Analysis of the wear of a resin-bonded diamond wheel in the grinding of tungsten carbide

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Abstract

This paper describes experimental results using a resin-bonded diamond wheel in the vertical dry grinding of P10 grade tungsten carbide. The conditions of the diamond abrasive cutting edge on the worn wheel surface, the bonding state between the abrasives and the matrix, and the grinding performance were investigated. It was found that for interrupted dry grinding, the abrasive cutting edges occurring on the worn wheel surface are mainly of protrusive (good) particles and the number of pull-out holes is also high as well, leading the wheel to produce a higher grinding ratio. However, under a greater stock removal rate, the grinding ratio would be reduced rapidly. When continuous dry grinding was employed, the resulting worn abrasives produce a greater proportion of particle pull-out and coated grit exposed on the wheel surface, thereby causing very poor grinding performance. Graphite fillers added to the resin bond have a positive influence on the grinding performance of the wheel in dry grinding. In addition, the roughness of the ground surface is similar to that effected by mechanical polishing. © 1997 Elsevier Science S.A.

Keywords: Grinding; Resin-bonded diamond wheel; Tungsten carbide

1. Introduction

Diamond grinding wheels are used widely in the metalworking industry for grinding various cemented tungsten carbide tools. The high hardness, toughness, and resistance to abrasive wear of cemented carbides make them extremely difficult to grind. Hence, the proper selection and use of the wheel during grinding are very important, and are dependent on various complex factors, these factors involving the mode of cutting (up-cut or down-cut), the wheel speed, the table speed, the depth of cut, the machine condition, and the properties of the workpiece material.

Usually, wheels of friable forms of nickel-coated or copper-coated diamond abrasive are recommended for the grinding of cemented carbides. The irregular coating prevents the thermal degradation of the resin bond, and provides an improved holding surface to increase the retention of the abrasive on the bond, which result in a longer wheel life [1]. Further, resin bonds are also adopted for wheels used to grind carbides. The resin bond is designed to wear or erode at the same rate as the diamond abrasive wear, thereby, sharp new diamond grits being exposed when needed. Due to the low strength and poor heat conductivity of the resin bond, various fillers such as SiC, Al₂O₃, Ag, Cu, Fe, graphite, and MoS₂, etc. are usually included to improve its properties. As a result, resin-bonded diamond grinding wheels maintain free cutting and produce a high grinding ratio.

For best results in the dry grinding of cemented carbides, the following guidelines are adopted: (i) a low wheel speed of around 18 m s⁻¹; (ii) a low table speed of 2–3 m min⁻¹; (iii) a low depth of cut in the 0.01 to 0.05 mm range; and (iv) reduction in the area of contact [1].

Metzger [2] stated that in the typical plunge grinding of cemented carbide wheels, replacing the 120–140 US mesh by 230–270 US mesh grit size would lead to an increase in the grinding ratio and a decrease in the...
spindle power drawn. This is in sharp contrast with the decrease in grinding ratio usually observed in conventional reciprocating grinding.

Zelwer and Malkin [3,4] indicated that in grinding of WC-Co cemented carbides, coarser diamond grains on the wheel have more cutting points per grain than finer grains and will increase the specific grinding energy, the material removal rate and the grinding ratio. In addition, the finished WC-Co surfaces after grinding were noted to have grooves running along the grinding direction. Partially exposed WC grains were observed in the groove valleys, and the ridges along the sides of the grooves were found to have a high cobalt content.

Based on the early study of the abrasive wear by Tsuma [5], five changing types of conventional abrasive cutting edges in grinding have been classified, these being wear, breakage, pull-out, newly appearing, and partial breakage. Breakage occurs on a much greater scale than does wear, so that the acting grains are worn grains.

Even though some studies related to wear conditions and the performance of diamond wheels in the grinding of cemented carbides have been carried out, the behavior of the diamond wheels has not been understood thoroughly. In this paper, the investigation of the worn behavior of diamond wheels in the vertical type dry grinding of P10 cemented carbide is presented. In addition, the grinding forces, grinding ratio, and the SEM examination of the wheel wear and the ground surface during grinding are discussed.

2. Experimental procedure

Grinding tests were performed on a vertical CNC machining center, its engagement kinematics in vertical grinding being shown in Fig. 1. Two cup-type grinding wheels were used in the tests, their specifications being listed in Table 1. Commercial Ni-coated diamond abrasives were used for the study. Fillers added into resin bond were SiC and graphite. The microstructure of wheels A and B used is shown in Fig. 2(a) and (b).

The operating conditions in the tests are given in Table 2. Cutting rates (defined as the product of the traverse rate and the depth of cut) of 25, 50 and 75 mm$^2$ min$^{-1}$ was chosen. The workpieces used were

<table>
<thead>
<tr>
<th>Number</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel type</td>
<td>Cup (11A2)</td>
<td>Cup (11A2)</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Rim width (mm)</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Rim thickness (mm)</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Diamond (US mesh size)</td>
<td>Ni coating (100-120)</td>
<td>Ni coating (100-120)</td>
</tr>
<tr>
<td>Concentration</td>
<td>115</td>
<td>90</td>
</tr>
<tr>
<td>Bond (filler)</td>
<td>Phenolic (SiC)</td>
<td>Phenolic (graphite)</td>
</tr>
</tbody>
</table>

Fig. 1. Geometry of vertical-type grinding.

Fig. 2. Microstructures of wheels: (a) A; and (b) B.
Table 2
Grinding conditions

<table>
<thead>
<tr>
<th>Machine</th>
<th>Vertical CNC machine center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding mode</td>
<td>Vertical and up grinding</td>
</tr>
<tr>
<td>Wheel speed, ( V'_w )</td>
<td>( 16.5 \text{ m s}^{-1} )</td>
</tr>
<tr>
<td>Table speed, ( V_w )</td>
<td>( 1-2 \text{ m min}^{-1} )</td>
</tr>
<tr>
<td>Depth of cut, ( d )</td>
<td>( 0.013-0.038 \text{ mm/pass} )</td>
</tr>
<tr>
<td>Coolant</td>
<td>No (dry)</td>
</tr>
<tr>
<td>Workpiece (size)</td>
<td>P10 carbide (4 × 30 × 70 mm)</td>
</tr>
<tr>
<td>Workpiece section being ground</td>
<td>4 × 70 mm</td>
</tr>
</tbody>
</table>

The average normal grinding force and tangential grinding force per unit contact area, the forces ratio, and the grinding ratio measured during grinding are shown in Fig. 3 for wheels A and B in interrupted dry grinding of 50 passes. It can be seen that the grinding forces produced during grinding with wheel A are greater than those with wheel B. The ratio of the tangential force to the normal force for wheel A is also greater than that of wheel B. The cause of greater grinding forces and a greater forces ratio for wheel A may be attributed to SiC filler and a greater diamond concentration. The SiC filler in resin bond and the greater amount of diamond abrasives would cause the wheel to become hard, thereby increasing the grinding forces and the friction force. The grinding ratio measured for wheel B is slightly greater than that for wheel A, which may be due to the graphite filler added in the resin bond of wheel B, which reduces the friction force and the thermal degradation of the resin bond: hence, a better grinding ratio of wheel B is observed. When using the greater cutting rate of \( 76 \text{ mm}^2 \text{ min}^{-1} \) \( (V'_w \times d = 2 \text{ m min}^{-1} \times 0.038 \text{ mm}) \), the grinding ratio for both wheel A and B obtained during grinding is very poor. However, the grinding ratios produced under the lower cutting rate are also low, the reason for which may be that grinding geometry and kinematics causes the wheel to be scraped by the P10 carbide workpiece as a result of shear.

The average normal and tangential grinding forces per unit contact area, the forces ratio, and the grinding ratio for wheels A and B under continuous-grinding conditions of 100 passes, with a table speed, \( V_w \), of 2 m min\(^{-1}\) and a depth of cut, \( d \), of 0.025 mm, are shown in Fig. 4. The grinding forces produced by wheel A are greater than those produced by wheel B. Comparing Fig. 3 with Fig. 4, it can be found that these grinding forces produced in 100 passes of continuous grinding are lower than in 50 passes of interrupted grinding.
which may be due to excessive grinding heat and the wheel being dressed by carbides during grinding, which causes the wheel to wear very quickly and makes abrasives work ineffectively. Hence, their grinding ratios are very low as a result.

3.2. Observations of diamond cutting edges

A typical SEM photograph of the worn grinding wheel surface is shown in Fig. 5. From many micro-observations of the worn surface of diamond wheels after the grinding of tungsten carbide, the diamond cutting edge conditions can be classified as follows:

(a) Coated particle. This is a coated diamond particle exposed above the bond (Fig. 6(a)). When the abrasive retention on the resin bond becomes poor, the particle is pulled out of the resin bond prematurely, before completing its effective working life.

(b) Protrusive (good) particle. This is a particle protruding above the surface of the bond, which performs the best cutting work (Fig. 6(b)). This type of particle is considered to be of great aid to free cutting during grinding.

(c) Flattened particle. This particle (Fig. 6(c)) displays a worn area of smooth or flat faces. The wear is most probably caused by the combination of mechanical attrition and local thermal effects. In this case, the wheel will produce a glazing appearance, and its cutting ability becomes less efficient.

(d) Breakage particle. This is a particle that has suffered gross fracture, where a small part of the particle is retained in the hole bond (Fig. 6(d)). Its cutting action is completely lost.

(e) Partial breakage particle. This presents partial cracks, crushes, or fragments on the grit (Fig. 6(e)), and may be a result of repeated impact with the workpiece materials or thermal fatigue. Such a particle would produce sharp new cutting edges and reduce the depth of penetration. However, it can still maintain a moderate cutting action.

(f) Pull-out hold. A coated particle completely plucked or pulled out of the resin bond results in a hole on the worn wheel surface (Fig. 6(f)). This condition demonstrates that the bonding between the crystal and the coating layer is better than that between the bond and the coating layer. This phenomenon may be due to thermal degradation of the resin bond, producing poor abrasive retention, or due to mechanical impact.

(g) Hole of retained coating layer. This is a particle entirely pulled out of the bond (Fig. 6(g)), and may be a result of poor heat dissipation, which leads the coating layer to become detached.

(h) Hole of partial retained coating layer. There is a partial coating layer retained in a hole (Fig. 6(h)). A crater-type appearance will usually occur during grinding.

Fig. 7 shows the modes of these cutting edges.

3.3. Evaluation of wheel grinding surfaces

The percentage of each classification of diamond abrasive cutting edge (see Figs. 6 and 7) counted on the worn surface of wheels A and B after 50 passes of interrupted dry grinding is shown in Fig. 8(a) and (b), respectively, for a table speed, \( V_w \), of 2 m min\(^{-1}\) and depth of cut, \( d \), of 0.025 mm. It can be seen that the percentages of protrusive particle with a better cutting ability and partial breakage abrasive on the surface of wheel B are 51.2 and 14.6%, respectively, and that these percentages are greater than those for wheel A. Further, the percentage of particle pull-out from wheel B is much lower than that from wheel A, the reason for which may be that the resin bond with graphite filler has a positive influence on abrasive retention. Because
Fig. 6. Micrographs showing the worn abrasive conditions: (a) coated particle; (b) protrusive particle; (c) flattened particle; (d) breakage particle; (e) partial breakage particle; (f) pull-out hole; (g) hole of retained coating layer; (h) hole of partially-retained coating layer.
graphite fillers act as a lubricant to reduce friction, it decreases the thermal degradation of the resin bond. Hence, the proportion of particles falling from out of the bond is lower, and the abrasive protrusion above the worn surface is better, which causes wheel B to have a relatively greater grinding ratio (see Fig. 3). However, the cause of the greater proportion of abrasive pull-out of wheel A may be due to there being a large amount of SiC filler contained in the resin bond, which leads the bond to weaken, thereby producing poor diamond abrasive retention on the bond. Another reason may be that is a result of mechanical impact, intense scraping and grinding heat.

For continuous dry grinding of 100 passes with a table speed, $V_w$, of 2 m min$^{-1}$ and a depth of cut, $d$, of 0.025 mm, the percentage of each type of abrasive cutting edges on the worn surface of wheel A is shown in Fig. 9(a), whilst that for wheel B is shown in Fig. 9(b). The proportion of particle pull-out and coated abrasive produced on wheels A and B is high. The reason why these occurred are possibly that the resin bond under continuous dry grinding had been excessively degraded by the high grinding heat, thereby significantly reducing or destroying the retention of the particles. This phenomenon can be inferred from the appearance of the resin bond, which shows loose cracks.
(Fig. 10) and particles are separated from the bond (Fig. 11). Hence, the result will be a greater number of abrasive pull-out and coated particles exposed on the bond. Another reason may be that the wheel surface is intensely scraped by the workpiece (P10 carbide) by a shearing process, hence the grinding wheel wears very quickly. The grinding ratio measured was very low (refer to Fig. 4). In addition, the percentage of protrusive abrasive and partial-fracture particle with the cutting action is relatively low, so that the grinding forces were also low. As many abrasives had been plucked out of the bond slide and/or had rolled over the workpiece, grinding was not very effective.

3.4. Surface roughness of the workpiece

The surface roughness of the workpiece generated by dry grinding for wheels A and B is shown in Fig. 12. The roughness of the ground surface is relatively good, their values being about 0.1 μm Ra. Fig. 13 shows an SEM photogaph of a typical ground surface produced by wheel A under a table speed, \( V_w \), of 2 m min\(^{-1}\) and a depth of cut, \( d \), of 0.013 mm. From this figure, it can be seen that the ground surface is very smooth and flat with some scratches. The metallurgical microstructure of the ground surface can also be seen clearly. The white sites are WC particles and the dark gray sites are a combination of WC, TiC, TaC, and Co. This surface is similar to effect that produced by mechanical polishing. The reason for this may be due to there being many abrasives acting simultaneously on the workpiece, the large contact area of the workpiece, and the grinding kinematics.

4. Conclusions

Based on the present experimental results, the following conclusions can be drawn.

In interrupted dry grinding, the abrasive cutting edges occurring on the worn wheel surface are mainly of the protrusive (good) particle type, whilst the number of pull-out holes is high also, making the wheel produce a higher grinding ratio. However, the grinding ratio under a greater stock removal rate could be reduced rapidly, as a result of the wheel being scraped by the workpiece and substantial grinding heat.

When using continuous dry grinding, the resulting worn abrasives produce a greater proportion of particle pull-out and coated grit exposed on the wheel surface, thereby causing poor grinding performance. This may be due to excessive grinding heat and the wheel being dressed by carbides.
Graphite fillers added to the resin bond have a positive effect on the grinding performance of the wheel in dry grinding.

In vertical grinding using a cup-type wheel, the ground surface roughness is similar to that produced by mechanical polishing. The metallurgical microstructures in the ground surface can be observed.

Acknowledgements

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References


