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Research on the Tooth-Surface Controlling and Honing Machining of the Ultral-Precision CBN Gear

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Abstract: With the popularization of precision-machining process by the hard tooth-surface gear, special machining tools have also been developed rapidly, which is mainly manifested in as aspects as the application of new materials and cutting tools' coating technology, the mature of ultra-hard-grain CBN tools' preparation technology, and the pefecting day by day of tool-structure design and tool-integration technology and so on. This topic introduces the CBN gear's honing-machining characteristic and designing principles. And it also contains the application status of the ultra-precision tooth surface and the importance of the tooth-surface morphology in the process of gearing transmitting. At the same time, this topic briefly describes several common processes and key processing technologies in the modern gear-manufacturing area.

Keywords: CBN gear, honing machining, tooth-surface morphology, ultra-precision tooth surface.

1. INTRODUCTION

The gear-honing has a direct impact on the tooth-surface quality and service life of the machined gear as a kind of gear surface-smooth handing technology. But gear-honing process usually exists disadvantages of low profile precision, low cutting efficiency, and weak error-correction ability, so research of the gear-honing process is very necessary. Honing makes extrusion and cutting to the machined gear mainly depending on the CBN (cubic boron nitride) grain on the surface of honing wheel. Therefore the CBN grain's cutting process directly affects the quality and performance of the machined honing-wheel [1]. And with the development of modern cutting technology in the direction of high quality, efficient, precise, and intelligent, the requirement on the material and performance of tool and cutted work piece has been becoming higher and higher, and the research on cutting process has been getting more and more important. Some kinds of grinding and cutting tools with CBN material are shown in Fig. (**1a-d**).

2. BRIEF INTRODUCTION OF CBN GEAR AND THE CUTTING CHARACTERISTICS OF CBN GRAIN

2.1. Analysis on the Machining Characteristics of the Single CBN Grain

1) Using the nonlinear dynamics theory of the large finite-element analysis software, ANSYS/LS-DYNA, to do the simulation of the 45-steel's cutting process by the single CBN grain. The unit adopts the linear three-dimensional entity element, Solidl64, of 8 nodes, and applies the Lagrange algorithm of single point integral to establish the three-dimensional explicit and dynamic analyzing finite-element model of cutting process. Johnson-Cook plastic model is used in the model. The reasonable grid partition of the single grain and the workpiece can not only reduce the CPU time, but also avoid the grid distortion caused by the unreasonable grid partition. At the same time, it is necessary to carry on the reasonable restraint and additional load to the single CBN grain and the workpiece, because the unreasonable restraint will cause big distortion to the workpiece material, and this will influence the cutting process and even stop it [2]. The cutting path of the single CBN grain depends on the applied load, so the applying of the load is also important to the cutting process. By setting the cutting model and calculating parameters reasonably, the three-dimensional large-deformation cutting process of 45 steel under different speed can be realized by using the single CBN grain. The results of numerical analysis clearly simulate out the chip morphology of the under-cutting material in plastic-deformation stage, stage of shear slip, chip-formation stage and different cutting speed, and finally comes to the conclusive relationship among the cutting speed, the chip morphology and the cutting temperature after analying the effective stress under different speed, the effective plastic deformation and the temperature field theory. The reasonable control of the cutting speed can not only control chip morphology, but also

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can take timely and reasonable chip-breaking measures to prevent the chip flying or cutting chip too long, which may influence the cutting process [3].

2) Using ANSYS/LS-DYNA and the Solidl64 element to establish the thermal coupled analysis model of three-dimensional large deformation in cutting by setting up different rake-angle of minus 10 degrees, minus 15 degrees, minus 20 degrees, minus 25 degrees, minus 30 degrees and minus 35 degrees of the tool. The under-cutting material on the cutting layer should adopt the elastic and visco plastic model with thermal analysis ability, and use reasonable contact and separation criterion to simulate the chip shape and temperature distribution. The numerical simulation results simulate out the chip shapes and stress conditions in the same cutting speed but different rake angle, and the analysis and research on temperature field theory with different rake- angle of the tool finally figure out the relationship among the tool's rake-angle, the chip morphology and the maximum cutting temperature. Reasonable rake-angle of the tool can not only reduce the cutting force and cutting temperature, but also reduce the chip-deformation and thickness. Therefore, it is very important to optimize the cutting process and cutting parameters [4].

2.2. The Design Principles of External Skew-tooth of CBN Honing Wheel

The design of external skew-tooth of CBN honing wheel is the mainly based on the normal moudle, the normal tooth-angle, the pitch angle, the number of teeth and the precision grade of the by-honing gear. The main design principles are as follows:

1) The honing wheel's normal modulus and normal tooth-angle must be the same as the by-honing gear's.

2) The honing wheel's pitch angle and rotating direction should be confirmed by the by-honing gear's. The shaft angle between the honing wheel and the gear should be controlled appropriately in range of 10 degrees to 15 degrees.

3) The value of the honing wheel's pitch-circle diameter shall be taken as great as possible within the allowed range of machines and gear in order to increase the normal overlap coefficient and improve honing-cutting speed; Tooth number of honing wheel should be relatively prime with the gear wheel's in order to improve teeth-space accuracy.

4) The reasonable selection of honing-wheel width should be made, the tooth width should be a smaller value under the premise of normal meshing in honing process.

5) It's necessary to consider that the CBN coating thickness effects the honing-wheel thickness, the top diameter and the root diameter in the matrix design of honing wheel.

(**a**) CBN vitrified honing disc

(**b**) Ultra-precision CBN tools

(**c**) CBN-diamond grit

(**d**) CBN grinding wheel

Fig. (1). Grinding and cutting tools with CBN material.

6) The structure of honing wheel should be reasonable, and it's better to reduce the weight of the honing wheel under the premise of satisfying the strength and stiffness requirements.

7) There should be some necessary checking computations in the honing-wheel design, such as checking whether the top cut and under cut are needed, checking the radial clearance size between the addendum and dedendum, and checking the overshooting amount of the effective length of end-surface meshing line caused by honing cutting [5].

2.3. The Reasonable Application of CBN Grinding

When grinding the same material, the grinding ratio of CBN grinding wheels with different trademakers may be different from two times to five times, therefore, the grinding wheel is chosen according to the specific processing conditions. Anchoring agent of CBN grinding wheel contains resin, ceramics, electroplating, brazing and metal binding agent, etc. The application range of grinding wheel of resin binder is relatively wide, which is mainly used for cutting tools, grinding hole, outer circle and plane grinding. Metal binder is mainly used in cutting grinding, profiling grinding of optical curve grinding machine and grinding single cutting-edge tool, and also applied to grind helicla flute of the high speed small steel drill [6]. As a result of the binder to be brittle and porous structure, the CBN grinding wheel of ceramic binder is more suitable for the diamond roller dressing. Therefore, it has been widely used in recent years, its superiority is shown more especially in the mass production. The electroplating grinding wheel is suitable for high speed grinding and forming grinding, and can also be used in the high efficiency hole grinding and coordinate grinding. Brazing grinding wheel is suitable for ultra high speed grinding. The CBN grain is distinguished with low strength, medium strength and high strength, the grain surface can be metal plated or not plated, the reseanable choice should be according to different processing conditions such as the type of binder, materials processing, dry grinding and wet grinding, ect. Dry grinding generally use copper, such as CBN-C, while wet grinding can use nickel, such as CBN-N [7]. In recent years a kind of grinding wheel of ceramic binder with titanium vest has been appeared, and it's said that the grinding wheel and the ceramic binder may have chemical combination after plating titanium vest, which can improve the grinding performance.

2.4. Preliminary Study on Micro-Cutting Process

From the microscopic point of view, the gear honing process of the CBN honing wheel and is the extrusion and cutting process on the gear surface by the large grit cutting edges on the honing-wheel surface. The angle of abrasive blade is 90 degrees ~120 degrees, thus cutting is basically in negative rake angle.

(1) The average gap of abrasive is symboled with W, clearance of abrasive on the honing-wheel surface is in the Gauss distribution with a mean gap as the center. The results show that the value of W is generally 1~2 times as the diameter of the wear particles.

(2) The clearance of continuous cutting edge, marked with e, is the distance of continuous cutting edge on the circumference of the honing wheel. The larger the size of honing wheel is, or the lower the hardness is, the more the value of *e* will be.

$$e = \frac{W^2}{d} \tag{1}$$

In the formula, d is the average width of cutting-honing stripes.

(3) The arc length, L, of the honing wheel and the workpiece contacting

$$L = \sqrt{\frac{2\mathrm{r}Rh}{r+R}} \tag{2}$$

h types honing-wheel cutting depth, r and R are respectively the curvature-radius of the contact point of the gear wheel and the honing wheel.

(4) The cutting off area is am

$$\mathrm{a}m = \frac{W^2 vh}{V} \tag{3}$$

In the formula, v and V are respectively the peripheral feed rate and cutting speed.

(5) The maximum cutting depth of the abrasive is H

$$H = \frac{ev}{V}\sqrt{\frac{2H(\mathrm{R}+\mathrm{r})}{rR}} \tag{4}$$

Formula (2.4) shows that the high cutting speed and low feed speed should be used in gear honing.

3. THE KEY TECHNOLOGIES OF HARD-SURFACE GEAR FINISH MACHINING

Finish machining of hard-surface gear has the goal of high efficiency, high quality, and low cost as a kind of gear finishing technology for high-efficiency removal of material. With the development of hard alloy materials, tool coating technology, preparation techniques of ultra-hard grain-tool and gear finishing machine technology, quenching hard-gear machining technology and machining accuracy of gear have been significantly improved, and the cost of high-precision gear machining is greatly reduced [8]. At present, the processing methods used in quenched hard-surface gear are hard tooth-surface shaving, hard tooth-surface finish-rolling (scraping), hard tooth-surface grinding and the hard-surface gear honing technology, etc. The hard-surface gear shaving and hard-surface finish-rolling are suitable for gear finish machining, when the tooth-surface hardness of HRC is in the rang of 45 to 53, and the hard-surface gear grinding and the hard-surface gear honing are suitable for gear finish machining, when the tooth-surface hardness of HRC is more than or equal to 45. Hard-surface gear finish-machining technologies mainly include the material removal-mechanism, machine-tool design, tool preparation technology, and Integrated technology, *etc*. [9]. Fig. (**2**) presents the key technologies required for hard-surface gear

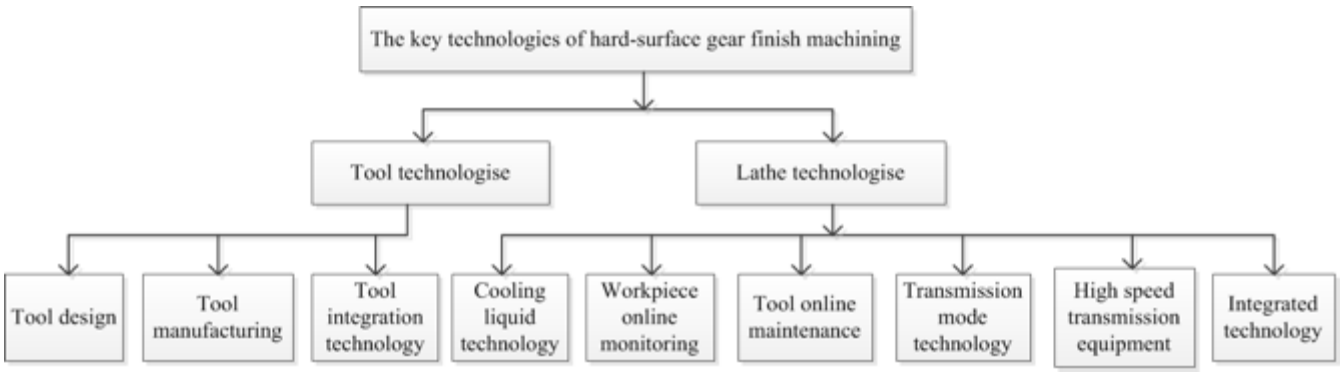

Fig. (2). The Framework of hard-surface gear finish machining.

finishing, of which the design and manufacture of high-performance machine tools are the most important factors that effect the hard-surface gear finish machining.

4. ULTRA-PRECISION GEAR AND GEAR PROCESSING TECHNOLOGY

4.1. Summary of Ultra-Precision Gear

The manufacturing level of the ultra-precision gear symbolizes the development level of a national gear manufacturing industry. The so-called ultra-precision gear refers to the gear of which the manufacturing precision of gear teeth achieves the international gear standard of 1328-1:1995 ISO. A class of ultra-precision gear is used for national defense, while the other class of it is used as a benchmark for the transmission of gear accuracy, and it is also used to test the common accuracy of the standard gear or gear-measuring instrument, *etc*. [10]. In recent decades, China's gear industry has kept sustained and rapid development, and the yield has increased, but the overall industry manufacturing precision is less than the United States, Germany and other countries for 1 to 2 grades. In addition, all the world's famous companies which product ultra-precision gear are trying to improve the precision on the high-precision grinding machine or make specialized gear grinding machine, and the company select skilled workers and technicians by itself to operate the equipment to grind the ultra-precision gear. In precision grinding technology, each company is very confidential, they neither receive visitors, nor apply for specials. There is not any public literature of introduction of precision grinding technology or the experience of grinding teeth [11]. If China want to become a powerful gear-manufacturing country, we must take the road of independent innovation, and the first solution is to break through the manufacturing quality of ultra-precision gears. So, the development of standard gear and ultra-precision gear cutting tools, which have the independent intellectual property rights, has important and practical significance to improve the gear manufacturing and the development of the industry in China as a whole.

4.2. Methods of Gear Honing

Gear honing is a kind of Tooth surface processing methods which applies the free meshing movement between honing gear of gear type or worm type and by-honing wheel, and uses the relative sliding velocity and pressure between the tooth-surfaces for honing-cutting. It contains two kinds of different methods as follows:

1) Honing method of external-tooth honing wheel: The ordinary soft-surface honing wheel is low in durability, and can improve the quality of tooth surface only a little, so it's only used for scavenging quenching black. Hard-surface honing wheel can not only fitting, but also correct gear tooth-profile error, pitch error, and tooth-direction error, and improve gear accuracy by more than 1 level. In recent years, the Germany Harth company has carried out of a synchronous CNC external-meshing honing machine, which is principlely in essence of the gear shaped CBN coated tool, similar to space-mesh cutting of cross axis in shaving . 2) Honing method of internal-tooth honing wheel:In 1979, the Swiss Fassler company introduced gear-honing machine of internal honing wheel. The internal honing wheel has greater overlap coefficient with the workpiece, this brings a stronger correction ability than external honing wheel, but this random meshing is not ideal for modifing tooth profile of the workpiece or correcting the tooth-pitch error. In recent years, the Gleason-Hurth company developed a kind of strong internal honing, its the biggest feature is controlling the CNC axis to achieve forced transmission between the internal honing wheel and gear honing, this can not only improve the tooth shape and tooth precision, but also greatly improve the pitch accuracy of workpiece. It's very effective to reduce the noise of gear, and improve the honing-gear accuracy up to level 6, further more, the processing cost is only the half of the grinding's [12].

4.3. The Grinding Process

1) The grinding-teeth are divided into 2 categories: the exhibiting grinding-teeth and the forming grinding-teeth. In general, the first kind of teeth is lower in efficience, its grinding cost is higher due to complex and expensive machine tools. So, the widely using is limited in the production, while it's only be used in minority of precision machinery and tooling industry. And the forming grinding-teeth has the advantages of simple machine tools, high efficiency and low cost, but its past problem of dressing the grinding wheel has not been solved very well, so, its application has also being prevented in the production [13]. Fig. (**3**) presents the classification of exhibiting grinding-teeth

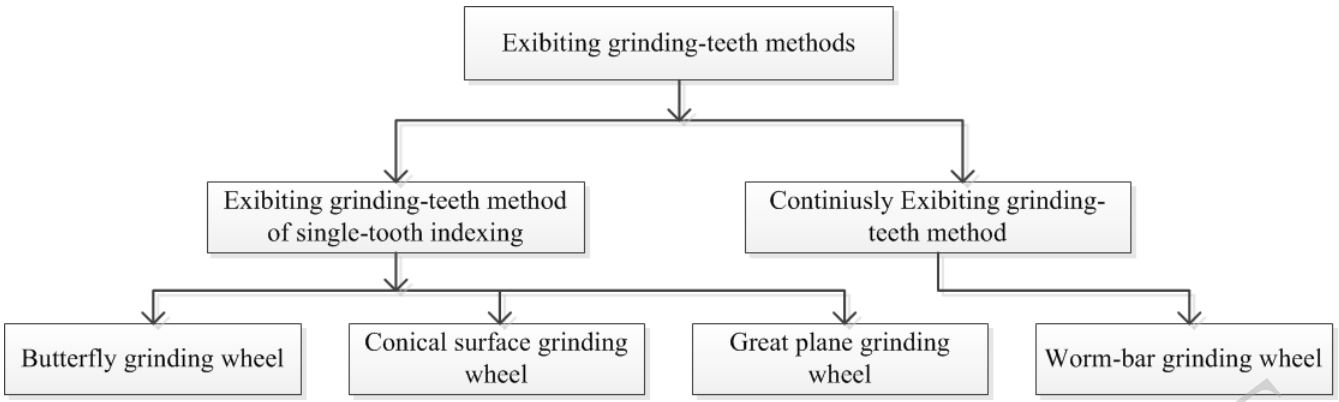

Fig. (3). The classification of exhibiting grinding-teeth methods.

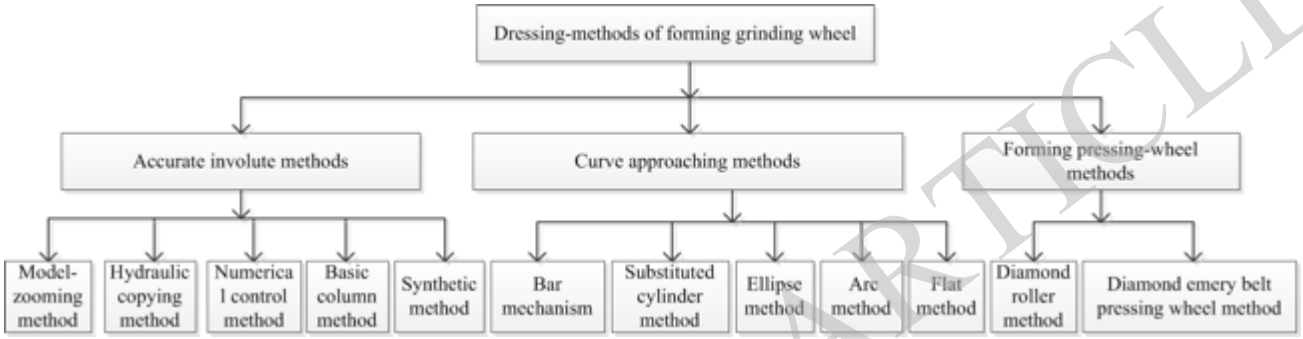

Fig. (4). The classification of dressing-methods of forming grinding wheel.

methods. Nowadays, all the countries in the world are actively studying new types of grinding machines with high precision, high efficiency, multi function and stable performance.

2) To solve the problem of efficient and economical tooth grinding for large quantities of gear, in recent years, many countries in the world (such as the mentioned Swiss Maag company and Germany, Japan, Britain, the United States and other countries) are actively studying the forming grinding technology. The precision of forming gear grinding is comparable with the precison of exhibiting gear grinding, the productivity of the first kind is many times higher than the second one's (but still below the worm-bar gear grinding), and the efficiency will be further improved after strong and efficient grinding applications are used in forming grinding. Forming grinding -teeth is generally suitable for mass production of gears with 5 to 6 grade precision. It is also particularly suitable for gear machining with large modulus, few teeth, and big tooth-width. The first problem to solve is to create a general dresser of forming grinding-teeth, and in recent years, a lot of patents and results have appeared, as shown in Fig. (**4**). Foreign forming grinding-teeth machine has four-bar mechanism dresser, but this dresser has disadvantages of poor accuracy and stability, big copying number and difficult to adjust. Because the complex structure of the precise involute dresser influence of the accuracy, many kinds of approximate-involute dressing methods are developed. It is difficult to solve the influence of the wear of the diamond wheel on the accuracy of the shape dressing. Therefore, dressing method of diamond roller is developed. Because the manufacturing of forming diamond roller is complex and very expensive, the foreign country developed emery-wheel method. In recent years, numeral-control dresser of forming grinding wheel has being developed at home and abroad, using three-coordinate closed-loop system, in order to guarantee the accuracy and automatically adjust to compensate the wear of diamond pen. But this device is complex and expensive, so it has not being formally applied in production.

5. THE IMPORTANCE OF GEAR-SURFACE MORPHOLOGY IN GEAR DRIVING

At present, the contact theory is usually used to deal with the problem of gear transmission at home and abroad, the contact between the gear mesh is regarded as the contact between the elastomer, and the contact of the gear is simplified as a spring and damping. And establishing a dynamic model, forming relevant kinetic equations, and finding the gear changing speed, dynamic meshing force and other parameters according to the mathematical method, or solving by theoretical modeling and analysis *via* the application of computer contacting software. But the influence of the surface morphology of the gear on the transmission is ignored. In the transmission of gear meshing, the gear mounting error and loaded deformation of gear, gear shaft and gear wheel box, the stiffness-cycle changing of gear mesh brings dynamic load and other dynamic factors, which resulting in the impact of gear, vibration and noise, that seriously affect the service life of the gear. Because of the machining error and heat-treatment deformation of tooth

surface, the surface of machining parts can not be completely flat in the micro, when the two member group pair of element, the surface morphology directly influence the strength and stiffness of contact surface, and the friction, wear and lubrication of the machined surface, this resulting in the deviation of actual mesh point of the tooth surface from the theoretical point of engagement, which results in the speed ratio in the gear-meshing transmission. Due to the change of the microscopic appearance of the tooth surface, The contact trace and contact area of the real tooth surface can not be obtained with the classical gear meshing theory [14].

6. GEAR MODIFICATION

6.1. Tooth-Profile Modification

(1) The maximum amount of modification of addendum should be able to compensate for pitch errors and basepitch errors caused by load deformation.

(2) To ensure a smooth transition to the load in tooth pair number conversion, the starting point of modification should be located in the conversion point from the single-tooth meshing area to the double-teeth meshing area.

(3) The modification curve is determined according to the principle of uniform load variation. The vaule at the starting point of modification is zero, and gradually becomes the maximum when reaches the top of the tooth.

6.2. Tooth-Direction Profile

The purpose of the tooth-direction profile modification is to improve the load distribution along the tooth profile, and avoid the overload at the end of the load. We can take tooth-end repairing, spiral line repairing and drum-shaping finishing. The tooth-end repairing is used to prevent the overload at the end of the tooth. Spiral dressing is mainly considered by the load deformation, especially the helical line error of small gear caused by bending and torsion deformation, to adjust the helix to a predetermined rule. In order to obtain more uniform load distribution. Drum-shaping finishing is mainly used to compensate for the manufacturing error and the gear deformation caused by the load, and it's generally used in the form of a equal radius circle in the middle of a small gear, such as the midpoint of the working surface.

CONCLUSION

The ultra-precision machining technology of the CBN honing wheel has been a more and more important role in the field of modern processing machinery. The improvement of this technical has got more and more attention, which need the improvement of the ultra- precision honing-machining technology, and good tooth-repairing technology. Let's hope that this technology can get much more improvement and development.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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