Application and Development of High-efficiency Abrasive Process

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Abstract

Abrasive machining is a widely employed finishing process for different materials such as metals, ceramics, glass, rocks, etc to achieve close tolerances and good dimensional accuracy and surface integrity. High efficiency abrasive machining is one of the important techniques of advanced manufacture. Combined with raw and finishing machining, it can attain high material removal rate like turning, milling and planning. The difficult-to-grinding materials can also be ground by means of this method with high performance. In the present paper, development status and latest progresses on high efficiency abrasive machining technologies relate to high speed and super-high speed grinding, quick point-grinding, high efficiency deep-cut grinding, creep feed deep grinding, heavy-duty snagging and abrasive belt grinding were summarized. The efficiency and parameters range of these abrasive machining processes were compared. The key technologies of high efficiency abrasive machining, including grinding wheel, spindle and bearing, grinder, coolant supplying, installation and orientation of wheel and workpiece and safety defended, as well as intelligent monitor and NC grinding were investigated. It is concluded that high efficiency abrasive machining is a promising technology in the future.

Keywords: *high efficiency abrasive machining, super high speed grinding, high efficiency deep-cut grinding, abrasive belt grinding*

1. Introduction

Abrasive Process is a designation for the material removing process with hard mineral (abrasive) grains being used as the cutting tool. The grinding technique, which adopts abrasive wheel or belt to remove materials, is the most widely applied. In addition, abrasive process also involves various techniques such as Honing, Lapping, Polishing and Abrasive Jet Machining [1-6]. Compared with other techniques, abrasive process has the following advantages: (1).Various high-hardness materials can be machined, especially hard and brittle materials such as optical glass, ceramics and semiconducting materials; (2).As an important approach to precision finishing and ultra-precision machining, it can easily produce surfaces with high precision and low roughness values; (3).With high technical adaptability, it is available for various kinds of precision machining on various materials and surfaces, and is widely applied in various industries such as mechanical manufacturing, light industry, construction and refractory; (4).It has become a technique is characterized by a combination of high precision and high efficiency, an integration of rough machining, semi-finishing and finishing, semi-permanent tools and stable process. It has been increasingly applied in the mass production in which high quality stability is required [7-12].

Presently, grinders have taken up over 25% of total metal cutting machines in industrial countries. The grinder quantity in China in 1998 also accounted for around 13% of the total machine quantity.

With the increasing requirements of modern industrial technology and high-performance technological products in respect of part precision, surface integrity, machining efficiency and batch-quality stability, grinding has played a more and more important role. It becomes an important part of advanced machining technology and equipment, and is a research frontier in manufacturing science.

Generally, the wheel velocity between 30 and 35m/s is defined as conventional grinding; The wheel speed exceeding 45 to 50m/s is defined as high speed grinding; The wheel speed between 150 and 180m/s or higher is defined as Super-high Speed Grinding.

The factors affecting grinding are complex. As previous approaches for process control largely depended on workers' skills, the process exhibited poor stability and reproducibility, and grinding was known as a deep dark mystery. With deepened research work as well as the application of computer technology, information technology and automation technology, such techniques as database, computer and artificial intelligence began to be employed to evaluate, predict, simulate, optimize and control the grinding process, so as to improve the grinding process in respect of numerical control (NC), automation, intelligence and virtualization, and to make them automatically-controlled, stable and green techniques suitable for high-efficiency batched machining. As important foundation for grinding technique, those techniques concerning grinders, abrasive and abrasive tools were also improved greatly.

The specific material removal rate in conventional grinding is less than $10mm^3/(mm \cdot s)$. It has long been a pursuit in academe and engineering field to improve grinding efficiency. There are three approaches: (1). adopting high-speed, super-high speed or wide-wheel grinding to increase the amount of active abrasive per unit time; (2). increasing cutting depth so as to increase the length of grinding debris; (3). adopting powerful grinding to increase the mean cross-sectional area of grinding debris. Any grinding techniques adopting single or multiple methods mentioned above to improve specific material removal rate in comparison with conventional grinding can be called as high-efficiency grinding techniques. Among them, the development of high-speed/super-high speed grinding, creep-feed deep-cutting grinding, high-efficiency deep-cutting grinding, belt grinding and heavy-duty snagging has drawn most of the attentions.

High-efficiency grinding technique and relevant equipment represent the development trend of machining technology, and are hot spots and frontiers in the basic and application research of machining science.

2. High-speed/super-high Speed Grinding

2.1. Development of high-speed/super-high Speed Grinding

High-speed grinding has been developed for a long time. With deepened research and the application of Cubic boron nitride (CBN) as well as improved grinder manufacturing, high-speed/super-high speed grinding techniques have attracted extensive attentions once more since 1990s. The grinding speed of 150 to 250m/s for industrial practice has been achieved in Germany, U.S., Japan and Switzerland, etc.; the lab grinding speed has reached 500m/s, and a super-high speed grinding stage has begun.

Perfectly combining excellence and high efficiency, super-high speed grinding represents a revolutionary process change. It was praised as the peak of modern grinding techniques. In Japan, super-high speed machining was ranked among five modern manufacturing technologies. In an annual meeting of CIRP, super-high speed grinding technique was formally designated as one of the research directions in the 21st century. It has become the most attractive technique in the grinding field.

2.2. Characteristics of high-speed/super-high Speed Grinding Technique

When the material removal rate is fixed, the increase in grinding wheel's rotation speed causes the active abrasive amount per unit time to increase greatly, and the cutting thickness of each abrasive grain is thinned if the feed rate is fixed. Besides, material removal in super-high speed grinding is also accompanied by a process of heat-insulating shock-induced chip formation with extremely high strain rate [13]. Therefore, high-speed/super-high speed grinding has the following characteristics: (1).High production efficiency. The material removal rate is multiplied and can reach as much as 2000mm^3/(mm·s)[14]; (2).It improves the dynamic wearability of grains and increases the service life of abrasive wheel, being favorable to grinding automation. The service life of grinding wheel at the speed of 200m/s is twice that at 80m/s when the abrasive force is fixed; the service life of abrasive wheel at 200m/s is 7.8 times of that at 80m/s when the grinding efficiency is fixed [15]; (3).The grain cutting thickness decreases, the height of surface plastic-upheaval decreases, and the value of surface roughness decreases. The cutting debris is formed under extremely high strain rate and insulated cutting state, and the material removing mechanism changes. Thus, it can achieve high-performance machining on brittle materials and materials difficult to machine; (4).Low abrasive force and high machining precision. At the same cutting depth, the abrasive force at the grinding speed of 250m/s is reduced by nearly one half in comparison with that at 180m/s; (5).The amount of grinding heat transferred into workpieces is reduced, which causes the grinding temperature at the workpiece surface to decrease [16-20]. The layer under denatured force and high temperature is thinned, and the surface integrity improves. With CBN abrasive wheel to grind steel parts at 200m/s, the layer with surface residual stress has the depth less than 10μm [21]; (6).The excellent properties of superhard abrasive, such as high hardness and high wearability, can be fully exhibited, and high-temperature brazing-metal bonded wheel is presently a novel abrasive wheel for super-high speed grinding; (7)It is a latest grinding technique capable of achieving high efficiency and high precision simultaneously as well as performing machining on various materials and shapes.

2.3. Key Technologies in high-speed/super-high Speed Grinding

2.3.1. High-speed/super-high Speed Superhard Abrasive Wheel Technique: The super-high speed wheel is made of high-strength matrix, and the abrasive layer is mostly CBN wheel made of resin bond (less than 150m/s) and ceramic bond (200m/s) or with single-layer plating (above 250m/s).

2.3.2. Grinder Spindle Technology: Grinder spindle was equiped with large power, high dynamic precision, high damping, high vibration-resistance and heat stability spindle system. High-speed/super-high speed grinder requires its spindle system to have large power, high dynamic precision, high damping, high vibration-resistance and heat stability. With high feed rate and motion acceleration, the machine can achieve high-level automation and reliable grinding process. For spindle bearing, various types can be adopted, such as ceramic rolling bearing, magnetic bearing, aerostatic bearing and hydraulic dynamic-static bearing. Currently, motorized spindle with ceramic ball bearing is the dominant one adopted in foreign countries.

2.3.3. Grinding Fluid and Relevant Supply Techniques: The barrier of high-speed/super-high speed grinding gas-flow blocks grinding fluid's entrance in the grinding zone, so it is of extreme importance of adopting proper grinding-fluid injection method. Under high-speed/super-high speed grinding conditions, enough jetting momentum is required for grinding fluid in cooling and debris-clearing, and grinding-fluid filtering system with high filtering precision and high efficiency must be employed[22].

2.3.4. Techniques Concerning Installation, Positioning and Safety Protection of Abrasive Wheel and Workpieces: High-speed/super-high speed grinding wheel has great kinetic energy, so semi-closed or closed wheel protection shield with high strength must be provided. It is preferable of covering cushioning material in the shield so as to reduce the secondary ejection of wheel fragments.

2.3.5. Grinding Status Monitor and Numerical Control Technique: Grinding status monitor and numerical control techniques concerning wheel abrasion and disrepair, and the size precision, shape precision, position precision and surface quality of workpieces, etc. was the most key technologies in high-speed/super-high speed grinding. Wheel fragmentation emerges frequently due to the extremely high circumferential velocity of abrasive wheel. Monitoring of wheel fragmentation and abrasion status is the key technology to grinding process security as well as the assurance of the machining quality and part surface integrity. Besides, the tool-setting precision of abrasive wheel against workpieces as well as freeing wheel affects the precision of workpiece size and the dressing quality of abrasive wheel. The monitoring technology concerning wheel abrasion and disrepair, the on-line monitoring technology on the size precision, shape precision, position precision and machined-surface quality of workpieces, and highly-precise, highly-reliable and highly-practical testing technology and numerical control technology are absolutely necessary and key technologies for high-speed/super-high speed grinding.

2.4. Key Technologies in high-speed/super-high Speed Grinding

2.4.1. High Efficiency Deep Grinding (HEDG): HEDG is a high-speed, high-efficiency grinding technique integrating super-high wheel rotation speed, fast feed and large cut depth. It was primarily developed in Germany in 1980s, and deep-cutting grinders with the super-high speed of 200 to 300m/s were developed on the basis of CBN abrasive wheel. In high-efficiency deep-cutting grinding, the cutting depth is 0.1 to 30mm, the workpiece velocity is 0.5 to 10m/min, and the wheel velocity is 80 to 200m/s[23,24]. High metal removal rate and high surface quality can be obtained with it. The surface roughness of workpieces approaches that in conventional grinding, and the metal removal rate is 100 to 1000 times higher than that in conventional grinding (see Table 1). German FD613 grinder can reach the feed rate of 3000mm/min when grinding with CBN, a 10mm-wide and 30mm-deep rotor slot at 150m/s wheel velocity[25]. In U.S., the dominant development type is multi-axis CNC high-efficiency deep-grinding machine, and the surface quality of the hardened steel obtained through high-efficiency deep grinding using CBN formed abrasive wheel can match that of conventional grinders.

Table 1. Conventional Grinding and High Efficiency Abrasive Machining Parameters and Efficiency Compared Table

Parameters	General grinding	High speed grinding	Creep feed grinding	High efficiency deep grinding	Abrasive belt grinding
Cut depth a_p(mm)	0.001~0.05	0.003~0.05	0.1~30	0.1~30	0.01~0.1
Workpiece velocity v_w(m/min)	1~30	1~10	0.05~0.5	0.5~10	0.02~0.3
Wheel velocity vs(m/s)	20~60	100~200	20~60	80~200	12~30
Specific grinding energy Z_W(mm^3/mm. s)	0.1~10	0.1~60	0.1~10	50~2000	50~200

2.4.2. Super-high Speed Cylindrical Grinding: In CNC super-high speed cylindrical grinding, CBN wheel is used to perform super-high speed, high-efficiency, high-precision grinding on the cylindrical rotary surfaces of parts such as stepped shafts and crankshafts, with the wheel cylindrical velocity of 150 to 200m/s. Such a technique has been successfully applied in automobile industry. For example, a ductile-iron camshaft with the grinding depth of 5mm from a CNC super-high speed cylindrical grinder (GCH63B, Toyota Industrial Machinery OMIC) produced in Japan achieves the special removal rate ZW as much as 174mm3/mm·s, the wheel grinding ratio (G ration) can reach 33500, and a roughcast can be ground into a finished product directly. Employing CBN abrasive wheel, a RB625 super-high speed cylindrical grinder from Guhring Automation in German can grind roughcast into a spindle in one time, and can grind off 2kg of metal each minute[26].

2.4.3. Quick-point Grinding: Quick-point Grinding developed in Germany in 1994 is a new application form of super-high speed grinding. Integrating three advanced technologies: NC flexible machining, CBN superhard abrasive and super-high speed grinding, it is mainly used to machine parts such as shafts and disks. Its wheel axis forms a certain angle against the workpiece axis in horizontal and vertical directions, shown as in Fig.1, so the wheel and workpiece form small-area point contact. Combined with continuous-path NC technology, it achieves both high flexibility in NC turning as well as higher efficiency and precision; moreover, the service life of abrasive wheel is extended.

The technique has been applied in industries of automobile and machine tools and has extensive application prospect. Automobile manufacturing enterprises in China also introduced this technique and related equipment in large scale, which were used to machine camshafts and gear shafts, etc., and to achieve significant economic benefits[27].

Volkswagen Group China applied the technique to grind engine camshafts. The wheel rotation-velocity is 4300r/min, and 3000 workpieces can be ground each wheel dressing. NC quick-point grinding is also the development trend of applying semi-permanent tools to NC turning.

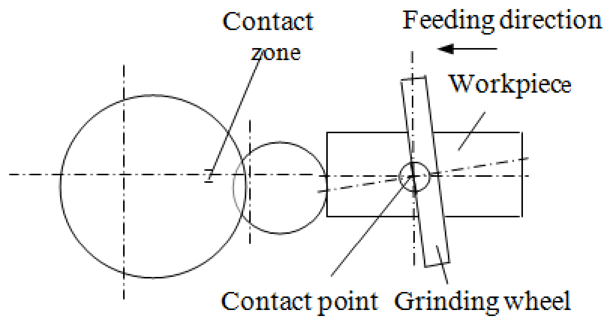

Figure 1. Contact Diagram of Wheel and Part in Quick-point Grinding

2.4.4. Super-high speed grinding of hard and brittle materials: With the development of modern hi-tech and industrialization, hard and brittle materials, such as engineering ceramics, functional ceramics, single-crystal silicon, ruby and sapphire, and optical glass, has found increasingly wide applications. Grinding hard and brittle materials with superhard abrasive under high speed/super-high speed has becomes almost the only machining method. The abrasive can penetrate deeper into workpieces under conventional grinding conditions, and grinding debris is mainly generated in the form of brittle fracture. In super-high speed grinding, the cutting thickness of single abrasive is extremely thin, so it is easier to achieve ductile grinding for hard and brittle materials.

When materials difficult to grind, such as Ni-based heat-resistant alloy and Ti-alloy, are ground at high speed, the deformation rate of grinding debris approaches the propagation speed of static plastic deformation stress waves. The plastic deformation lags and reduces the hardening tendency, so brittle machining on ductile materials can be realized. In pure-aluminum grinding at 200m/s (approximately the propagation speed of static stress waves of pure aluminum), the workpiece surface hardness is 50HV, and the surface roughness Ra is 2.2μm; when the grinding speed is at 280m/s, the workpiece surface hardness is 45HV, and Ra is 1.8μm[28].

2.5. Research Directions of high-speed/super-high Speed Grinding

The stress deformation field in the grinding zone and temperature-field models are to be established based on related theories such as grinding dynamics and kinematics, elastic-plastic dynamics, high-speed shock dynamics, micro-fracture mechanics and damage mechanics;

The laws of wheel properties, technical parameters and grinding fluid affecting grinding-debris removal, grinding force, grinding temperature and wheel abrasion are to be studied;

The brittleness under extremely high strain rate and the grinding-debris removal mechanism of plastic materials as well as surface integrity evaluation and relevant control techniques are to be investigated;

High-speed/super-high speed parameter optimization and database are to be established;

The wheel abrasion law under high speed is to be studied; and so on.

3. Powerful Grinding

Powerful grinding using radial feed or normal grinding force tens to hundreds times of those in conventional grinding to increase the average cross-sectional area of grinding debris and improve machining efficiency.

Through power grinding, desired shapes and sizes can be obtained upon the roughcast surface directly. This method is especially suitable for grinding various shaping surfaces and grooves, and generally involves high-speed powerful cylindrical grinding, creep-feed grinding and high-speed heavy-duty snagging.

High-speed powerful cylindrical grinding combining cylindrical high-speed grinding and powerful grinding, which adopts up-grinding to make grinding speed equal to the sum of wheel speed and workpiece speed. Its special removal rate can reach 8 to $40mm^3/(mm \cdot s)$.

The process of high-speed cylindrical powerful grinding is generally divided into two stages: firstly, most margins are cut off with high efficiency through large radial feed; then, the radial feed is reduced to perform conventional high-speed grinding on workpieces and carry out finish machining.

Creep feed grinding technique adopting large cutting depth (1 to 30mm) and low workpiece feed rate (3 to 300mm/min). It achieves high material removal rate by increasing the length of grinding debris, and is mainly used to grind grooves and shaping surfaces in surface grinding.

4. Belt Grinding

Belt grinding belongs to elastic grinding and has the multi-functions of grinding, milling and polishing, etc. It is characterized by good workpiece-shape adaptability, low vibration of grinding system, low roughness of machining surface, maintenance of residual compressive stresses, low grinding temperature and resistance to workpiece burning; it also has the feature of cool grinding. Belt grinding has the advantages of flexible process, wide machining range, wide application fields, high material cutting rate, high power utilization, high belt grinding ratio, low cost for comprehensive machining, low investment and fast effect. The precision of hard-brittle material machined using ultramicro-abrasive belt with electrophoresis absorption can reach tens of nanometers, and ductile grinding can be realized. Therefore, belt grinding has been developed into an effective method for high-efficiency precision machining.

Presently, about one third of abrasive-wheel grinding has been replaced by belt grinding. The quantity of belt grinders has approached that of abrasive-wheel grinders. Their yield ratio is 49:51 in U.S., 45:55 in Germany, and 25:75 in Japan. Currently nearly 400,000 belt grinders and $950,000,000m^2$ of belts are produced each year around the world[29-32].

Belt grinder is developing rapidly in directions of small size as well as high strength, high efficiency, automation, large power and wide belt. The maximum width of belt grinder has reached 4.9m, the maximum power has exceeded 200kW, and belt grinders with the high speed of 100m/min are in pilot production.

Advanced technologies, such as ultrasonic belt grinding, electroplated belt grinding, electrolytic belt grinding and powerful belt grinding, have emerged and been applied successively. Novel belt manufacturing technologies, such as hollow ball compounded abrasive, cork belt abrasive, multilayer coating abrasive and vitrified corundum abrasive, have been developed rapidly.

In recently years, belt grinding has been applied to precision machining and ultra-precision machining in other countries. The precision has reached micron level, and the surface roughness Ra has reached 0.01 to 0.25μm.

5. Hard and Brittle Materials High-efficiency Grinding

For hard and brittle materials, only under plastic flow removal mode that fracture and cracks will not emerge, and high-precision machining can be realized.

Ductile regime grinding technique with which hard and brittle materials can be removed in a manner of plastic flow under certain grinding conditions, and with which defect-free surface can be obtained.

As a high-quality and high-precision machining method for hard and brittle materials, ductile regime grinding has drawn special attentions in industrial circles.

The key to hard-brittle material grinding with diamond abrasive wheel is the fabrication and dressing of submicron superhard abrasive and dense diamond abrasive wheel. Corresponding machine tools have strict requirements on static stiffness, dynamic stiffness and thermal stiffness. For hard and brittle materials, high-efficiency and non-injury machining can be achieved in one grinding process with cup shape wheel face grinding being applied. Face-grinding fast-feed deep-grinding numerical-control machining centers exclusively for hard and brittle materials have been developed in other countries. The rate of Si3N4 ceramic removal reaches 50 to 125 $mm^3/(mm \cdot s)$.

The cup wheel grinding blade can be divided into a main grinding zone, a transition and a repair-grinding zone. The grinding cracks emerging in the main grinding zone and the transition zone will disappear with the removal of grinding debris, and intact machined surface can be obtained. With cup wheel face grinding under creep feed mode being applied, ceramic materials can be machined with high efficiency and high precision [32-35].

Stone machining is an important field of grinding application. With stone and diamond for sawing, the removal rate is tens or even hundreds times of that in conventional material grinding. Therefore, the combined sawing method with dozens of saw blades machining simultaneously has become a typical high-efficiency grinding method.

While improving efficiency, stone sawing technology should also take stone-resources saving and environmental-pollution reduction into account. Main present development trend of stone sawing technology includes:

(1) Super-thin stone plate sawing and super-thin blade sawing.

(2) The blade speed is improved so as to reduce the blade thickness provided that the dynamic stiffness of blades is fixed. High-speed sawing is the precondition to realizing debris cutting.

(3) Improvement of hard-stone cutting efficiency is the focus and hot spot in future research.

(4) Using high-quality stone to produce parts of precision machines is a new development trend for precision measuring instrument and precision machinery.

(5) The key technology and the theory of high-efficiency stone grinding with diamond tools are important research directions.

6. Grinding Improvement in Respect of Numerical Control, Automation, Intelligence and Virtualization

CNC grinding has developed rapidly in recent years, and grinding centers capable of online measurement, automatic wheel replacement and automatic workpiece assembly and disassembly have emerged, so have grinding robots. For aspherical grinding, lapping and polishing, Computer Controlled Optical Surfacing (CCOS) is applied to control grinding-disk pressure and the relative velocity at grinding points according to required material removal quantity at a certain point on the machined surface.

With continuous track NC grinding, point grinding for cam profile, crankshaft and complex surfaces can be realized.

Intelligent grinding is currently an important research direction. Intelligent grinding system processes process information based on multi-sensor information fusion, so the information can be provided for decision making and control planning, and act on the machining process through NC controller to achieve optimal grinding control. Besides, it is also capable of self learning and maintenance. An acoustic emission sensor can monitor grinding process, finishing process, wheel abrasion and disrepair, and workpiece surface integrity effectively. Another new development in grinding sensors is the application of multi-frequency multi-sensors' grinding burning, surface hardening and hardened-layer depth in online inspection system. In Hanoverian University, a new optical measuring method combining 32mW continuous laser tube, position photosensitive detector and lens was adopted to evaluate the impact of wheel shape on the stability of grinding process and to carry out online decision on the micro-characteristic information and status of abrasive wheel.

Due to the complexity of grinding process, in-depth research is still required on problems concerning the monitoring system in grinding process in respect of theory and practice. S. Malkin in U.S. also developed an intelligent abrasive wheel which collects and monitors acoustic emission signals through the sensors properly distributed and mounted on abrasive wheel and a collection and storage chip based on digital signal processor. It can perform real-time signal collection and data processing on rotating wheel and carry out computer system control and online monitoring of the grinding process and finishing process, etc. of ceramic grinding.

Simulation and prediction of grinding process and results through computer provides a new approach to grinding mechanism research. Developed in U.S., a grinding software package (GRINDSIM) has the functions of simulation, calibration and optimization, etc. In Germany, kinematics simulation was used to analyze and predict three grinding process. Three-dimensional mathematical models describing the macro and micro morphology of abrasive wheel were built based on abrasive and wheel examination, including abrasive shape, size and distribution, and bond uplifts, etc. Multi-abrasive accumulated cutting was adopted to simulate grinding process [23].

In grinding simulating technique, vivid virtual grinding environment is established based on modeling and simulation to evaluate and predict grinding process. The built wheel morphology model is applied in the dynamic simulation of the process grinding-debris formation, energy conversion, grinding force variation, grinding-area temperature, grinding precision and ground-surface quality , and to reproduce the grinding process with the impact of grinding and geometrical parameters, grinding force and heat, grinding vibration and deformation, etc. taken into account, by which the grinding performance and effects under different conditions can be analyzed and predicted [24 and 25].

Molecular dynamics analysis plus grinding mechanism simulation is a new method in grinding mechanism research. Molecular dynamics is a micro method to analyze the characteristics of atomic and molecular solid models from the atomic angle. It can provide considerable information that cannot be obtained through existing experimental methods, and is a powerful tool in the research of micro-machining mechanism. In Japan in 1990, an atomic-scale cutting model was built for the micro-machining process of single-crystal copper and diamond; in 1994, simulation of machined-surface structure was performed based on molecular dynamics. The results show that accurate blade with the blunt radius of 1/10 to 1/20 can achieve micro-cutting, and the workpiece atoms disturbed by the ploughing cutting blade are rearranged perfectly after the cutting blade passes.

7. High-speed/high-efficiency Grinding Abrasives

High-speed/super-high speed grinding wheel should have excellent wearability, dynamic balance accuracy, crack resistance, damping characteristics, stiffness and thermal conductivity, etc., and the abrasive layer and the body should bear extremely strong bond. In powerful grinding, single abrasive is highly stressed, and the grinding temperature is high. In creep-feed grinding, the cutting debris is long and seriously deformed in the grinding area, which may easily cause wheel block. It is an important topic for high-speed/high-efficiency grinding realization as how to fabricate, finish and use abrasives [27].

Diamond and CBN superhard abrasive is the basis of high-speed and high-efficiency grinding. Superhard abrasives are applied extensively in developed countries; especially, CBN abrasive has been developed. In China, the application of CBN abrasives is unsatisfactory due to various factors in respect of manufacturing, finishing, cost and machine tools, etc.

In recent years, research and use of brazed single-layer diamond and CBN tools have attracted attentions. Brazing method enables so strong a chemical metallurgical bond to be formed between the abrasive and the body, that diamond grain can be exposed at a height two third of its diameter and, in the mean time, may not fall off in operation; moreover, the distribution of abrasive in the body can be optimized in design.

The cutting piece made of high-precision super-thin superhard material developed by China has the thickness as thin as 0.01mm and the tolerance between thickness and inner hole as low as 0.004mm, and has been successfully applied in production. According to reports, directionally-arranged whisker abrasive tools and new-material ones of diamond-like fiber were also developed in China. They have high grinding capability, good wearability and long service life, and the grinding efficiency is raised by over ten times.

According to statistics, 22.1% of the global superhard-material tools market is dominated by stone machining. Sixty percent of diamond produced in China was used for stone and construction-material machining. In 2001, the diamond consumption in domestic stone machining reached 750 million carat. Attentions should also be paid to key-technology issues concerning the fabrication and use of the diamond for stone machining [28].

In high-speed/high-efficiency grinding, a new-type microcrystalline alumina abrasive, namely Seeded Gel (SG), has drawn great attentions. SG abrasive has both high hardness and excellent toughness. Its machining capability is between corundum and CBN abrasive. As the assistant cutting edge can sharpen itself when SG abrasive is in grinding, the grinding force and the heat produced in the grinding zone decrease distinctly; meanwhile, wheel abrasion is reduced so that the material removal rate as well as the wheel finishing interval are raised. Compared with CBN abrasive, SG abrasive requires not only low cost, but also almost nothing special on grinding machines, and the method for wheel finishing is also the same as that for conventional abrasive wheel. In the experiment of tempered steel grinding at the wheel speed of 125m/s, the special removal rate reached 100 $mm^3/(mm\cdot s)$.

8. Problems and Differences

8.1. Differences

Presently, China lags much behind developed countries in the field of high-speed/super-high speed and high-efficiency grinding, and the difference is embodied as follows:

(1).There is still no market providing finalized machine products, and the high-speed/super-high speed and high-efficiency grinding equipment used in China is basically obtained through import;

(2).There is still no decent abrasive tool production, and the abrasive wheel used in high-speed and high-efficiency grinder still depends on import;

(3). Enterprises have limited knowledge for the introduced high-speed high-efficiency grinding technology and are incapable of making independent design and improving grinding technologies;

(4).The research of high-speed/super-high speed and high-efficiency grinding mechanism still lags behind in comparison with international levels; particularly, the research on key techniques is still in the tracing stage. No core technology with independent intellectual properties has ever been formed.

8.2. Problems

Grinding is a very complex physical and chemical process. Especially under high-speed/super-high speed and high-efficiency grinding conditions, the understanding is still superficial, and many basic problems need to be addressed and solved. They are mainly:

(1) In-depth understanding and discussions of high-speed/super-high speed grinding mechanism, e.g., material removal mechanism under extremely high strain rate, surface generation mechanism and mechanisms of surface integrity control, temperature field, gas flow field, and grinding fluid supply and cooling;

(2) Basic research of core and key technologies and the theories for high-efficiency deep-cutting grinding and high-speed point grinding process, e.g., fast-rotation dynamic stiffness and stability of thin abrasive wheel, wheel abrasion model, connection and self-balance of large-centrifugal abrasive wheel, online finishing and status monitoring;

(3) Research of the key implementation technology and basic theory for powerful high-efficiency grinding technology and equipment;

(4) Theory of brittle/plastic transformation under complex grinding stress, damage mechanics in hard-brittle material grinding, and damage evaluation and control;

(5) Mechanism research of deep-cutting/creep-feed and high-speed/super-high speed face grinding using hard and brittle materials, and implementation technologies;

(6) Technologies concerning the design, manufacturing, evaluation, finishing and examination of advanced wheel, and basic theory research;

(7) Research and development of practical grinding database for engineering and NC supporting process software;

(8) Research and development of complex grinding monitoring system, expert system and simulation optimization system;

(9) Development and research of green grinding technologies with low/non grinding fluid, low energy consumption, and low wheel abrasion, etc.

9. Research Direction

(1) Research of basic theories and key technologies for high-speed/super-high speed grinding (super-high speed grinding, high-efficiency deep-cutting grinding and quick-point grinding): including understanding and discussions of high-speed/super-high speed grinding mechanism, surface generation and integrity control, core and key technologies and theoretical research of high-efficiency deep grinding and quick-point grinding;

(2) Research of basic theories and key technologies for high-efficiency grinding: including key technologies and basic theories for powerful high-efficiency grinding process and equipment, and research of high-efficiency low-pollution stone grinding technology and theory;

(3) Research of basic theories and key technologies for hard-brittle material grinding: including theories for brittle/plastic transformation under complex grinding stress, grinding damage mechanism of hard and brittle materials, damage evaluation and control, and mechanism research and implementation of deep-cutting, creep-feed and high-speed/super-high speed grinding with hard and brittle materials;

(4) Research of basic theories and key technologies for intelligent examination and control of the grinding process: including research on the parameter information sensing in grinding process and multi-sensor signal fusion, and methods, theories and implementation of intelligent control in grinding process;

(5) Research of basic theories and key technologies for complex surface automation and high-efficiency grinding: including research and technical implementation of complex-surface robot grinding and NC grinding, and that for complex-surface automatic high-efficiency grinding processes;

(6) Research of basic theories and key technologies in fabrication and application of novel abrasive tools: including technologies for developing and combining novel abrasives and bond systems, structures and preparation technology innovation of novel abrasive wheel for high-speed/super-high speed and high-efficiency grinding, quantitive evaluation technology and system for the finishing and machining performance of superhard abrasives;

(7) New principles, methods and process exploration for non-pollution and low-pollution grinding.

10. Conclusion

High efficiency abrasive machining is one of the advanced manufacture technologies. It can large-scale increase manufacturing efficiency and finished quality, and diminish manufacturing cost. At present, developments in abrasive technology, particularly high efficiency grinding machining such as super-high speed grinding, high efficiency deep-cutting grinding, creep feed deep grinding, abrasive belt grinding, heavy-duty machining are remarkable. Although abrasive technologies are thousands of years old, in their developed form they play an important role in manufacturing. The need for high accuracy finishing and for high efficiency machining of difficult-to-machine materials is making the application of abrasive technologies increasingly important. It is concluded that high efficiency abrasive machining is a promising technology in the future.

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