enhanced. However, experiments showed that the mechanical strength of the grinding parts was reduced, which was mainly attributed to the enlarged unit normal grinding force. In the normal wearing, due to normal friction, wearing and self-sharpening effect of the wheel, the grinding force, force ratio and specific energy could maintain an approximate constant, and the grinding wheel wearing was slow, as shown in Figure 7. Based on this, Wang Changqiong and other scholars proposed that when using the diamond grinding wheel for the engineering ceramics grinding, people need not to adjust the wheel frequently. However, according to Shi Xingkuan and others, during advanced grinding on the smooth surface of hard and brittle material, it is crucial to adjust diamond grinding wheel. The Japanese scholar Chisato Tsutsumi and others also verified that the electrochemistry in-process dressing generated a much smaller grinding force than normal grinding. Besides, in the entire grinding process, the grinding force basically remained the same, which significantly extended the grinding time.

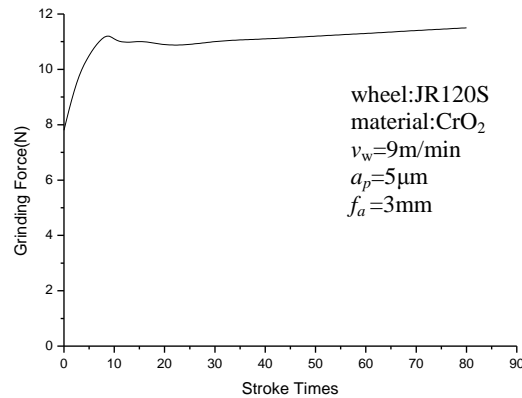


Figure 7. Variation of the grinding force as the stroke times

5.8 Impact of the grinding fluid on the grinding force

In the grinding, the proper selection of the grinding fluid helps reduce the grinding temperature and the grinding force while extending the service life of the grinding wheel. Guo Cheng and others, with grinding experiments of metal ceramics, proved that different kinds of grinding fluids influenced the final grinding force. Among them, the grinding fluid with stronger infiltration capacity generates smaller grinding force. The role of the grinding fluid includes reducing the grinding force, preventing thermal cracks and cleaning. Shi Ping and others believed that the grinding of high-performance ceramic materials needed coolant, for its role in reducing the grinding force, preventing thermal cracks and cleaning. However, Ke Hongfa believed that when conducting semi - ductile regime grinding of ceramics, due to poor thermal conductivity of ceramics, coolant will rapidly cool the material, enhancing the brittleness of ceramics and generating micro-cracks on the surface of the material. He pointed out that to acquire premium finished surface, coolant should not be used so that ceramics can

be removed by plastic deformation as much as possible. Therefore, the selection of the grinding fluid should abide by the specific processing requirements.

5.9 Impact of rigidity of machine tools and the process system on the grinding force

In the grinding, the rigidity and precision of machine tools and process systems will influence the size of the grinding force and its variation. When the rigidity is poor, the grinding force will have a longer initial rising. To a certain degree, the increase of grinding force tends to give rise to self-excited vibration so that the grinding force generates greater volatility and instability, followed by the sharp rise of the grinding force. Low precision of machine tools leads to uneven allowance during grinding as well as the volatility of the grinding force.

During the ceramics grinding, a large normal grinding force acts on the normal direction of the workpiece surface, and the grinding process system produces a large elastic deformation, which will seriously affect the machining accuracy. To solve this problem, the Japanese scholar I.Inasaki introduced the concept of “rigidity of specific grinding”, that is, the normal grinding force F_n/a_a at the unit depth of cutting, to interpret the impact of the normal grinding force on machining errors. a_a (one-stroke grinding) can be calculated as follows:

$$\frac{a_a}{a_p} = \frac{1}{1 + b_s k_w / k_s} \quad (4)$$

a_a -actual depth, a_p -nominal depth of cutting, k_s -rigidity of machine tools, k_w -specific grinding rigidity.

As can be seen from Eq.(4), the larger the specific grinding rigidity is, the smaller the actual depth is. This also increases the rate of machining errors.

6. Current & Future Developments

Because of the excellent features of engineering ceramics, such as wear resistance, high hardness and corrosion resistance, it has been more and more highlighted. Diamond grinding wheel is commonly used in the machining of engineering ceramics. The grinding force is a major parameter in grinding process, which is closely related with the grinding mechanism of engineering ceramics, fiber structure and performance of ceramic materials as well as the selection of grinding parameters. It is also a key indicator to evaluate the grindability of a material. Substantial experiments are needed to motivate the research on grinding force and to obtain a more precise model, which can facilitate the calculation. The following aspects will be studied in the future:

- (1) There are a wide range of engineering ceramic materials, showing different grinding performance and formation mechanisms. The chemical composition of different ceramic materials, composition ratio and the influence rule of its mechanical properties on the grinding force of ceramics should be studied to further enrich and develop theories of ceramics grinding and better guide the practices.
- (2) The research on real-time monitoring and control technology of grinding characteristic parameters needs to be further strengthened. Currently, studies on the dynamic grinding force in ceramics grinding are rarely seen, which influence and constraint on the studies of the grinding force and other parameters to a certain extent.
- (3) The scope and areas of research needs to be further expanded. Currently, China's studies on engineering ceramic grinding mainly focus on the ceramic surface quality, showing the deficiency of studies on edge quality of workpiece. Studies on this area will further enrich and

develop theories of efficient and advanced abrasive grinding of engineering ceramics, and improve the performance of engineering ceramic parts.

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Conflict of Interests

The authors hereby confirm that no conflict of interest exists for this article.

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