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Surface Grinding of Tungsten Carbide for High Quality Using Diamond Wheel

Seoung-Jung Heo*, Duck-Hyun Wang**, Won-Il Kim**

Abstract

Various surface grinding experiments using resin bonded diamond abrasive wheels are carried out for tungsten-carbide materials in order to minimize the damage on the ground surface and to purse the the precise dimension compared to conventional grinding machine. When grinding quality is constant, theoreticalgrinding effect is changed according to the speed of workpiece. Accordingly, grinding forces, which are Fn, Ft, were analyzed for the machining processes of tungsten-carbide material to obtain optimum grinding conditions. Brief investigation is carried out to decrease the dressing efficiency of resinoid bonded diamond grinding wheel to grind tungsten-carbide. Truing is also carried out to provide a desired shape on a wheel or to correct a dulled profile.

High quality in dimensional accuracy and surface are often required as a structural components, therefore 3-points bending test is carried out to check machining damage on the ground surface layer, which is one of sintered brittle material. From this experimental study,

some useful machining data and information to determine proper machining condition for grinding of tungsten-carbide materials are obtained.

Keywords : Tungsten-carbide material, Turing & dressing efficiency, Theoretical grinding condition, 3-point bending test, Weibull coefficient

Nomenclature

a : space of sucessive cutting edge(mm)
b : width of wheel trace on the machined surface(mm)
B : width of grinding wheel(mm)
D : wheel diameter(mm)
f : feedrate((mm/rev)
g : grain depth of cut(mm)
F : fraction of failed
l_p : contact arc length(mm)
m : weibull slope or coefficient
N : life characteristic constant
No : number of experiments
r : radius of grinding wheel(mm)

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* Assistant professor, Doowon Technical College, Mechanical Engr., Aansong, Korea
** Assistant professor, Kyungnam University, Mechanical Engr., Masan, Korea
*** Professor, Kyungnam University, Mechanical Engr., Masan, Korea

R_{max} : surface roughness
S : fatigue life of weibull distribution
S_r : deformation recovery value by elasto−plastic(mm)
t : depth of cut established(μm)
V_s : peripheral spindle speed(m/min)
V_w : workpiece speed or table speed(mm/min)
Z : metal removal rate($mm^3/mm \cdot s$)

1. Introduction

Tungsten−carbide materials are characterized by various physical properties such as excellent strength, low−and high−temperature handness, wear resistance and corrision resistance. Due to the antifriction and anticorrosion, these alloys are used primarily for metal moulding and cutting tools. Though tungsten−carbide materials are manufactured product state when sintered, it is required finish trimming for high accuracy and surface profile. The processing is decided by the purposes of efficiency and quality. The one is for the shape of pruducts, dimensional accuracy, and state of surface; and the other is for machining efficiency. Nonconventional processes are widely used for machining tungsten carbide materilas, but grinding process with high abrasive is also possible method as a conventional process.

The greatest care must be taken for surface grinding of sintered brittle materials in consideration of the qualities such as shape of manufactured articles, dimensional precision, surface conditions, and the machining efficiency. Optimal grinding condition for various materials is required, because grinding efficiency is mainly affected by grinding wheel, grain size, bond, grade, etc. The relationship between grinding conditions and damages on ground surface is required for solving serious problem of bending tests, which represent brittleness structural characteristics, generation of microcracks and defects of ground surface during the grinding process of sintered materials, such as tungsten carbide, cermet, ceramics[1,2] Structural bending test is able to give considerable information about the machining condition such as the proportional limit, yielding point and ultimate strength or tensile strength. In that respect bending test data with high reliability are more essential than other mechanical properties for using these materials.

Thiel[3] considered that the wet grinding of tungsten−carbide/steel of the study on grinding of these materials. Buttner[4] researched that the plunge grinding of tungsten−carbide. Also it was reported previously that the study on ultra−precision grinding condition of WC−Co[5] and high efficiency grinding of WC−Co[6]. Various surface grinding experiments using diamond wheels[7] are carried out to obtain the most excellent quality of workpiece. Material removal process, machinability, quantitative estimation of residual cracks, and optimum dressing conditions are also discussed when grinding tungsten−carbide materials with a diamond grinding wheel. Finally, the optimum grinding conditions and high bending strength values with reliability are obtained by 3−point bending test based on Korean Standard from various machining experiments of WC−Co workpieces.

It is reported that the partial fraction of defects are easily developed than over−all fracture due to the smaller strength in the grain boundary and interface for sintering materials like tungsten carbide8). It is also observed that the internal effect like pore and coarse grain can result in partial fracture by stress concentration[9]. The deterioration of strength value in sintered materials can be produced by the grinding damage.[10]

Therefore, the purpose of this study is to obtain the high quality of ground surface to improve the reliability of bending test of the WC−Co material, and sintered brittle property which has P10 and V2 grade. This material is widely used as cutting tools and moulding material part because of excellent quality represented in terms of strength, hardness, resistance to corrosion and wear. Based on the selection of grinding condition from the theoretical background. the grinding resistances, surface roughness and bending strength analyzed by weibull distributiuon are observed for high quality and guaranted strength of various conditions.

2. Theorectical Background

2.1 Selection of optimum grinding condition

It is required to consider high efficiency for the shpe and size by removal maching of deformation from raw material or of unnecessary part, and also guaranted strength for the quality of surface in the consideration of restraining the defect caused by machining. The metal removal rate[11] of surface grinding relating with high efficiency and quality, is represented as

$$Z = t \cdot V_w - S_r \quad \cdots\cdots (1)$$

The surface roughness characteristic obtained from surface grinding process ca n be generally expressed as[12]

$$R_{max} = \frac{1}{16} \cdot \left(\frac{1}{D}\right) \cdot \left(\frac{V_w}{V_s} \cdot a\right)^2 \cdot \frac{1}{8} \cdot \frac{b^2}{r} \cdot \left(\frac{f^2}{B}\right) \cdots\cdots (2)$$

From Eq. (2), it is expected that the surface roughness is affected by the grinding conditions.

Grain depth of cut in the straight surface grinding g is

$$g = 2a\frac{V_w}{V_s} \cdot \sqrt{t/D} \quad \cdots\cdots (3)$$

The arc length of contact l_p for various grinding processes can be generally expressed as:

$$l_p = \sqrt{t} \cdot \sqrt{D} \cdot (1 + V_w/V_s) \quad \cdots\cdots (4)$$

According to above Eqs., it is possible to predict qualitatively the effects of changes in the grinding condition on surface roughness. In consideration of machining process by the use of conventional grinding machine, it is necessary to determine the value of $(V_w/V_s) \cdot \sqrt{t}$. If the value of $(V_w/V_s) \cdot \sqrt{t}$ is regularized, theoretical optimum condition according to the workpiece velocity will be obtained. some changes of theoretical grinding depth for surface uniformed by initial condition are summarized in Table 1.

Table 1. Theoretical grinding depth for surface uniformed by initial condition

$V_w/V_s \cdot \sqrt{t}$ (μm) \ V_w (m/min)		16	12	8	4	2
0.0129	t_{th} (μm)	2.0	3.539	7.961	31.848	127.402
0.0183		4.0	7.129	16.025	64.098	256.408
0.0224		6.0	10.672	24.01	96.04	384.16
0.0259		8.0	14.266	32.107	128.394	513.577
0.0289		10.0	17.764	39.96	159.855	639.47
0.0354		15.0	26.654	59.96	239.855	959.45
0.0408		20.0	35.403	79.655	318.62	1274.49

Fig. 1 represents theoretical value of grinding depth according to initial condition under constant grinding roughness. the grinding depth is changed according to the table speed, for constant value of $(V_w/V_s) \cdot \sqrt{t}$.

From the Eq.(3), the efficiency of material removing is increased as the values of V_w/V_s and depth of cut increased, but the surface becomes rough due to the increasing g and the wear amount of grinding wheel is increased due to the high load. If the value of V_w is increased with the constant of V_w/V_s the value of Z is increased. The relative velocity of V_s+V_w is also increased, and the value of S_r induced to the elasto-plastic deformation is decreased. These results induced high efficiency of material removing and quality of surface, but it is far from the real grinding condition.

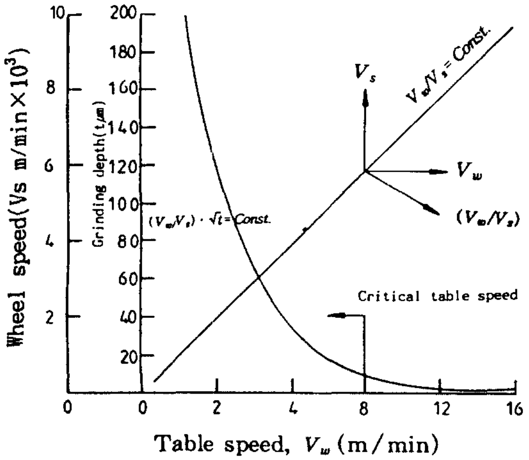


Fig.1 The theoretical value of depth according to initial condition under constant grinding roughness

Therefore it is recommanded that the optimum material removal is obtained based on the theoretical grain depth due to the V_w under the constant value of $(V_w/V_s)\cdot\sqrt{t}$. From Fig. 1, the value of Z can be elevated due to the increased V_w and decreased S_r if the value of V_w/V_s is moved to the arrow direction for the flexible change of speed, under the constant value of V_w/V_s.

2.2 Theroy of weibull distribution and its plotting

The strength value of brittle material like ceramics and tungsten carbide represents large deviation from the average strength. Therefore, weibull plotting is applied, which represents fracture probability under a given stress state. The experimental fatigue life of weibull distribution is represents

$$S=\exp^{-(\frac{N}{N_0})^m} \quad \cdots\cdots(5)$$

The value of S represents the number of specimens, not induced fracture after N times under constant load. The fraction of failed F can be shown such as

$$F=1-S=1-\exp^{-(\frac{N}{N_0})^m} \quad \cdots\cdots(6)$$

This can be changed to

$$\exp^{(\frac{N}{N_0})^m}=\frac{1}{1-F} \quad \cdots\cdots(7)$$

Taking natural logarithm and then common logarithm of above Eq.

$$\log\ \ln(\frac{1}{1-F}) = m\log N - m\log N_0 \quad \cdots\cdots(8)$$

From the experiemnts, the slope m can be obtained from plotting F,N values. The weibull modulus, which is slope m, represents an extent of standard deviation of strength. As the slope is larger, the standard deviation becomes smaller.

The weibull slope or coefficient has relation with the standard deviation of average strength. If the standard deviation becomes smaller, then the slope will be larger. This result can present the fracture probability or predominance of various grinding condition.

3. Experimental equipments and procedures

3.1 Equipments and specification

All workpieces were ground by conventional surface grinding machine, which has horizontal spindle reciprocating process. Details on experimental equipments and specifications of measuring apparatus are shown in Table 2. The sintered brittle materials has not only defects in the internal construction and scratches on the surface, but also unnatural sharp scratches on the ground surface. These scratches may be penetrated and spreaded from the grinding surface and may create deterioration of strength value.

Table 2. Experimental equipment and specification

Equipments	Specification
Multi cutting machine	Ceramicron MX−833
Universial bending strength tester	UTM 250
Metallugical microscope	Nikon Co.
Tool dynamometer	Piezoelectric type, 9207 A model, Kistler Co.
Charge amplifier	504 A, 2channel, Kistler Co.
Stereoscopic macroscope & SEM	Nikon Co.
Surface roughness tester	Stylus type, Mitutoyo Co.
Repicorder	A2101 type, made in Japan SAe−El Co.

The optimum grinding condition based on evaluation of characteristics is needed to prevent deterioration of strength value. One of methods for evalution of characteristics, 3−point bending test is constructed, which is based on KS B 0803 and KS L 1591. External appearance of bending test specimen is right angled shape and dimensions are L40㎜ × W4.0㎜ × t3.0㎜.

3.2 Experimental conditions and procedures

It is proven[13] that the grinding ratio is the highest under the extent of 1500∼1750m/min peripheral grinding speed, when grinding tungsten carbide with diamond wheel under wet condition. Therefore the grinding condition of V_w is changed from 2 m/min to 16 m/min under constant V_s of 1750m/min. When the condition is applied, the quality of surface according to the initial grinding condition is changed. As shown in Fig. 1, a visible line is obtained from initial condition value of Table 1 for V_w of 16m/min. The effective theoretical workpiece speed is below than 8m/min for elevation of material removing without deteriorating quality of surface. From this experimental study, the bending strength values are obtained and evaluated for V_w of 8m/min and varying depth t in consideration of mechanical characteristics of tungsten carbide materials.

In testpiece group No. 1 and 2, bending strength is compared for P10 type and V2 type tungsten carbide under the same grinding condition. In group No. 3, upper and lower surfaces were ground 10㎛ depth with ♯120 grinding wheel and 6㎛ depth with ♯325 wheel as continued to satisfy the prescribed dimension of 0.2㎜. For group No.4 after remaining 0.2㎜, 6㎛ depth with ♯325 wheel for 0.15 ㎜ and 2㎛ depth with ♯600 wheel for 0.05㎜ are grinding condition. In group No.5 and 6, ♯600 wheel and ♯525 wheel are used for grinding 0.2㎜.

Table. 3 Comparison of grinding conditions(unit : ㎛)

Testpiece Group No.	Grain size of diamond wheel and depth of cut		
	♯120	♯325	♯600
1−1	10(P10)		
1−2	10(V20)		
2	10(V20)	6	
3	10(V20)	6	2
4	10(V20)		2
5	10(V20)	2	

Details on the experimental methods employed are described in Table 3. The surface of workpieces before using in the main experiment, were prepared by grinding process to obtain fine surface finish. For this reason, three distinct phases are involved in a complete grinding cycle for each experimental run−truing, dressing, final cut, and spark−out. Truing, dressing, and the main experimental equipment and conditions are shown in Table 4. Figures 2 and 3 show the experimental measurement set up and photographs of truing and dressing process, respectively. From Fig. 2, surface roughness and bending strength were measured after grinding and grinding resistants were measured by on−line system.

On the basis of these results, this study is carried out mainly 8m/min, which is critical table speed. This speed is in contrast with general practice for Al material, where V_s is normally about 1150m/min, and the value of table speed is changed more or less fast in comparision with Al material[14] which critical table speed is 4m/min.

Table 4. Truing, dressing and principle experimental condition

Grinding machine (Motor power of grinding spindle)	Vertical type surface grinding machine ELB-SCHLIFF Edmund Lang, Germany Model type SWN-6 3.75 Kw
Workpiece	WC-Co P10, WC-Co V20
Grinding wheel	1A1 straight type wheel SDC120N100RW-3.0 SDC325N100RW-3.0 SDC600N100RW-3.0 Size: D300×d76×w15×t3
Grinding type	Down & up cutting Plunge & traverse cutting type Wet-type(Coolant: soluble type×40)
Principle grinding speed(m/min)	1,750
Table speed (m/min)	8
Depth of cut(μm)	2, 6, 10
Cross-feed rate(mm/pass)	2, 4
Truing	Using brake type truier with C80(-170)M wheel Depth of cut: 5~15μm/pass Traverse cutting type Table speed: 4~10m/min Coolant is injected strongly
Dressing	Using WA stick type honing stone(#220~2000) Depth of cut: 2~100μm/pass Plunge cutting type Table speed: 4~6m/min Coolant is injected lightly

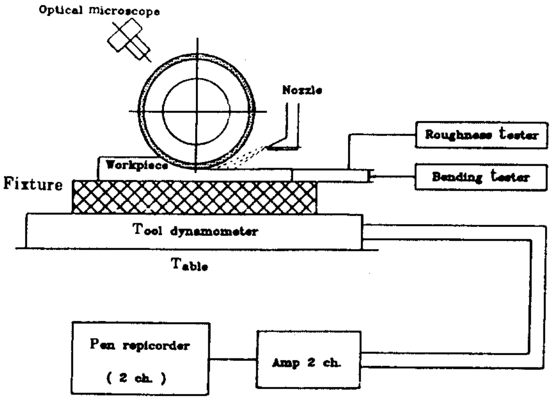
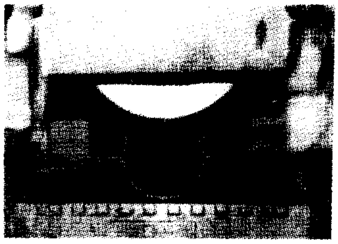
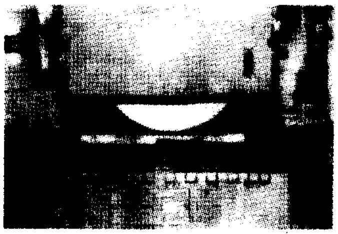


Fig.2 Diagram of grinding experimental system



(a) Truing process



(b) Dressing process

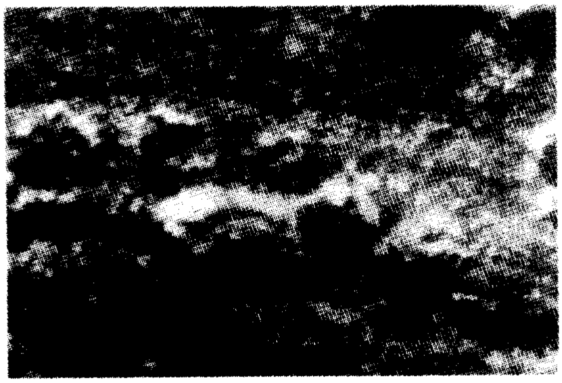
Fig.3 Photographs of truing and dressing processes

4. Results and Discussion

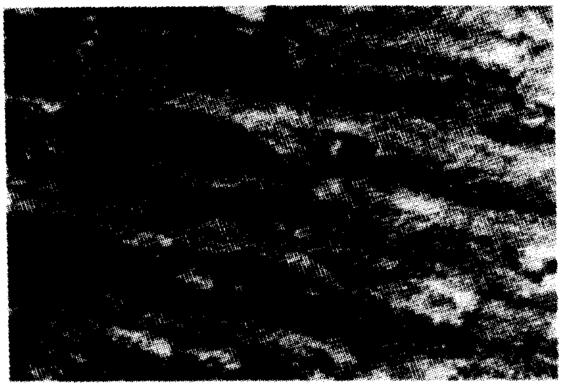
4.1 Effect of abrasive grain size on surface and grinding resistance

The microphotographs of diamond grinding wheel surface after truied, dressed, and used, are shown in Fig. 4. These were taken from truied and dressed stable region, from worn transient region, respectively. In stable region, striated form is revealed on the working grits amd amount to rubbing and grains. Flat phenomena are also the characteristics of the wheel truing and dressing technique. Therefore diamond grains are observed to have grazing and loading in the course of grinding process, so it needs controlling surface of grinding wheel periodically.

(a) Truied shape



(b) Dressed shape



(c) Worn shape

Fig. 4. Microphotographs of diamond abrasive wheel

The effect of worn abrasive grains and new ones on the grinding force for various table speed and depth of cut are shown as Fig. 5. The grinding force is increased for both worn and new abrasive grains as increased depth of cut. But the grinding resistance(Fn) is decreased rapidly as increased table speed. This result is in contrast with general phenomena for other materials[15]. This result might be induced from the less depth of cut due to the lower stiffness as the increased table speed or from the difficulty of chip flow due to the loading of grain. The latter reason will produce lower efficiency of grinding.[16]

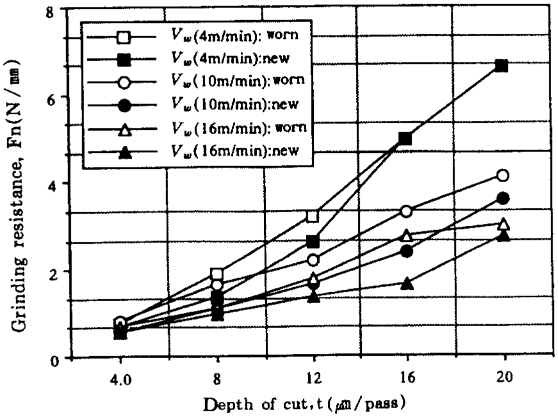


Fig.5 Effect of worn and new abrasive grains ones on the grinding resistance for various table speed and depth of cut

Surface roughness parameters such as Rmax and Ra, for each grinding condition testpiece group, are shown in Fig. 6. It was found that the group No. 3 revealed the best result of all the groups. Fig. 7 shows the ratio of grinding force for SM45C, tungsten – carbide, and alumina ceramics to compare machinability. It is shown that the tungsten–carbide is required higher normal grinding force than SM45C. It was found that the less tangential force compared with normal force is required for hard–brittle materials, inducing less grinding effect due to the higher hardness. The grinding effect of hard brittle material may be from the infinitesimal fracture phenomenum resulting in residual damage on the ground surface.

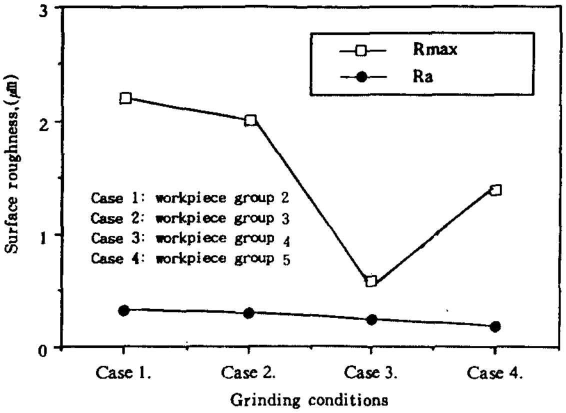


Fig.6 Surface roughness Rmax and Ra for grinding conditions

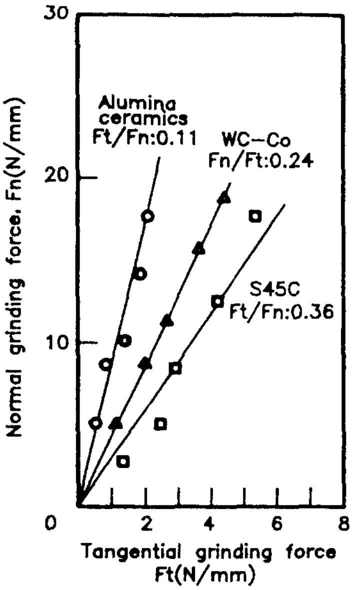


Fig.7 Comparison of grinding force between metallic and hard-brittle materials

4.2 Sustaining effect of cutting edge after dressing

The change of grinding forces was observed to find the dressing period for various conditions from Fig. 8 (a) and (b). The normal and tangential grinding forces were

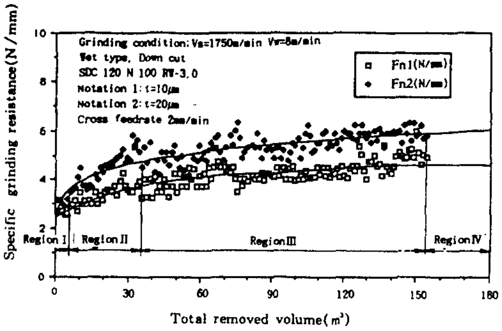


Fig.8 (a) Effect of total removed volume on the normal grinding resistance(Fn) for various depth of cut in the case of traverse type

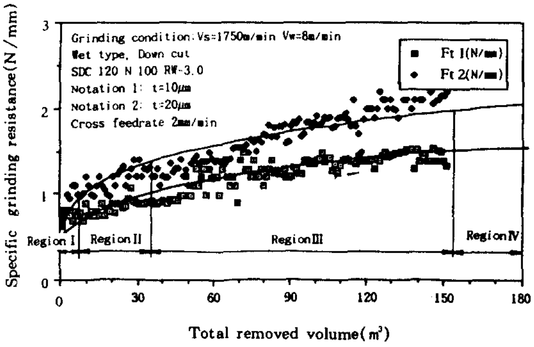


Fig.8 (b) Effect of total removed volume on the tangential grinding resistance(Ft) for various depth of cut in the case of traverse type obtained for different depth such as 10μm/pass and 20μm/pass in traverse type grinding. Variations in wheel dressing procedure affected the unstable Region I(initial abrasive process) of the force pattern and the magnitude of the force in the stable Region II(transient grinding process) before they commence to climb in Region III (normal grinding process), and in Region IV appeared the burning by plastic deformation and oxidation because of increasing wear relief surface of abrasive grain.

From the results of this present research for tungsten-carbide, it is necessary to dress in a pertinent time. Therefore it is proper after about 200 grinding times in the case of traverse type, and proper after $150mm^3$ removing volume of materials when grinding depth is 10μm.

When the cross feed rate is increased 2 times (4mm/min) under 10μm/pass depth, the change of grinding force according to the total removal volume was obtained in Fig. 9. It was proven that a tendency of incresement for grinding force almost 1.8~2.4 times under 4m/min compared with 2m/min. This phenonenum results from fast wear mechanism of grinding wheel for higher cross feed rate.

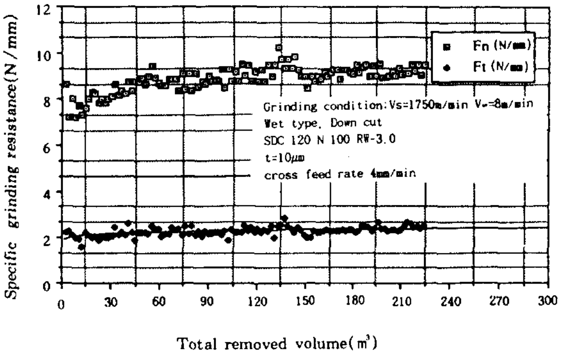


Fig.9. Effect of total removed volume on the grinding resistance for changing cross feed rate

When used pluged type grinding as same method, the change of nomal and tangential forces for 10μm and 5μm depht was shown in Fig. 10 (a) and (b). From this result, it was found that the region III including plastic deformation and oxidation was produced after 200 times for 10μm depth.

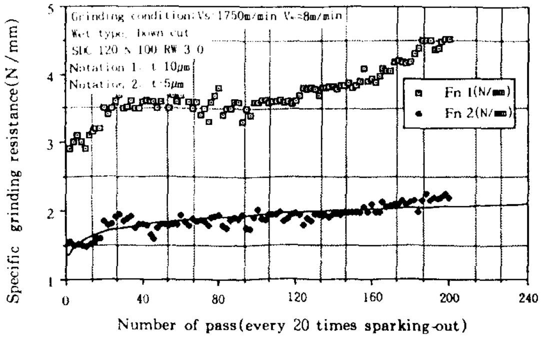


Fig.10 (a) Effect of the number of grinding times on the normal grinding resistance(Fn) for various depth of cut in the case of plunge type

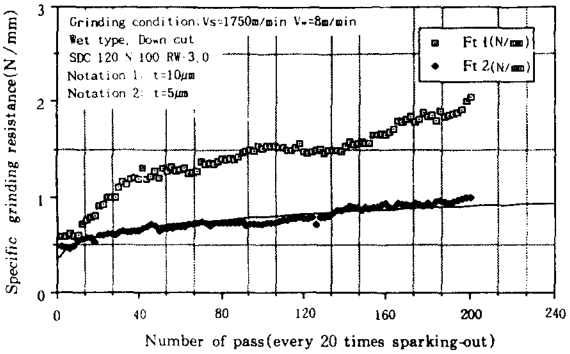


Fig.10 (b) Effect of the number of grinding times on the tangential grinding resistance(Fn) for various depth of cut in the case of plunge type

4.3 Comparison of bending strength value

In order to find the best grinding condition, average strength, its standard deviation, and weibull coefficient valuse are compared. 3-point bending strength test based on Korean Standards was executed to evaluate the tungsten-carbide workpiece, and also find the failure probability, and standard deviation of the workpiece.

The results from the 3-point bending test after machining with various conditions are summarized in Table 5 and 6. The bending strength value is about 185.7 ~189.8kgf/㎟ and standard deviation is lower about 2.94 as presented. The bending strength was obtained from $\sigma_b = 3PL/2wt^2$, and its standard deviation was derived from

$$S = \sqrt{\sum_{i=1}^{n}}\ (xi-\bar{x})/(\sqrt{n-1}).$$

Table 5. Example of calculated factors for Weibull plotting

○ Average value rank method……… $F = \frac{i}{N+1}$

○ Middle value rank method……… $F = \frac{i-0.3}{N+0.4}$

Pank	1		2		3		4		5		6		F=i/N+1	ln ln (1/1−F)
	σ	lnσ	σ	lnσ	σ	lnσ	σ	lnσ	σ	lnσ	σ	lnσ		
1	143.2	4.964	181.7	5.202	182.9	5.209	185.3	5.222	184.0	5.215	183.3	5.211	0.0909	−2.351
2	145.2	4.978	182.9	5.208	184.1	5.215	185.9	5.225	185.6	5.224	185.1	5.221	1.1818	−1.601
3	145.6	4.981	183.2	5.211	184.6	5.218	187.3	5.233	186.9	5.231	185.6	5.224	0.2727	−1.144
4	147.4	4.993	183.8	5.214	185.7	5.224	189.9	5.246	189.2	5.242	185.9	5.225	0.3636	−0.794
5	148.2	4.999	185.1	5.221	186.5	5.228	190.1	5.248	189.4	5.244	186.8	5.230	0.4545	−0.501
6	148.5	5.000	185.7	5.224	187.4	5.233	190.5	5.250	190.0	5.247	187.5	5.234	0.5454	−0.238
7	148.6	5.001	186.8	5.231	187.9	5.236	191.0	5.252	190.4	5.249	188.7	5.240	0.6364	−0.012
8	148.9	5.003	188.5	5.239	189.3	5.243	191.5	5.255	191.4	5.254	189.4	5.244	0.7273	0.262
9	149.4	5.007	188.7	5.240	189.4	5.244	193.1	5.263	192.5	5.260	191.0	5.252	0.8182	0.533
10	150.8	5.016	190.1	5.248	190.7	5.251	193.5	5.265	193.1	5.263	191.8	5.256	0.9091	0.874

Table 6. Comparison of average bending strength value and standard deviation value (unit : ㎛)

Workpiece group No.	Average bending strength(Kgf/㎟)	Standard deviation (S)
1	147.58	2.27
2	185.65	2.82
3	186.85	2.55
4	189.81	2.81
5	189.25	2.94
6	187.51	2.71

When we used the same grain mesh of diamond wheel for different classes of tungsten carbide, the relation between the depth of cut and the bending strength values of workpiece groups No.1 and 2 is shown in Fig. 11. Relationships between grinding depth of previous process and bending strength of following process are presented in Figs. 12 and 13. As shown in Fig. 12, in case of the different grain meshes ♯120 and ♯325 with different depth of cut, it was observed that the results of group No.2 were more excellent than those of group No.3 in all respects of average strength, standard deviation, and weibull coefficient(gradient of the graph). Group No.4 was compared with other groups in order to find possibility of removing machining damage, as shown in Fig. 13.

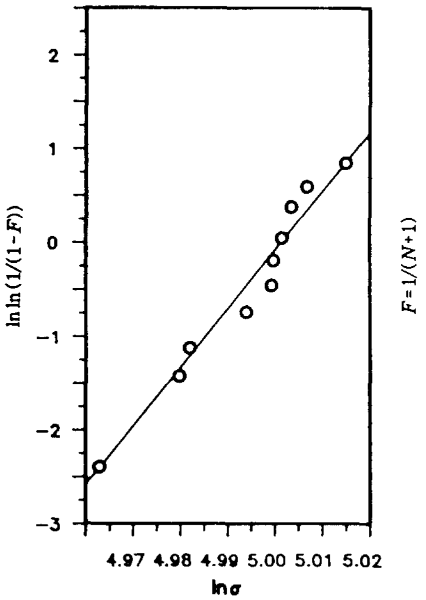


Fig.11. Weibull plotting of bending strength value(workpiece group of Table 5)

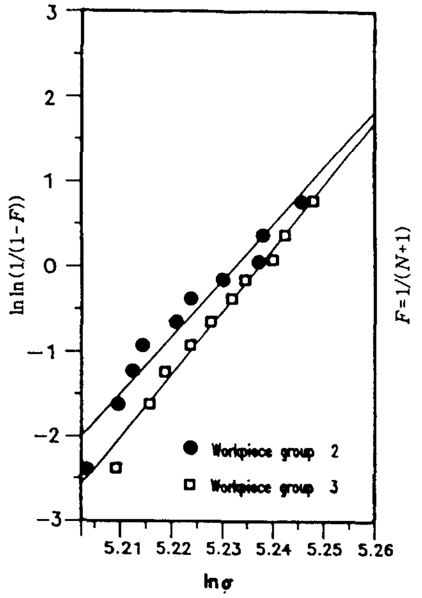


Fig.12. Weibull plotting of bending strength values (comparision of workpiece group 2 with workpice group e of table 5)

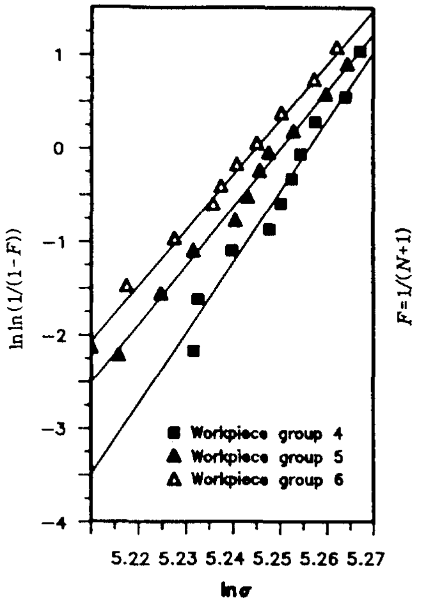
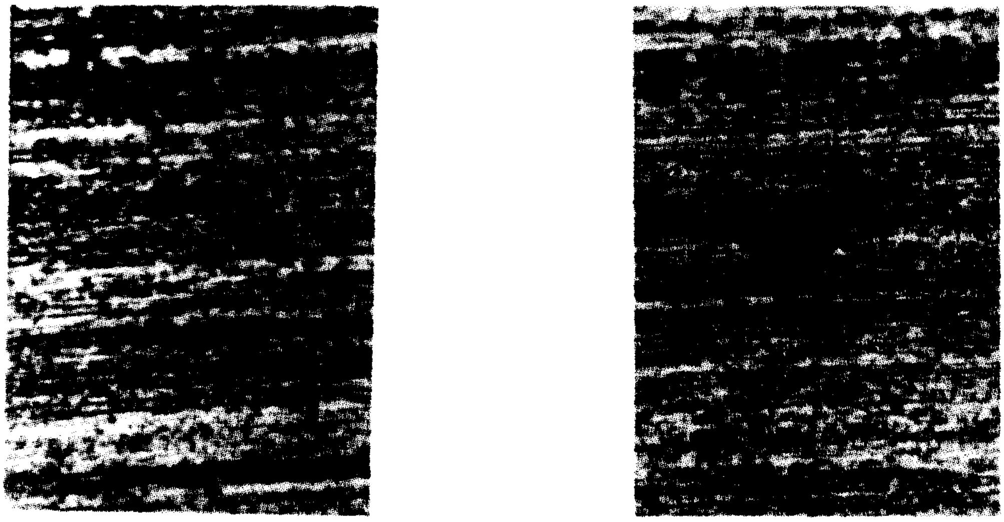


Fig.13 Weibull plotting of bending strength values (comparison of various workpiece group 4, 5 and 6 of Table 5)

It is expected that the suitable extent of feedrates are decided to restrain the grinding residual cracks and defects in the case of surface grinding using diamond wheels for rough grinding condition, which is around # 120 grain mesh of wheel. It is also expected that the machining is accomplished with two devided regions, which are rough grinding and smooth grinding for the grinding of tungsten carbide with high quality. Weibull distribution plotted as bending strength valuse for comparing each workpiece group machined by values grinding conditions. Consequently, each group was found to have relation with grain mesh of diamond wheel and depth of cut. Therefore, it is concluded that smaller grit has the better quality, and it is also concluded improved surface finish is obtained by reducing the depth of cut.

Fig. 14 is the surface finishing ground on each grinding cases to research crazing of the ground surface (hair line crack) and discoloured burn marking. These figures indicate the kind of interference as a grit passes along the trochoidal path of workpiece. The best quality is obtained by group No. 4 though it is necessary to refrain from excessive material removing in the respect of efficiency.



(a) Workpiece group 1

(b) Workpiece group 2

(c) Workpiece group 4

(d) Workpiece group 6

Fig.14 Microphotograph of ground surface

5. Conclusions

From the experimental study on the grinding WC−Co materials, optimal grinding velocity is obtained for higher material removal without deteriorating surface quality from theoretical background. After observing the effects of truing and dressing. the grinding resistances, surface roughness and bending strength according to the grinding conditions are evaluated for higher quality and guaranted strength, and following results are obtained.

1. It is necessary to dress in a pertinent time. Form the case of plunge cutting type and tarverse type, it is proper after about 200 times, and proper after 150㎜^{3} removing volume of material respectively when grinding depth is 10㎛.
2. From the results from machining experiment of tungsten carbide, workpieces for bending strength test based on Korean Standards, satisfiable surface qualities are obtained. Bending strength value over about 189.8kgf/mm^2 and standard deviation lower about 2.94 are obtained.
3. Variable grinding condition for tungsten carbide can be shown to produce higher quality with removing damage of previous grinding.
4. Strength evaluation with weibull plotting, can be shown the better result in variable grinding and proven higher quality as smaller grit upto ♯600, because less grinding effect.

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