The Analysis of Grinding Machinability for the High-speed End Mill of Cemented Tungsten Carbide

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Abstract

This paper investigates the influence of grinding parameters to surface roughness in a case of grinding a high-speed endmill of cemented tungsten carbide using a five-axis CNC tool grinder. The values of surface roughness have a significant influence on wear resistance, lubricating capability, precision, noise and life of an endmill. Therefore, it can be served as a significant performance index for evaluating the grinding quality of tools. The grinding parameters effecting surface roughness most are grinding speed, feed rate, and grain mesh size. In this study, three levels are selected for each grinding parameter. The layout of experiments is obtained using the full factorial design. The results show that, among these three controllable grinding parameters, grain mesh size has the most significant influence on surface roughness, while grinding speed has the least. As grain mesh size is #800, feed rate has no notable effect. In order to get a desirable minimum value for surface roughness, the optimal combination of grinding conditions is grinding speed of 1000 m/min, feed rate of 100 mm/min, grain mesh size of #800. As for enhancing grinding efficiency, the desired combination of grinding conditions is grinding speed of 1000 m/min, feed rate of 400 mm/min, and grain mesh size of #800.

Keyword: surface roughness, tool grinding, grinding parameters.

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I. Introduction

An important trend of developing machine tools in industry is promoting a high-speed technology combined with high rotational speeds, high-speed feed rate, as well as low-depth cutting. It's commonly applied in aviation, automobile, mold, and 3C industry etc. for finishing. A desirable high-speed cutting technology requires not only a high-speed machine center with excellent performance but also a tool with high quality.

Endmill grinding is a kind of precision finishing. Hence, to get this tool with excellent quality requires a relatively high-level technology. The performance indexes selected to effectively evaluate its quality are not only basic geometric characteristics of tools but also a more important index called surface roughness of tools. Generally, the latter has a significant influence on wear resistance, lubricating capability, precision, noise and life of tools. Hence, an optimal grinding quality can be achieved by fully understanding the influence of surface roughness on grinding parameters and properly selecting values of grinding parameters.

In the past few years, researches have written a lot of papers documenting the influence of surface roughness on grinding parameters and the construction of prediction models of surface roughness [1-6]. However, a related research was rarely done on high-speed tool grinding. Therefore, this study is focused on grinding a high-speed endmill of cemented tungsten carbide using a five-axis CNC tool grinder. A surface roughness meter is used to measure the surface roughness of radial relief to exam its relation with grinding parameters; furthermore, suitable values of grinding parameters are determined to improve the quality of tool grinding.

In the following, the basic concept of tool grinding is introduced first. The experimental apparatus and experimental design are described next. The succeeding section illustrates the effects of the grinding parameters on the surface roughness of radial relief. Finally, conclusions are drawn.

II. Basic Concept of Tool Grinding

The geometric shape of a endmill is illustrated in Fig. 1. Its grinding processing is operated in the sequence of radial rake angle →radial relief and clearance angle →axial rake angle →axial relief and clearance angle (including end angle) [7, 8].

1. Grinding of Radial Rake Angle

To grind a flute on a circular bar, the machine must be equipped with a capability that it can be programmed to operate along X, Z, and C axis. As shown in Fig. 2, As the required condition of length

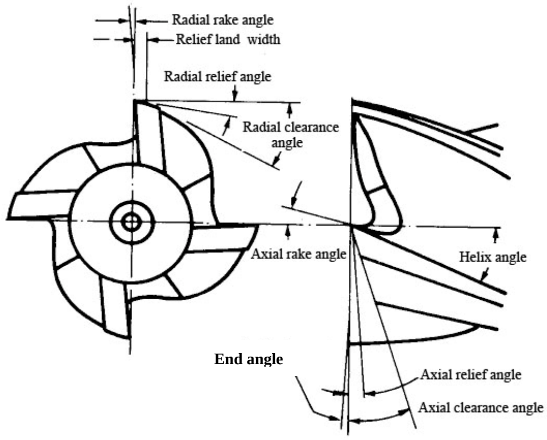

Fig.1 Various angles specified for endmills

for lead of helix is given, and the relative position between wheel grinding face and endmill cutting face is determined, the grinding process starts on point *a* and ends on point *b* with moving in X direction and rotating in C direction simultaneously. Then, the grinding wheel is retract from the generated flute by moving vertically along Z axis, and quickly returned to the original point *a* with moving in X direction and rotating in C direction simultaneously. A grinding process of radial rake angle is completed.

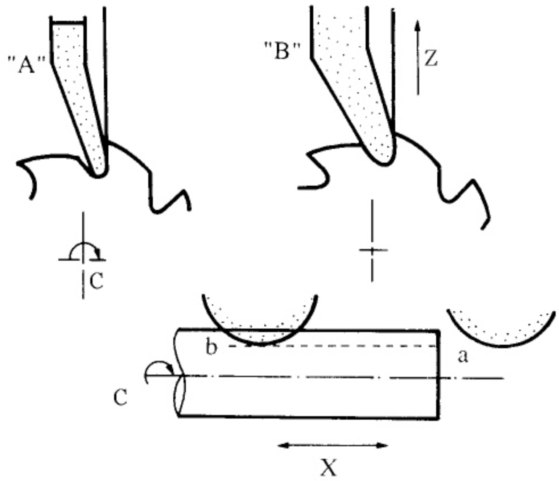

Fig.2 Grinding of radial rake angle

2. Grinding of Radial Relief and Clearance Angle

Due to the various types of grinding wheels and grinding method to be selected, the relief angle of an endmill can be classified into three types, e.g. concave relief angle, flat relief angle, and eccentric relief angle. As shown in Fig. 3.

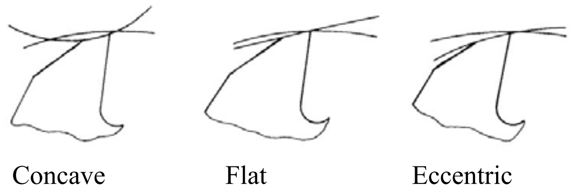

Fig.3　Common types of relief angle

i. Grinding of Concave Relief Angle

Endmills with concave relief angle are the most uncommon, since they have relatively low mechanical strength and can only be used for light cutting. The grinding wheels are usually of dish, cup, or plain shape. As shown in Fig. 4, they are deliberately chosen in the range of 125~200 mm in diameter and 45°~60° in angle so that the undesirable heat generated by frictional contact between the grinding wheel and the workpiece can be reduced, and a resulting burning phenomenon can be avoided.

The geometric relation of relief angle during grinding is shown in Fig. 5. The position of the endmill to be cut is fixed in the center point, while the height of the grinding wheel is subject to adjustment to control concave relief angle. The height difference between the center of the endmill and that of the grinding wheel can be expressed as:

$$H = \frac{D}{2}\sin\alpha = R\sin\alpha \qquad (1)$$

D : diameter of grinding wheel
R : radius of grinding wheel
α : radial relief angle of endmill

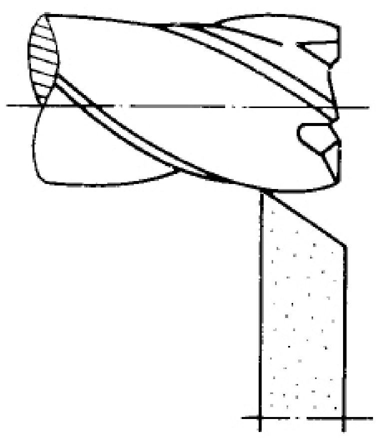

Fig.4　Grinding of concave relief angle using the tip of a grinding wheel

ii. Grinding of Flat Relief Angle

Among the various mills of the relief-angle type, the one of the flat-relief type is the most popular. The grinding wheel selected is usually of cup shape or dish shape and 100~125 mm in diameter.

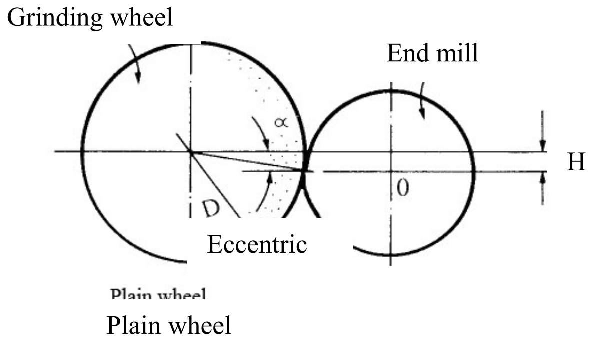

Fig.5　Height difference between the center of the endmill and that of the grinding wheel in grinding of concave relief angle

The height difference between the center of the endmill and that of the grinding wheel is similar to that of concave-relief type, and is shown in Fig. 6.

The grinding wheel can be inclined from radial direction to an angle equal to the radial relief angle of the mill. That is, the grinding wheel can be stayed in radial direction, while the mill is rotated to the required relief angle. It should be noted that the center of the grinding wheel still needs to be adjusted to the same horizontal position of the endmill. As the grinding wheel is operated up to the cutting edge, the mill will be automatically turned to the designated value of clearance angle. At this time, the grinding wheel should be controlled and kept in constant land of relief plane, the specified distance to the position where the wheel feed during grinding. As shown in Fig. 7, the calculated result can be an input to the computer program as a basis for modification.

$$Y = \frac{D}{2}\left(\cos\alpha_1 - \cos\alpha_3\right) - \sin\alpha_2 \times b_F \qquad (2)$$

D : diameter of the endmil
α_1 : radial relief angle
α_2 : radial clearance angle
$\alpha_2 : \alpha_3 - \alpha_1$
b_F : land of radial relief

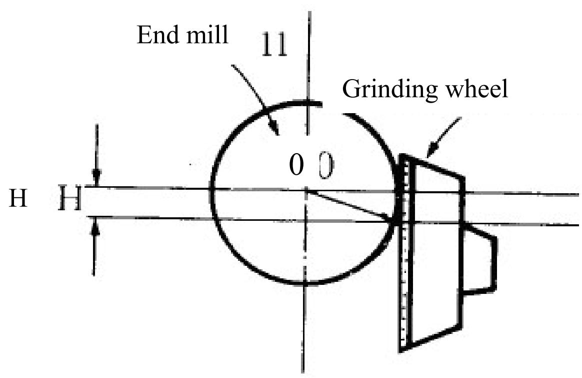

Fig.6　Height difference between the center of the endmill and that of the grinding wheel in grinding of flat relief angle

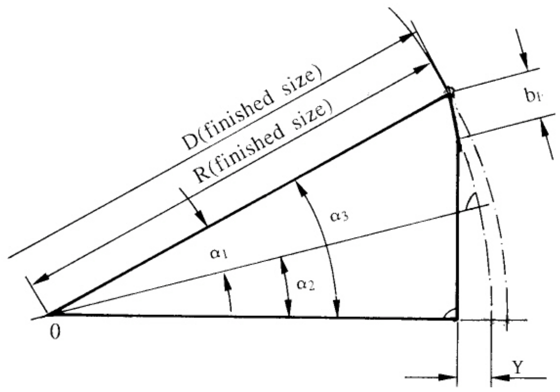

Fig.7　Geometric relation for calculating land of relief plane

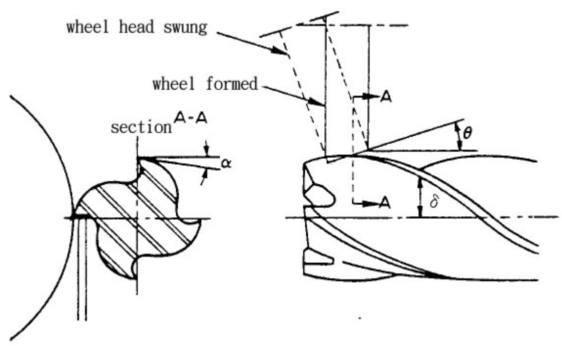

Fig.8　Geometric setting for the eccentric relief angle of the endmill and the grinding wheel

iii. Grinding of Eccentric Relief Angle

The endmill with the eccentric relief angle possess the best qualities in mechanical strength and cutting durability. Generally, a plain-shape grinding wheel is used for this type of endmill. The layout of the grinding wheel and the endmill is illustrated in Fig. 8. The center of the cutting edge of the endmill and that of the grinding whee l are located in the same horizontal position. The rotational angle in horizontal direction for the grinding wheel is dependent on the helical angle and the required eccentric relief angle of the endmill, that is,

$$\tan\theta = \tan\alpha \times \tan\delta \tag{3}$$

θ: rotational angle in horizontal direction for the grinding wheel

α : required relief angle of the endmill

δ: helix angle of the endmill

III. Experimental Apparatus

These experiments are carried out on a five-axis TG5 CNC tool grinder with 10 Hp using wet-cutting operation throughout the whole process. The workpiece for making tools is a circular bar made of cemented tungsten carbide with 60 mm in length and 8 mm in diameter. It is clamped on the chuck of the tool grinder with an overhung length of 45 mm. The relief angle is of flat-relief-angle type. Fig. 10 shows the schematic diagram of the grinding operations for flat relief angle.

The grinding wheel is a diamond grinding wheel of cup shape. Its specifications are grain mesh size of #300, #600 and #800, with $\phi 100mm \times W8mm$, $\phi 90mm \times W8mmx$, and $\phi 85mm \times W8mm$ respectively. A KEE JAAN KJ-1000 image measuring system is utilized to measure the diameter and the relative position for each grinding wheel. A SE3500 profilemeter is used to measure surface roughness of radial relief. The surface roughness parameter selected for this study is the average surface Ra that is widely used in industry. Its values are attained by taking measurement with a sampling length of 3mm and at a measuring speed of 0.1mm/s.

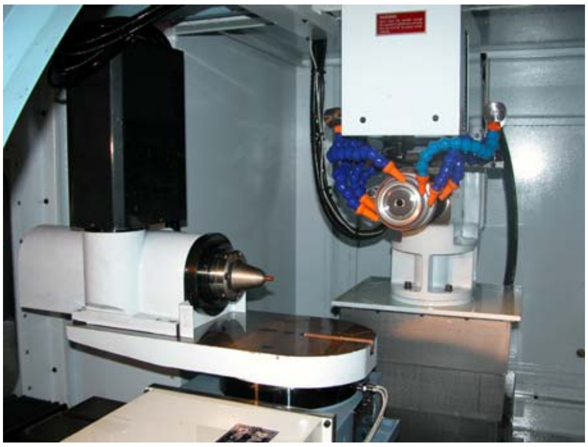

Fig. 9　Five-axis CNC tool grinder

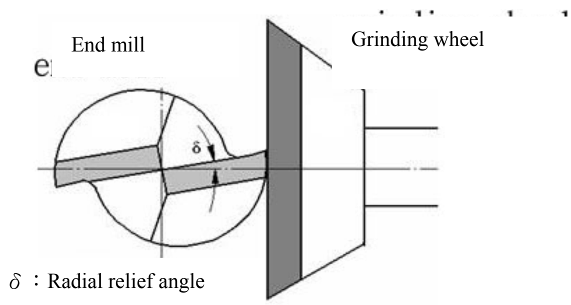

Fig.10　Schematic diagram for grinding of flat relief angle

IV. Experimental Design

In order to study the interrelation between surface roughness of radial relief and grinding parameters, a series of grinding experiments needs to be performed by selecting three grinding parameters and three levels for each parameter. The values of the grinding parameters and their levels are listed in Table 1. Since all the possible combinations of levels of grinding parameters need to be considered, the full factorial design is favorably adopted. The layout and results of the experiments are listed in Table 2.

Table 1 Grinding parameters and their levels

Grinding parameters	Unit	Level 1	Level 2	Level 3
Grinding speed	m/min	1400	1500	1600
Feed rate	mm/min	100	250	400
Grain mesh size	#	300	600	800

Table 2 Experimental layout and experimental results

No.	Grain mesh Size （#）	Grinding speed （m/min）	Feed rate （mm/min）	Surface roughness （μm）
1	300	1400	100	0.30
2	300	1400	250	0.62
3	300	1400	400	0.88
4	300	1500	100	0.27
5	300	1500	250	0.65
6	300	1500	400	0.90
7	300	1600	100	0.21
8	300	1600	250	0.52
9	300	1600	400	0.73
10	600	1400	100	0.27
11	600	1400	250	0.41
12	600	1400	400	0.50
13	600	1500	100	0.22
14	600	1500	250	0.38
15	600	1500	400	0.50
16	600	1600	100	0.19
17	600	1600	250	0.36
18	600	1600	400	0.48
19	800	1400	100	0.07
20	800	1400	250	0.11
21	800	1400	400	0.12
22	800	1500	100	0.08
23	800	1500	250	0.12
24	800	1500	400	0.14
25	800	1600	100	0.06
26	800	1600	250	0.09
27	800	1600	400	0.10

V. Results and Discussion

The effects of varying each grinding parameters on the surface roughness is shown from Fig.11 to Fig. 13.

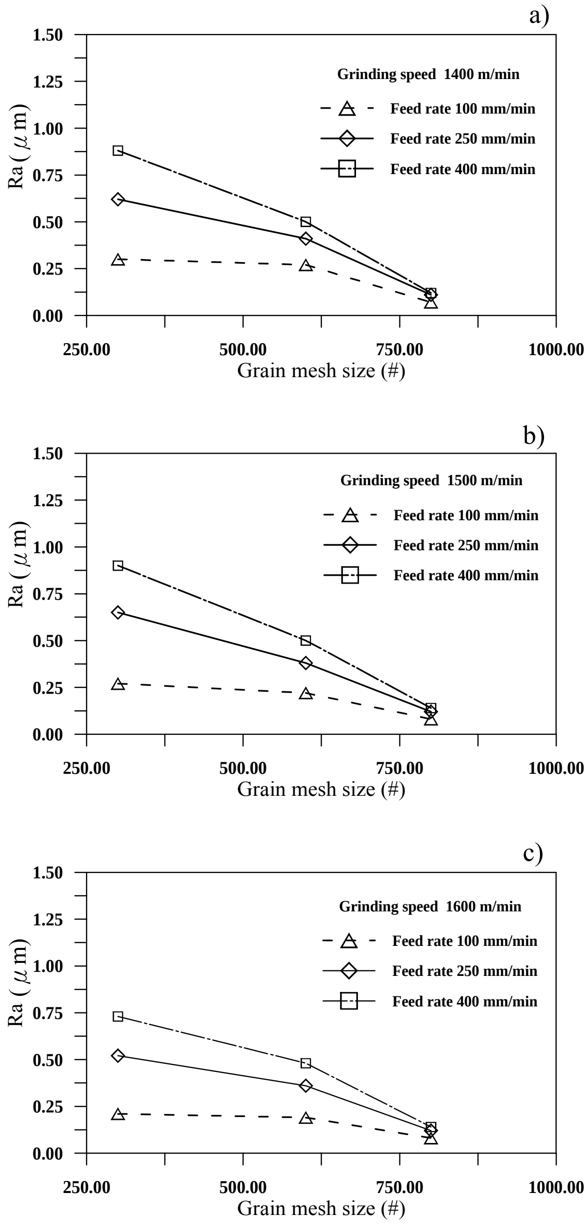

Fig.11 Effects of grain mesh size on surface roughness

1. Effect of Grain Mesh Size on Surface Roughness of Radial Relief

Fig.11 shows the effect of grain mesh size on the surface roughness of radial relief during the grinding process. It can be seen that surface roughness decreases as grain mesh size increases. The reason can be explained as follow. The larger grain mesh size is, the smaller abrasive grain is. Since the latter are the ones removed from the surface of the workpiece grinding, a smaller value of abrasive grain means that the corresponding value of surface roughness is smaller. Furthermore, the steep slopes of the three characteristic curves indicate that grain mesh size has a significant influence on surface roughness. This is further confirmed by the results using the analysis of variance shown in section 5.4. It can also be shown in Fig. 11 that the variations of three characteristic curves respect to various values of feed rate become relatively small as grain mesh size increases up to #800. Especially when grain mesh size is #800, the corresponding three curves are nearly coincided with each other. This shows that the effects of feed rate on surface roughness turn out to be more insignificant if grain mesh size is larger.

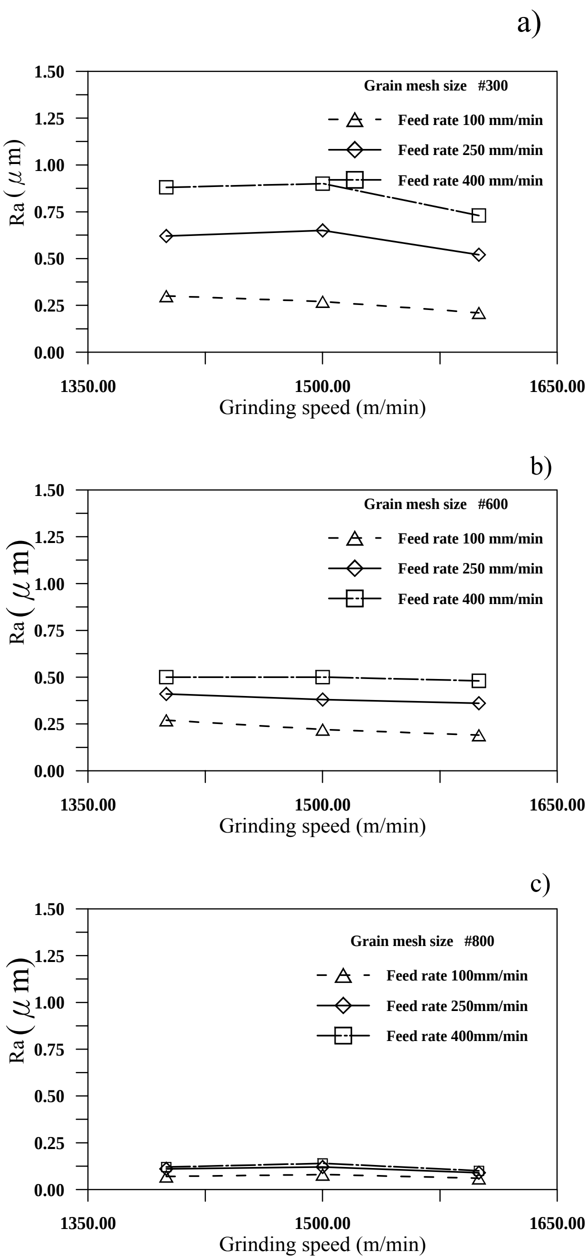

Fig.12 Effects of grinding speed on surface roughness

2. Effect of Grinding Speed on Surface Roughness of Radial Relief

Fig.12 reveals how grinding speed effects surface roughness of radial relief during grinding process. The influence of surface roughness of the workpiece is insignificant as grinding speed is in the range of 1400 mm/min to 1600 mm/min, since the corresponding slopes shown in the diagram are relatively small. This can be inferred that the grinding speed within this range has relatively small effects on surface roughness of workpices. This can be identified with the results using the analysis of variance shown in section 5.4. Furthermore, as seen in Fig.12(c), the three characteristic curves with grain mesh size of #800 almost overlap. This indicates that the effects of feed rate on surface roughness are negligible if grain mesh size is #800.

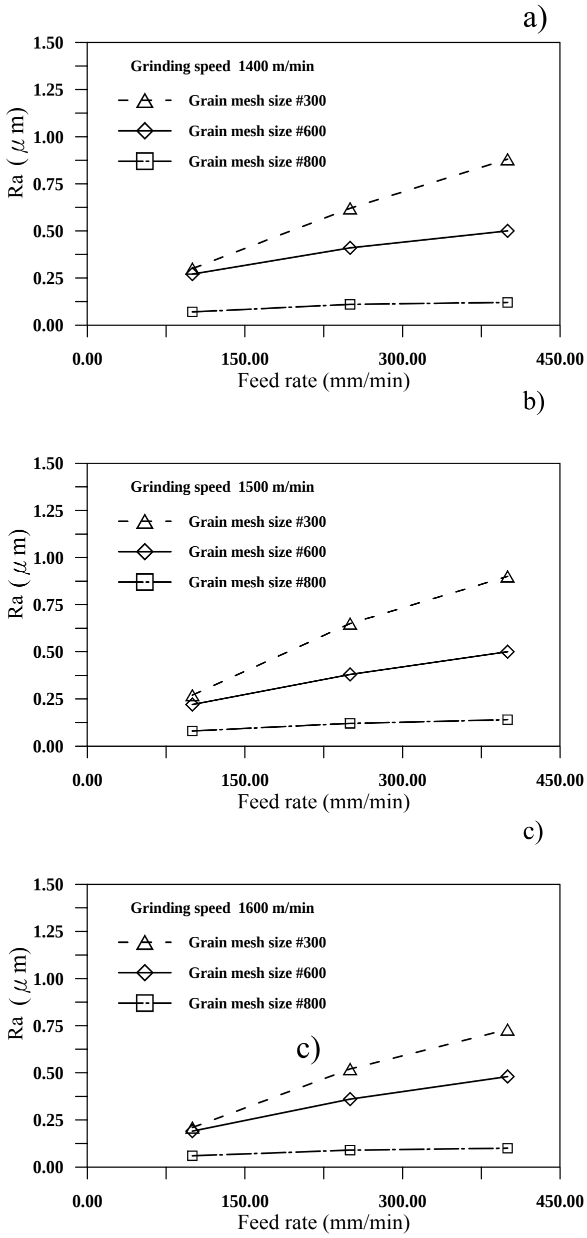

Fig.13 Effects of feed rate on surface roughness

3. Effect of Feed Rate on Surface Roughness of Radial Relief

Fig. 13 illustrates how surface roughness varies respect to feed rate. Surface roughness increases as feed rate increases. This is similar to the cutting performance of multi-edge. It can also be found that as grain mesh size becomes larger, the slopes of the corresponding curves become smaller. This also means that as abrasive grain turns smaller, the influence of feed rate on surface roughness of workpieces turns less significant. In addition, the differences of surface roughness caused by varying grain mesh size get large as feed rate increases. This indicates that, for higher feed rate, grain mesh size has stronger effects on surface roughness of workpieces.

4. Analysis of Variance

The analysis of variance (ANOVA) is to investigate which grinding parameter considerably affects the quality characteristic. Based on Table 2, Table 3 shows the results of ANOVA for surface roughness of radial relief plane. It can be found that grain mesh size and feed rate are the significant grinding parameters affecting surface roughness. On the contrary, the grinding speed in the range given in Table 1 does not change surface roughness too much. The grinding parameters according to their contribution to surface roughness are grain mesh size, feed rate, and grinding speed in descent order.

Table 3 Analysis of variance table for surface roughness

Grinding parameter	Degrees of freedom	Sum of squares	Mean squares	F-ratio	Contribution (%)
Grain mesh size	2	0.9832	0.4916	43.12	60.12
Grinding speed	2	0.0208	0.0104	0.91	1.27
Feed rate	2	0.4037	0.2034	17.84	24.69
Error	20	0.2277	0.0114		13.92
Total	26	1.6324			100.00

F_{05} (2,20) = 3.49

VI. Conclusions.

The grinding qualities represented by surface roughness corresponding to various combinations of grinding conditions are studied experimentally here. From the experimental results described in this paper, the following conclusions can be drawn:

1. The analysis of variance shows that, under the selected range for grinding conditions, the effect of grain mesh size on surface roughness is the most significant, while that of grinding speed can be neglected.
2. As grain mesh size becomes larger, the resultingsurface roughness becomes smaller, and the effect of feed rate on surface roughness becomes smaller.
3. As feed rate gets larger, the resulting surface roughness gets larger, and the effect of grain mesh size on surface roughness becomes larger.
4. In this study, the optimal combination of grinding conditions to obtain minimum surface roughness is grain mesh size of #800, feed rate of 100 mm/min, and grinding speed of 1600 m/min.

References

1. Tso Pei-Lum “Study on the grinding of Inconel 718”, J. Mater. Process. Technol. 55, 421-426(1995).
2. Xu, Y. S., Hu, J., Lin, B., and Li, Z. C., “Studies on the surface guality of the unsteady-state grinding technigne”, J. Mater. Process. Technol. 129, 364-368(2002).
3. Ali, Y. M., and Zhang, L. C., “Surface roughness prediction of ground components using a fuzzy logic approach”, J. Mater. Process. Technol. 89-90, 561-568(1999).
4. Hecker, Rogelio L., and Liang, Steven Y., “Predictive modeling of surface roughness in grinding”, Int. J. Mach. Tool. Manuf. 43, 755-761(2003).
5. Zhou, X., and Xi F., “Modeling and predicting surface roughness of the grinding process”, Int. J. Mach. Tool. Manuf. 42, 969-977(2002).
6. Agarwal, S., and Rao, P. V., A “probabilistic approach to predict surface roughness in ceramic grinding”, Int. J. Mach. Tool. Manuf. 45, 609-616(2005).
7. United States Cutting Tool Institute, Metal Cutting Tool Handbook, New York, 1998.
8. Chiang, Y. L., Theory of Cutting Tools-Grinding Technology of Cutting Tools, published by Chwa Technology Co. Ltd, Taiwan, 1996.

國立虎尾科技大學學報　第二十六卷第三期 （民國九十六年月）: 9-16

碳化鎢高速端銑刀研磨性能分析

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摘要

本文以五軸 CNC 刀具磨床研磨碳化鎢端銑刀，探討磨削參數對表面粗糙度之影響。表面粗糙度值的大小對於端銑刀的耐磨性、潤滑性、精度、噪音與壽命均有顯著的影響，故表面粗糙度爲評估刀具研磨品質之ㄧ重要的性能指標。影響表面粗糙度主要磨削參數(grinding parameters)有磨削數度(grinding speed)、進給率及磨輪粒度(grain mesh size)。文中將每一磨削參數取三個水平，實驗設計採用全因子設計(full factorial design)。實驗結果顯示，在三種可控制的磨削參數中，grain mesh size 對表面粗糙度影響程度最大。磨削速度表面粗糙度的影響程度最小。Grain mesh size # 1800 時，進給率對表面粗糙度沒有顯著影響。欲得到最小的表面粗糙度，磨削條件組合爲：磨削速度 1600m/min，進給率 100mm/mim，grain mesh size #800。欲提昇研磨效率，磨削條件組合爲：磨削速度 1600m/min，進給率 400mm/min，grain mesh size #800。

關鍵詞：表面粗糙度，磨削參數，刀具研磨

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