The Study of Nanometer-Grade Grinding Surface for Precision Molds

Ho-Hua Chung*, K. L. Yang** and Hsin-Tzu Liao***

Keywords: Precision grinding, Surface roughness, Grinding speed.

ABSTRACT

The SKH mold steels were pre-processed, ground by the precise sharpening stone to have $Ra=10^{-15}$ μm for subsequent precise grinding allowance, and then precisely ground by the CBN grinding wheel. The influence of the main axle rotation speed and the sample hardness on the grinding situation was discussed in this study. The result shows that the surface roughness of the low hardness SKH51 mold steel could be improved markedly as rotation speed increased. On the contrary, there is no obvious improvement for the high hardness SKH59 mold steel. With increasing rotation speed, the surface roughness of workpieces improved significantly due to the increasing of grinding force. However, at high rotation speed, it was unable to get further improvement since the grinding force nearly remaining the same level, causing the less improvement on the surface roughness of workpieces.

INTRODUCTION

Cutting machining technology is among the most effective methods for mold machining. At present, machining by using CNC lathes with milling turret and end milling machining in a leading CNC machine center are the most common methods for products machining. However, after the rough machining, the surface of the mold is extremely rough. To smooth the mold surface, it should be treated again by the finish machining and hand polishing. This process relies on experienced technician, and it costs a long time. Moreover, the precision and the quality of molds are difficult to be further enhanced by the manual operation. Therefore, the main goal of high-speed mold processing is to obtain the high precision of free curve surface, to shorten the polishing operation time, and to lower the manufacturing cost. Especially, in the recent years, the combination of high-speed mold processing with high hardness materials is usually used in the mold industry to enhance the competitiveness of processing technology.

In order to obtain submicron-grade ($10^{-7}$-$10^{-8}$ m) shape accuracy and nanometer-grade ($10^{-9}$ m) surface roughness, diamond milling, diamond lathing, and diamond grinding are usually used in ultraprecision machining. Computer simulation done by Hasegawa and Miyazima pointed out that the improvement of surface roughness of workpieces would reach a saturation value under a long time polish, and it’s hard to be further improved. Weck developed an ultraprecision machining by using a diamond-cutting tool, by which the surface roughness of workpieces could be reduced to below 5 nm. As a consequence, the manufactured miniature components could also be applied in the semiconductor industry. Takeuchi developed a five-axle ultraprecision machine, which have hydropressure ball screws and a servomotor within its cap. This machine usually attached a super-resolution optical encoder with 6,400 million pulses per revolution. The surface roughness could be reduced to about 50 nm under extreme low feeding rate, because there were no friction force and backlash questions.

It is necessary for machining tools to have excellent dynamic characteristics and high rigidity especially for machining brittle materials. Patent Tetraform “C” developed by Stephenson and Corbett reported that the surface finish was produced better than 10 nm by using a 76 μm CBN wheel and the electrolytic in-process dressing (ELID) assisted grinding. Combination of the high-rigidity
machine and manufacturing process, the removing rate of ultraprecision machining could be increased significantly. Shape accuracy and surface roughness are also very important in the semiconductor industry. Surface roughness demanding for silicon wafer is about at nanometer grade. Surface roughness for optoelectronics and memory devices is an important factor directly affecting the performance of product. In brief, the current trends in ultraprecise machining are to achieve nanometer-grade milling and turning in hardened steels, to improve the precision of products, to extend the life of precision molds, and to reduction of surface roughness of workpieces.

In order to save energy and environmental conservation, surface roughness in degree of nanometer of fasteners for transmission parts used in vehicles has increased its essentiality. At present, hardened mold steel, which is a common precision fastener material, is usually manufactured by precise grinding. In the future, high-efficiency precise grinding and variant nanometer hard turning technologies will be developed for grinding precision molds. In this research, SKH tool steels are chosen as the mold workpieces, and the effect of grinding speed, material hardness, grinding force and feeding rate on the surface roughness of workpiece will be studied.

**EXPERIMENT METHOD**

**Equipmental set-up**

In this study, a high rotation speed micro-grinder installing the peripheral measurement system and many kinds of different processing equipment (such as numerical control lathe/milling machine, fourth axle) were used to conduct the research. As illustrated in Fig. 1, the operation procedures of this high rotation speed automatic precise micro-grinder were showed. Firstly, after heat treatment, the high hardness material was pretreated by diamond machining and diamond cutting. Secondly, the surface roughness of workpieces was reduced to $R_a=10-15 \, \mu m$ for subsequent precise grinding allowance. Thirdly, matching CBN grinding wheel at...
high rotation speed, XYZ axle and the fourth axle reciprocation with moves, the curved surface and line grinding-truncating by the diamond scribing tool, and constructing the outline of grinding-truncating by the CAD/CAM with parameters obtained from experiments, the unwanted part of the surface of workpiece was removed and the incisive extremely hard ultra micron diamond burr or abrasive particles were revealed. Finally, the movement path of grinding wheel produced by the diamond scribing tool was duplicated to the heat-treated mold tool steel to have the micrometer-grade precise contact type grinding and then the surface roughness can reach below 50 nm.

**Experimental procedure**

Three types of mold tool steels (SKH51, SKH55 and SKH59) were chosen as the work samples, and then were marked with different colors in classified. The processing of work samples was carried on as the following steps:

1. Cutting: Rough cutting to close to the sample length.
2. Rough machining: Contour machining by the disc or cylinder grinding wheel. Trimming: Trim two sides of the cutting end.
3. CNC rough lathe: Lathe the outer diameter from the lathe program.
4. CNC rough milling: Shape milling from the milling program.
5. Thermal treatment: Work samples were austenized at 1165°C, 1200°C and 1165°C, respectively, and then quenched. Subsequently, the samples were annealed at 560°C three times to obtain the Rockwell hardness of 60, 63 and 67 HRc. The chemical compositions of the samples were summarized in Table 1.
6. Precision lathing: Lathe to standard length.
7. Precision grinding: Grinded to the geometry as illustrated in Figure 2, and then cleaned before conducting the experiment.

The workpieces were using acetone placed in an ultrasonic cleaner cleaned for several minutes, and then the surface roughness were measured by the surface roughness measurement instrument. The workpieces were fixed on the speed micro-grinder with super-high rotation speed (Fig. 1). In order to investigate the influence of the cutting speed and the sample hardness on the grinding situation, the operation variables were rotation speed, depth of cut, horizontal feeding rate, cooling jet, concentration and temperature of grinding slurry. The detailed experimental condition was as listed in Table 2.

<table>
<thead>
<tr>
<th>Test sample</th>
<th>Chemical Composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample C</td>
<td>Cr</td>
</tr>
<tr>
<td>SKH51</td>
<td>1.07</td>
</tr>
<tr>
<td>SKH55</td>
<td>1.11</td>
</tr>
<tr>
<td>SKH59</td>
<td>1.17</td>
</tr>
</tbody>
</table>

**Table 2:** The experimental conditions for the grinding process of mold tools

<table>
<thead>
<tr>
<th>Item</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test sample material</td>
<td>SKH51, SKH55, SKH59</td>
</tr>
<tr>
<td>Grinding wheel</td>
<td>CBN80N75B11V26, d=125mm</td>
</tr>
<tr>
<td>Rotation speed (rpm)</td>
<td>5000, 6500, 7000, 8000, 9000</td>
</tr>
<tr>
<td>Work table velocity (mm/min)</td>
<td>90-150</td>
</tr>
<tr>
<td>Optimum depth of cut (mm)</td>
<td>0.03-0.2</td>
</tr>
<tr>
<td>Grinding slurry temperature (°C)</td>
<td>Input: 28-29; Output: 30-31</td>
</tr>
<tr>
<td>Grinding slurry concentration</td>
<td>original grinding fluid/water=3:97</td>
</tr>
<tr>
<td>Cooling jet</td>
<td>Volumetric flow rate: 20 m³/h · pressure: 8 bar</td>
</tr>
</tbody>
</table>

**Figure 2:** The geometry of the precision grinded hexagon punch.
Under each kind of rotation speed, depth of cut, feeding rate, grinding force, the vibration frequency, and the grinding temperature of grinding slurry were determined by the high-precision load cell, the digital storage vibrations measuring meter and the non-contact thermometer. After grinding, the surface morphology of workpieces was examined by the scanning electron microscope (SEM). Moreover, an energy dispersion spectroscope, the Rockwell hardness tester, and the surface roughness measurement instrument were also used to characterize the grinding mechanism of SKH steel processing surface. Finally, the processing efficiency of hard vehicle mill and precision grinding was assessed via the experimental result.

RESULTS AND DISCUSSIONS

Surface Behavior of CBN Grinding Wheel

The major purpose of high speed mold processing is to obtain the high accuracy free curved surface, to reduce the polishing time, and to lower the cost. The high efficient grinding is by the CBN grinding wheel, the high main axle rotation speed, and the high rate of movement and deeper entering. Its cutting quantity was several hundred times than the traditional grinder and the grinding wheel shape is all the same from the beginning to end during the period of the whole grinding process. Therefore, the nanometer-grade grinding surface could be obtained by omitting the repairing and maintaining procedure of grinding wheel and the change of cutting condition. The hardness of the mold surface was usually higher than HRc 60 and the general cutting tool could not process it when its surface was hardened after heat treatment. Moreover, the request of mold precision and surface smoothness was too high to be established by the general cutting tool. The CBN grinding wheel was the best method used for the precision processing of mold surface because it had the multi-cuttings angle and the regeneration property.

Figure 3 shows the relationship between grinding force and cutting speed for different SKH mold steel materials when the feeding rate and the depth of cut were maintained at 150 mm/min and 0.05 mm, respectively. For the three kinds of SKH mold steel materials, it is clear that the grinding force decreased markedly when the cutting speed was increased from 2000 to 2750 m/min and then approached a saturation value. This result is due to the fact that the heat generated from the grinding of mold tool can be easily dissipated form CBN grinding wheel itself and not transfer to the workpiece because CBN has high thermal conductivity. Therefore, along with an increasing of cutting speed, the cutting temperature was easy to concentrate on the grinding particles of CBN grinding wheel and leading to reduce the grinding force gradually. On the other hand, it was also found from Figure 3 that, under the same value of cutting speed, the grinding force of SKH59 mold steel is smaller than that of SKH51 and SKH55 due to the higher carbon content and the higher hardness. This result can be explained by the phenomenon that SKH59 has lower soft temperature and the carbide can be separated after quenching. The separated carbide affects the friction factor of cutting surface and then leading to reduce the grinding force. The analysis of the separated material will be further discussed in the next section. Aspinwall and Ng studied the variation of grinding force with cutting speed for AISI H13 mold steel with different hardenability and the result showed that, with the same cutting condition and the same material, the grinding force was not necessarily large for the higher hardenability workpiece.

In the aspect to grinding force, the cutting temperature will increase to some degree with an increasing of cutting speed and then the heat concentrates on the grinding particles of the CBN grinding wheel. When the quantity of concentrated
heat surpassed the bonding strength of the grinding particles, the grinding force increased slightly from 3140 to 3533 N/min was generation due to excessive abrasion of grinding particles. Because the shape of grinding particles of the grinding wheel approaches the diamond very much, as shown in Figure 4, at the lower cutting temperature the attrition of grinding particles is from the base and the grinding wheel produces the smaller abrasive area. If the quantity of heat was too concentrated on the grinding particles of the CBN grinding wheel, the larger abrasive area and the higher softening temperature of the workpiece will be produced. Under the dual action, the grinding force presents a gradual and slight rise and then approaches a saturation value. The reason of using the CBN grinding wheel is that it has the advantages of higher material-removing rate, easily grinding, about 40-50% of CBN crystals exposing in outside, easily cutting, and maintaining the same shape from the beginning to the end. Therefore, the finishing procedure of grinding wheel can be omitted and the opportunity of heating damage of workpiece surface is also reduced. So, the surface roughness of workpiece is equivalent to the result of grinding. At the grinding process of high cutting speed, it is easier to enable the surface roughness of workpiece to achieve a finer result due to the reason that the grinding force is slightly increased and then approaches a saturation value.

Effect of cutting speed and hardness on surface roughness

The major purpose of using the hard grinding principle in the field of high hardened material processing is to obtain the high precision free curved surface and to shorten the surface polishing time. However, the influence of cutting speed and hardness on the roughness quality of workpiece is really large. With the same feeding rate, the variation of roughness with hardness at different axle rotation speed was illustrated in Figure 5. It can be seen from Figure 5 that the surface roughness was decreased with an increasing of axle rotation speed. On the other hand, the lower axle rotation speed is, the change of surface roughness quality is bigger but the effect of axle rotation speed is slight at higher rotation speed (8000-9000 rpm). This result is in agreement with the findings in Figure 3. When the cutting speed changes from 2000 m/min to 2500 m/min, the variation of surface roughness is quite marked since the variation of grinding forces is very large. It is also found that the grinding force decreases to a saturation value for the three materials (SKH-51, SKH-55, and SKH-59) when the cutting speed surpasses 2500 m/min. One can infer that the micro-grinding effect occurs on the workpiece surface by contacting with the CBN grinding wheel. The result limits the improvement of roughness of workpiece surface, and it is unable to further obtain a finer surface. In addition, from the result of Figure 5, it can be found that the surface roughness decreases with an increasing of workpiece hardness for a given axle rotation speed. Moreover, it is also seen that the effect of hardness on the surface roughness is not obvious at the high axle rotation speed.
According to the floating polishing process suggested by Su, machine tools under high speed machining, the wedge effect between the CBN grinding wheel and workpiece resulted a hydrodynamic pressure. The pressure acts as a slurry fluid film, promoting a shear flow field to abrasive grains. Hence, a steady state movement of abrasive grains between the grinding wheel and the workpiece was formed. The flow of abrasive grains continuously removed surface atoms of machine tools. As a consequence, surface roughness of the machine tools was reduced to 50 nm.

**Surface Morphology of the Grinding Materials**

Under the shear stress of the flow field, abrasive grains produced a machining force to atoms of the workpiece, grinding trails were resulted. The surface morphology of different SKH workpieces and the grinding wheel before and after grinding by the CBN grinding wheel would be revealed. The variation of axle rotation speed and hardness would affect surface roughness of the grinding surface. As a result, the rough surface undulations of the polishing surfaces and the fluid machining surfaces of the three mold tool steels after thermal treatments was compared. The grinding mechanism of the grind wheel and workpieces under different working conditions could be clarified.

Figure 7 shows the typical SEM micrographs of the three mold steels after thermal treatments. Carbides are precipitated at martensite matrix grain boundaries. The amounts and grain sizes of the precipitated carbides are modified with adding high-melting point elements such as Mo, W, and Co, etc., into mold steels or the variant carbon content of mold steels. After polishing by Al₂O₃ suspensions, Ra was reduced to 0.04-0.05 μm of the mold steels. The grain sizes of the precipitated carbides of SKH55 and SKH59 mold steels are larger than that of SKH51. In addition, it could be found that the larger precipitated carbides resulted in serious crack at grain boundaries due to the containing of the Co element. The hardness of the mold steels is also variant from the composition of the precipitated carbides, which
affecting the grinding mechanism.

Figure 8 shows the surface morphology with variant axle rotation speed of the grinding wheel for different hardness of SKH workpieces. In Fig. 8 (a), with the axle rotation speed of 5000 rpm, the surface of SKH51 mold steel, which has low hardness compared to the other SKH55 and SKH59, was very rough. As the rotation speed increased to 9000 rpm, the surface roughness was obviously improved and clear grinding trails caused by abrasive grains could be observed in Fig. 8 (b). However, there is no abrasive grain trails appeared in the high hardness SKH59 steel despite the increasing of rotation speed (Fig. 8 (e) and (f)). The surface roughness is reduced to about 50 nm for SKH59 mold steel and the morphology is similar to that in Fig. 7, only polishing with Al2O3 suspensions. Su and Hamrock reported that under hydrodynamic polishing process, surface roughness was gradually reduced while grinding but it could not further be reduced as the grinding degree approached a certain amount in the half-contact lubrication zone. From Fig. 3, as the cutting speed exceed 3000 m/min, the grinding force decreased to saturation value. It implies that surface roughness could not be further improved as the hydrodynamic pressure was formed, as seen in Fig. 8 (d) (e) (f). As a result, workpieces with high hardness would remain their surface roughness under lower cutting speed due to the limit work hardening capacity. It promoted the feasibility to grind miniature components by high

Figure 8: SEM micrographs showing the surface morphology for different thermal treated mold steels after grinding by the CBN grinding wheel under variant rotation speeds (magnification 3000x).
hardness precision mold. It could be concluded that with increasing cutting speed to 3533 m/min, surface roughness was obviously reduced for low hardness SKH51 mold steel. However, surface roughness was not changed while grinding even the cutting speed lower to 2000 m/min for high hardness SKH51 mold steel.

CONCLUSIONS

The effects of grinding force, feeding rate, and surface roughness on hardened SKH mold steels could be concluded as follows. These results provide a reference for grinding processing of precise mold steels.

(1) As the cutting speed remained within 2000 to 2750 m/min, a significant improvement of surface roughness was occurred due to the large grinding force. However, as the cutting speed increased exceeding 2750 m/min, the grinding force decreased markedly and then approached a saturation value. The surface roughness could not be further improved.

(2) Microstructural observation revealed the influence of the main axel rotation speed of grinding wheel and the hardness of workpieces on surface roughness. With increasing rotation speed, the surface roughness improved obviously for the low hardness SKH51 mold steel. However, minor improvement was observed for the high hardness SKH59.

(3) With proper precise grinding under the optimum grinding condition of feeding rate of 0.03~0.05 mm/pass, rotating speed of CBN grinding wheel of 9000 rpm, and work table velocity of 90 m/min, surface roughness of the heat treated SKH series mold steel could be reduced below 50 nm.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the sponsorship from National Science Council of Taiwan, ROC, under the project no. NSC-93-2622-E-244-010-CC3. They also acknowledge the Wan Yi Tool Co., Ltd., which supporting the corresponding materials and equipments.

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精密模具用的奈米級研磨
表面之研發

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摘要
模具加工高精度化之目的主要在於得到高精度化之自由曲面及短縮拋光作業時間。特別在高速磨削搭配高硬度材料的使用是近年來國內外模具業者競相採用以提高競爭力的加工技術。本研究係以不同系列SKH模具鋼材作前置加工，再用精密磨石研磨達Ra=10~15μm預留為微細加工部分，然後又以CBN砂輪精密研磨模具鋼表面。探討不同主軸轉速、進給率及工件硬度之一些加工機制，包括CBN砂輪特性、磨削力、工件表面粗糙度及磨痕顯微相片等變化。結果顯示在較低硬度SKH51模具鋼磨削時提高轉速時顯著改善表面粗糙度，但是對較高硬度SKH59模具鋼磨削時轉速的影響較不顯著。此外，當較低磨削速度時，磨削力變化很大，造成工件表面粗糙品質變化相當顯著。但當較高磨削速度時，磨削力變化幾乎維持水平，導致工件表面粗糙品質改善趨於緩和，無法在進一步得到較精緻表面粗糙度。