Surface Fine Grinding via a Regenerative Grinding Methodology

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Abstract. This paper presents a regenerative surface fine grinding methodology to remove grinding defects of traditional operations and to improve the quality of surface flatness. All possible surface defects produced by traditional and creep-feed grinding operations are carefully reviewed and circumvented. These defects include non-uniform traces, pitting spots, scratches, burnouts, and quenching breakage. To alleviate these traditional grinding defects, the paper presents a new approach by designing and constructing a regenerative surface fine grinding system that includes a mechanism that carries the submerged workpart in an oil-contained open box. The fine grinding tool held by the spindle-chuck unit of the CNC machine is moved in relative to the workpart surfaces by a combined trajectory of a cycloid path, a linear feed and a lateral travel. Some numerical simulations for selecting appropriate grinding trajectories are presented and simulated. The trajectory is selected based upon the resulting quality of contact uniformity and homogeneity as expressed in terms of contact frequency to each point on the workpart surface. The simulation model is then used to characterize appropriate working range of each grinding parameter. Different grinding paths are thus generated and superposed. A working machine is designed and built based upon the simulation results. Several experiments are carried out on the constructed grinding system with the grinding tool mounted to the spindle-chuck unit of the CNC machine. The surface quality of the ground workpart is measured. Tests on different system parameters demonstrate the importance of choosing the correct grinding wheel and grit size and an illustration of the proper selection of process and system parameters are presented. The experimental results are compared with those of analytical solutions. Good agreement between them is observed. In ninety minutes fine-grinding operations using the proposed method, the workpart surfaces generally possess no damage and surface roughness is reduced to the range of 0.02~0.04μm in Ra. To verify the effectiveness of the proposed method, the results of fine grinding operations using various process parameters are measured and recorded. The effects of various combinations of process parameters including trajectory density, uniformity and grinding efficiency on the effect of surface flatness enhancement are carefully examined and concluded.

1. Introduction

In the past decade, the operation of surface fine grinding has attracted much attention among various investigators since it is needed for many important industrial applications including weapon-building, production of precision dies and molds, silicon wafer manufacturing, and chip back-grinding, as given in Figure 1. Besides being a major flattening process, surface fine grinding has also been proposed to replace etching operations in microelectronics industry [Tricard and Subramanian, 1998]. Research and development of fine grinding machines are found very involved. The major difficulties include the
geometric complexity associated with zone interface, the characters of process parameters, the planning of fine grinding trajectory, and the control of contact mechanism and contact mechanics. Moreover, a limited number of articles regarding the surface fine grinding operations are available since many fine grinding techniques are still of commercial and military trade secrets and not open for public yet. In order to grasp the details of surface fine grinding technology, a new methodology is proposed and developed here to create a machine that can generate effective fine grinding trajectory by optimizing system parameters and contact forces.

This paper presents a design and construction procedure for the regenerative surface fine grinding system that comprises the characterization of fine grinding process parameters and the trajectory planning. Based upon the results of simulations obtained by a compact computer program, six key process parameters are identified. Their proper working ranges associated with various regenerative trajectories are estimated. The selected system and process parameters are then used to construct the constant-pressure high-speed fine grinding device that is driven by the spindle of a CNC machine.

The constant-pressure surface fine grinding system presented in this paper utilizes a fine-tuned regenerative trajectory planning technique to enhance the fine grinding uniformity and contact frequency for each surface point on workpart surfaces. The system thus built is independent of the precision of the attached machine itself. The free surface polished by using the proposed method can achieve the quality of sub-microns in terms of surface roughness.

The fabrication of a mold is a three-stage process. The shape of mold cavity is created first. Milling and EDM operations are two different machining operations used to produce the shape of mold cavity. The former is a traditional process having better efficiency and the latter is well suited for complicated shape and harder mold materials. Once the shape of the mold cavity is completed, the next stage is to finish the surface of the mold cavity. The objective here is to minimize the degree of surface roughness and to enhance the overall surface quality. This is usually accomplished by fine grinding operations using various oilstones. Once the mold surface is polished by the oilstone or the oilpaper clothe, the last stage is to finish the surface up to mirror quality. The materials of copper ring, wool felt, and diamond paste can usually be used to achieve that. However, the traditional and creep-feed grinding operation is not a perfect process [Matsui, 1988]. It is affected by many factors including structural rigidity, contact pressure, the grit size of the grinding particles, and surface pitting. These
factors can create various detrimental defects on the finished surface of the mold. The detrimental effects thus induced include (1) the scratches of tadpoles mainly created by coarser grinding particles on the surface of workpieces made of soft materials, (2) the non-uniform traces mainly created by the non-uniform and scattering fine grinding trajectory on the workpart surface, (3) the pitting spots mainly created by impurity particles intruded into the surface cavities, (4) the burnouts or the strain-hardening layer mainly created by the heat generated during fine grinding operations and left on the surface of the workpiece, and (5) the quenching breakage mainly created by residual stresses left on the workpart surface made of brittle materials.

The detrimental effects presented above are not fully reported in the literature. Only a few subsurface damage (SSD) problems have been discussed so far. Lundt et al. [1994], Zarudi and Zhang [1996], Van De Merwe [1998] and Pei et al. [1999] have studied the subsurface damages induced by surface grinding. It was reported that the size of the diamond grits has a most significant effect on the SSD. As grit size increases, the depth of the subsurface cracks increases. Tonshoff et al. [1994] discussed the effects of the topology of the abrasive layer, particularly the height distribution of the single grains on the grinding wheel. Their tests revealed that both plastic deformation and micro brittle fracture occurred during surface grinding. They attributed this to the unevenness of the grinding wheel. To alleviate these aforementioned grinding defects, the grinding operations are arranged in this paper to perform on workpart surfaces in submerged fluids. By so doing, the defects of burnout and quenching-breakage can be removed. Better grinding quality can also be obtained by employing fine grains of grinding particles mixed in the selected fluids to avoid the defects of pitting spots and scratches. As far as the defect of non-uniform traces is concerned, it can only be alleviated by employing sufficiently complicated fine grinding trajectories carefully designed and implemented to instruct the grinding tool head to weave smoothly and uniformly on the workpart surfaces.

Fine grinding of flat surfaces requires high predictability and consistency, which requires the grinding tool to possess self-sustaining ability, i.e., after initial truing, the grinding tool should not need any periodic dressing or replacement by external means. In other words, there should be “a perfect equilibrium between the rate of wear of the abrasive grains and the rate of release of worn abrasive grains” [Subramanian, 1999], hence maintaining the grinding force or pressure to be relatively constant. Due to its unique requirements, fine grinding of flat surfaces presents big changes to grinding tool manufacturers, grinding device builders and process engineers. To ensure the successful development of fine grinding of flat surface, a large amount of research work is still needed.

2. Trajectory planning for superfinish fine grinding
The proposed surface fine grinding system, as shown in Figure 2, is comprised of three major subsystems including (1) a bi-eccentric cycloid motion generator that creates a relative motion between the fine grinding tool head and the workpart surface, (2) a spinning fine grinding tool head attached to the high speed rotating spindle on a CNC machine, and (3) the workpart that is held and submerged in a fluid trough fixed on the automatic feeding worktable of the CNC machine. The fine grinding fluid trough is mounted on top of the bi-eccentric cycloid motion generator. The fine grinding generator is fixed on the worktable of the CNC machine. Thus, the motion trajectory of the complete planar surface fine grinding system is constituted by three different kinds of movements including (1) the feeding movement of the CNC worktable that generates the primary fine grinding path, (2) moving along with the primary path the bi-eccentric machine creates a secondary cycloid motion, (3) on top of the primary and secondary combined trajectory, a third minor motion path created by the high-speed spinning motion created by the fine grinding tool head that is attached to the spindle of the CNC machine system.

Mathematically, the compound motion trajectory of the proposed fine grinding system can be best described by the equations

\[ X = ut + e \cos \frac{2 \pi t}{60} + \frac{d}{2} \cos \frac{2 \pi t}{60} \]
where X and Y (in millimeters) are the x- and y- coordinates of an arbitrary point of the compound motion trajectory. u and v (in millimeters per minute) are feed-rates of the worktable respectively in x- and y- directions. e (in millimeters) is the bi-eccentricity of the cycloid motion generator machine system. f (in hertz) is the frequency of the cycloid motion. d (in millimeters) is the diameter of the grinder head, and n (in revolutions per minute) is the rotating speed of the grinder head and the spindle. The first terms on the right-hand side of the above equations are x- and y- components of the primary motion path. The second terms on the right-hand side of the above equations are x- and y- components of the secondary cycloid motion trajectory. The ending terms on the right-hand side of the above equations are x- and y- components of the high-speed rotating or spinning motion.

\[ Y = vt + e \sin \frac{2nf}{60} t + \left( \frac{d}{2} \right) \sin \frac{2n\pi}{60} t \]  

(1)

Figure 2. Combined fine grinding trajectory of a straight primary path.

Involved in Eqn. (1) are six key parameters that includes (1) the feed-rates of u and v, (2) the time span, t, for fine grinding operations, (3) the eccentricity, e, of the cycloid motion, (4) the frequency, f, of the cycloid motion, (5) the inner diameter, d, of the grinder head, and (6) the speed of spin, n, of the grinder head. The design and implementation of a structure-independent automated fine grinding machine system for a given set of design criteria will require the characterization and optimization of these key system parameters.

3. Computer simulation and parameter optimization

A computerized statistical simulation method is used here to evaluate the surface quality of workparts under various fine grinding conditions. Either the total traveled distance or the total elapsed time is used as the criteria to end a complete fine grinding cycle. In order to tell the goodness among various planned trajectories created by different parameter combinations, a uniformly distributed surface quality evaluation net is selected to cover the complete fine grinding zone. The evaluation net is designed so that the distance between any two neighboring nodes is just a little bit larger than the outer diameter of the fine grinding tool head. If the nodes of the net are distributed too densely, the grinder ring can cover more than one evaluation node at any given instant and the weaving frequency over each evaluation node will be counted unrealistically. On the other hand, if the nodes of the net are distributed too sparsely, the weaving frequency over each evaluation node will become too low. Important information can be lost and thus lead us to a misleading result.

In order to cover the complete fine grinding zone uniformly, the workpart fixed on the CNC worktable is programmed to move in a zigzag fashion. In other words, the workpart is first fixed in...
the fluid trough mounted on the cycloid motion generator that is fixed on the CNC worktable in a way that the longer side of the planar surface is in the x-direction, and the shorter side is in the y-direction. The worktable is controlled to move relative to the spinning grinder head in x-direction for a distance equal to the longer side of the planar surface. At the end of the travel on the longer side the workpart surface is then fed in y-direction for a small distance less than the outer diameter of the grinder ring. It is then controlled to travel back along the longer side in x-direction after lateral feed. At the end of long travel it is then fed laterally again and so on so forth until the complete fine grinding surface area is covered. If the total time span is not yet reached, it is then controlled to travel back in a reversed path.

The proposed zigzag type major fine grinding path is a good scheme that ensures the number of travels in the complete fine grinding zone is homogeneous. The surface quality can be evaluated visually based on the trajectory of simulation in one travel. The defects of non-uniform vacant zone, pitting-spot and scraping-trace can be easily detected and the corresponding fine grinding parameter combination can be excluded from the final candidate pool for machine design selection. The computer simulation of a complete superfinish fine grinding process can be carried out in following steps:

- Select a surface type, coordinates of the starting point and the working range of fine grinding zone, and the values of process and system parameters including eccentricity, speed, diameter of the grinder ring, cycloid motion frequency and the total fine grinding time span.
- Compute the distance between any two neighboring nodes on the surface quality evaluation net, total number of nodes and their corresponding coordinates based upon the given fine grinding zone data and the outer and inner diameters of grinder ring.
- Generate the fine grinding trajectory based upon the values of process and system parameters given and the motion equation of Eqn. (1).
- Compute the distance of each node to the center of grinder ring in every time step. Add one to the counter of each node which satisfies the condition that the computed distance is greater than or equal to the inner diameter of the grinder ring and is less than or equal to the outer diameter of the grinder ring. Otherwise, the process continues.
- Check the time elapsed in the whole fine grinding cycle. Stop if the elapsed time is equal to or greater than the time span given. Otherwise, go back to step number four and the process continues.
- Compute the overall average and standard deviation of the values in the counters of nodes on the evaluation net. Record the values of average and standard deviation for this particular set of parameters. Go back to step number three to generate another trajectory for another set of parameters and the process continues.
- Compare the average and the standard deviation values of various trajectories of different parameter sets. Select the best set that complies to the given design criteria.

Here the average value of the counted numbers recorded in the counters of evaluation net for a specific trajectory stands for the weaving frequency in fine grinding surface zone on average. The larger the number is, the better the surface quality will be. On the other hand, the standard deviation of the counted numbers recorded in the counters of evaluation net for a specific trajectory stands for the degree of scattering deviated from the average weaving frequency of superfinish fine grinding on the given zone surface. The smaller the number is the better the precision of the fine grinding for that particular trajectory or set of parameters. Thus, the surface quality of the finished product will also be better.

3.1. Effect of various feed-rates on fine grinding quality
The proposed fine grinding trajectory of Eqn. (1) can be expressed in terms of the standard form of cycloid curve as

\[ X = a \alpha t + e \cos \alpha t \]
\[ Y = a + \epsilon \sin \omega t \]  

(2)

where \( \omega \) is equal to \( 2 \pi f/60 \), and \( a \omega \) is equal to the feed-rate in longitudinal direction, \( u \). After simplification, one can easily obtain the relation between feed-rate, cycloid frequency, and eccentricity as

\[ u = \frac{2\pi \epsilon f}{60} \]  

(3)

If \( u < 2\pi \epsilon f/60 \), \( u \) is generally referred to as the long amplitude cycloid curve, and when \( u > 2\pi \epsilon f/60 \), it is called the short amplitude cycloid curve. The difference between the long and short amplitude curves is the degree of overlapping for the major trajectories. It is obvious that the long amplitude cycloid curve generates more complicated and uniform fine grinding trajectories than those of the short amplitude cycloid motion curve (trajectory of a single point of the fine grinding tool ring). It is clear that the travel speed of the grinder head increases, the number of non-uniform vacant zones obviously increases. The uniformity and compactness of the fine grinding trajectory are computed and listed in terms of the weaving frequency over evaluation nodal counters. The average value of the weaving frequency decreases, as the amplitude of the major trajectory becomes shorter. However, the amplitude of the major trajectory cannot be too small since it will significantly affect the efficiency of fine grinding operations. By considering both fine grinding efficiency and surface quality, the best choice of travel speed for fine grinding operations should be equal to or less than \( 2\pi \epsilon f/60 \).

3.2. Effect of Various Inner Diameters of Fine grinding Tool Rings on Fine grinding Quality

We can fix all other parameters and study only the effect of inner diameter of the fine grinding tool ring on fine grinding quality via computer modeling and simulation. One can easily conclude from these results that the larger the area of fine grinding tool ring is covered, the better the surface quality of the workpart will be. In sectional view of the grinder head, the speed of any arbitrary point on fine grinding tool head surface can be estimated by \( d \pi n/1000 \). It is obvious that the fine grinding speed of the spinning head becomes greater as the distance from the center become larger. Because of that, the ring type of fine grinding head is usually used in practice. As the distance from the center of the ring becomes smaller, the tangential fine grinding speed and the efficiency of the operation become negligibly small. In order to enhance the fine grinding efficiency and to temporarily store the chip and the departed particles, the ring type of fine grinding head is definitely a good choice.

3.3. Effect of Various Cycloid Motion Frequencies on Fine grinding Quality

The influence of cycloid motion frequency on the average (uniformity) and the standard deviation (compactness) of the contact frequency on each point of the workpart surface is not significant. This is because the amplitude of the cycloid curve mainly determines the pattern of moving trajectory. This is because when the frequency is increased, the time span for the fine grinding tool ring to stay in a region is decreased. As the frequency is decreased, the time span for the fine grinding tool ring to stay in a region is increased. However, the frequency cannot be too low or too high. In other words, if the frequency becomes too low, permanent white bank area will start to appear and surface quality degenerates. If the frequency becomes too high, structure induced vibration becomes severe and the fine grinding quality deteriorates. The best chosen frequency based upon the simulation result and reasoning given above is approximately 60 cycles per minute.

4. Fabrication of the cycloid motion generator machine

Generally speaking, the fine grinding quality of the workpart depends closely upon uniformity, homogeneity and the compactness of the trajectory planned for superfinish fine grinding operations. In other words, it depends on the optimally chosen parameter set obtained from the above simulation study. The synthesis of these three types of motion is not difficult at all theoretically. However, in real design process the structural stability becomes an extremely crucial issue, especially when the system
is operated at high speed. Various possible combinations that allow the fine grinding trajectory to be synthesized were tested. Among these four combinations, the first three are not ideal since in these cases the fine grinding tool head is rotated at high speed and travels in a planned path simultaneously. These combinations can introduce extra interference between the modes of self-spinning and the surface travel motion. The vibration in radial direction becomes severe and the operational instability can be easily induced. The fourth combination becomes the best synthetic machine that is stable since each mode of motion can be independently implemented on the CNC machine center. The interference between modes of motion is eliminated and the machine can be easily programmed to produce the planned fine grinding trajectory.

**Figure 3.** Principle of fine grinding operations.

**Figure 4.** Cycloid motion generator.

In the fabrication of the cycloid motion generation machine, we employed two eccentric rods connected by a flexible belt in between to drive the working platform. However, in practice the
system can sometimes be locked in certain motion cycles since the flexible connecting element between the two eccentric rods does not provide the synchronization in motion. The phase lag between these two rods can lock the system easily. In order to alleviate the problem, an innovative design is proposed and constructed, as given in Figures 3-5, for this study. The implemented system is composed of three layers of steel plates. A motor driven rotating bi-eccentric rod is used to drive these three layers of steel plates to produce required relative motion. The eccentricity at the bottom portion of the rod is used to create the relative left-right motion between the bottom two layers of steel plates. The relative front and back motion between the top two layers of steel plates is generated by the eccentricity built on the rotating rod. The function of this new design is almost the same as the two-rod design case. It is, however, structurally simple, stable and reliable for superfinish fine grinding operations.

An experimental study is conducted to verify the effectiveness of the proposed super-finish fine grinding technique and the validity of the fine grinding motion trajectory generating system. Figure 6 shows the complete experimental setup. The cycloid fine grinding motion generator is mounted on the worktable of the CNC machine center that is programmable for a complete planned trajectory. Four different types of workpart materials are used for tests. These include coppers (Cu), alloy steels (SKD-61), mirror-faced steels (FDACF), and tool and die steels (SLDF-11). Tables 1-3 list the fine grinding quality for various working conditions. From these experimental results the following conclusions may be drawn:

- The improvement on fine grinding quality can be greatly enhanced if the hardness of the surface layer is hardened. On the other hand, the improvement on fine grinding quality can be very limited if the hardness of the surface layer is not high enough. The workpart surface made of copper materials cannot produce fine grinding surface of expected quality. This is because the workpart surface made of soft materials can easily be intruded by impurity and thus the fine grinding quality is deteriorated.
The surface quality of the workpart ground at a feed-rate of 5mm/min is better than the result of the workpart ground at a feed-rate of 50mm/min. Theoretically speaking, the fine grinding trajectory at a feed-rate of 5mm/min falls into the range of long amplitude curve. The overlapping of the major path is high. The overall distribution of the major trajectory is complicated and homogeneous; the fine grinding surface quality is certainly better.

The improvement on the surface quality of the workpart is not very obvious even when the rotating speed of the fine grinding head is greatly increased.

**Figure 6.** Structure used for surface fine grinding experiments.

**Table 1.** Results of experiment (1).

| Parameter                        | Value 1 | Value 2 | Value 3 | Value 4 |
|----------------------------------|---------|---------|---------|---------|
| Feed-rate                        | s = 50 mm/sec |
| Gyroid motion frequency          | f = 60 cyc./min. |
| Diameter of the fine grinding tool head | d = 25 mm |
| Fine grinding speed               | n = 2000 rpm |
| Eccentricity                     | e = 1 mm |
| Working length                    | L = 3 cm |
| Tool material                     | FDACF, SKD-61, Cu, SLD-11 |

| Surface quality before fine grinding | R_a = 0.221μm, R_p = 0.407μm, R_s = 0.842μm, R_y = 0.142μm |
|-------------------------------------|---------------------------------------------------|
| Fine grinding for 45 min.           | R_a = 0.052μm, R_p = 0.102μm, R_s = 0.301μm, R_y = 0.063μm |
| Fine grinding for 90 min.           | R_a = 0.044μm, R_p = 0.061μm, R_s = 0.205μm, R_y = 0.057μm |

**Table 2.** Results of experiment (2).

| Parameter                        | Value 1 | Value 2 | Value 3 | Value 4 |
|----------------------------------|---------|---------|---------|---------|
| Feed-rate                        | s = 5mm/sec |
| Gyroid motion frequency          | f = 60 cycles/min. |
| Diameter of the fine grinding tool head | D = 25mm |
| Fine grinding speed               | N = 2000 rpm |
| Eccentricity                     | e = 1 mm |
| Working length                    | L = 3cm |
| Tool material                     | FDACF, SKD-61, Cu, SLD-11 |

| Surface quality before fine grinding | R_a = 0.195μm, R_p = 0.413μm, R_s = 0.629μm, R_y = 0.144μm |
|-------------------------------------|---------------------------------------------------|
| Fine grinding for 45 min.           | R_a = 0.041μm, R_p = 0.203μm, R_s = 0.211μm, R_y = 0.098μm |
| Fine grinding for 90 min.           | R_a = 0.030μm, R_p = 0.052μm, R_s = 0.127μm, R_y = 0.033μm |
Table 3. Results of experiment (3).

| Feed-rate | s = 5 mm/sec |
|-------------------------|-------------------------|
| Cycloid motion frequency | f = 60 cyc./min. |
| Diameter of the fine grinding tool head | d = 25mm |
| Fine grinding speed | n = 3000 rpm |
| Eccentricity | e = 1 mm |
| Working length | L = 3 cm |

| Tool Material | Before Fine Grinding | Fine Grinding for 45 min. | Fine Grinding for 90 min. |
|---------------|----------------------|--------------------------|--------------------------|
| FDACF SKD-61 Cu SLD-11 | $R_a = 0.194 \mu m$ $R_a = 0.408 \mu m$ $R_a = 0.306 \mu m$ $R_a = 0.152 \mu m$ |
| $R_a = 0.028 \mu m$ $R_a = 0.195 \mu m$ $R_a = 0.177 \mu m$ $R_a = 0.084 \mu m$ |
| $R_a = 0.020 \mu m$ $R_a = 0.041 \mu m$ $R_a = 0.101 \mu m$ $R_a = 0.022 \mu m$ |

The above conclusions of number two and number three drawn from experimental results agree very well with those of the analytical results. As far as the conclusion number one is concerned, the reason indeed is quite obvious and intuitive.

6. Conclusion

The fine grinding methodology presented in this paper is a new fine grinding technique that uses superfinish fine grinding trajectory planning approach to enhance surface quality of workparts in a short period of time. The method has several distinct features that are not shared by many existing fine grinding approaches. These features include:

- The superfinish fine grinding system presented in this paper utilizes a fine-tuned trajectory planning technique to enhance the uniformity, homogeneity, and compactness of the fine grinding contact frequency over each point on workpart surface under constant pressure. Based upon the simulation result obtained by using the compact computer program developed for this study, key process and system parameters and their associated working ranges for generating optimal regenerative trajectory plan can be characterized. The optimized parameters thus obtained are used to construct a constant-pressure high speed turning grinder device that is driven by the spindle of a NC machine.

- The superfinish fine grinding system thus built is independent of the inherent accuracy limit of the machine structure itself. It depends only upon the uniformity, homogeneity, and compactness of the fine grinding trajectory and contact frequency over each point on workpart surface under constant pressure. The planar surface thus produced by using the optimized system parameters can achieves the high level quality of 0.02 micron.

- Uniformity, homogeneity, and compactness of the fine grinding trajectory are major factors that affect the quality of the final product surface. As far as the feed-rate and eccentricity are concerned, the fine grinding trajectory will become denser as the value of eccentricity is greater than the feed-rate. If the surface quality is the only concern, the best condition occurs at the feed-rate that is one half of the value of eccentricity. When both of surface quality and fine grinding efficiency are considered, the best condition occurs at the feed-rate that is equal to the value of eccentricity.

- Since the study focuses upon the development of a structural independent superfinish fine grinding system, the initial surface condition of the workpart needs to be at least shaped and polished to the level of 5 μm. After 90 minutes fine grinding using the proposed theory and the optimally designed and built machine system, the surface quality can be improved to a level of 0.02μm.

- It is verified by experimental results presented above that the superfinish fine grinding system proposed in this paper can enhance surface quality of workparts in a short period of time. In addition, the method also possesses some distinct features including simplicity in system integration, low cost, high efficiency, easy operation and programmable automation. Since it
is independent of the stiffness of CNC machine structure, it does not require the personnel of advanced skills.

Further study on developing the system that allows various fine grinding curves other than the cycloid is on the way. The feasibility study of soft fine grinding tool heads and high-speed constant-pressure pneumatic fine grinding strut for free curve surface fine grinding is also in progress.

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