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Grinding of sub-micron-grade carbide: Contact and wear mechanisms, loading, conditioning, scrubbing and resin-bond degradation

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ABSTRACT

An investigation was made into grinding of sub-micron-grade tungsten-carbide in a cobalt matrix. Grit-workpiece contact and loading mechanisms were analyzed. Loading-removal methods – via conditioning and a cleaning nozzle – were analyzed both in terms of fundamental mechanisms and removal efficacy. A novel method of quantifying wheel-conditioning parameters was developed and validated experimentally. Wheel-wear mechanisms were investigated in terms of thermally-induced grain pull-out, particularly under low-aggressiveness conditions. A fundamental difference in the size-effect was seen for sub-micron grades.

1. Introduction

This paper addresses several unexplored areas of tungsten–carbide–cobalt (WC-Co) grinding, specifically: (a) the nature of loading, removal of loaded material, the quantifying of loading-removal parameters, and the efficacy of scrubber nozzles; (b) the anomalous specific energy curve when grinding sub-micron-grade WC-Co; (c) the effect of coolant starvation; and (d) the effect of non-aggressive, small chip-thickness conditions on temperatures and wheel wear via temperature-induced degradation of the resin bond material.

Malkin showed chip-formation energies in grinding of WC-Co proportional to the WC dissociation energy [1]. Hegeman and Hosson [2] found an extruded layer of cobalt at the surface, indicating that the hard WC particles are 'beaten down' into the matrix. Ren et al. [3] found larger specific energies for larger-grain carbides. Hughes [4] found G-ratios fell dramatically at both high and low wheel speeds. Luo et al. [5] found very little grain-flattening, with most wear coming from pull-out of the entire grit.

Wheel loading is a chronic issue in production grinding and little information exists in the literature on mechanisms, removal or removal parameters. In addition, G-ratios typically increase with less-aggressive grinding conditions. However, several sources [4,6,7] show less-aggressive WC-Co grinding conditions giving lower G-ratios, but without explanation for this atypical behavior. Finally, recently introduced sub-micron WC-Co grades are exhibiting unique behavior in terms of the 'size effect'. These aspects are addressed here via theoretical explanations, quantification and experimental measurements.

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2. Background and theory

Production grinding of WC-Co suffers from chronic loading, where workpiece material becomes embedded within the pores of the diamond wheel. The most common method to remove loading is stick-conditioning – also referred to as 'sticking' or 'dressing' – where an aluminum-oxide stick is forced into the wheel to 'open it up'. Until recently, conditioning was done by hand, with the force applied to the stick being at the discretion of the operator, usually done by feel.

Little information is available in the literature on sticking. One book [8] advises to 'stick aggressively' until the stick 'starts to wear rapidly'. Inasaki [9] measured forces at different feedrates to determine the grain-load during sticking. However, both deal with sticking to remove bond material after truing, not loading, and neither quantifies this 'aggressiveness'. Furthermore, recently introduced grinding machines have 'auto stickers' with feedrate as the input, so 'sticking by feel' is not possible.

Sticking is a form of face-grinding, where the Al_2O_3 stick is the workpiece. To quantify sticking aggressiveness, the alterable 'speeds and feeds' parameters can be taken from the equation for chip-thickness, h_{max} [10], and given as the non-dimensional term stick-conditioning Aggressiveness [11,12], $Aggr_{sc}$, a parameter which has been used successfully to quantify the aggressiveness in grinding without the troublesome task of quantifying cutting-point density and chip-thickness ratio. It is defined as:

$$Aggr_{sc} = 10^6 \cdot \frac{Q}{A_c} \cdot \frac{1}{v_s} = 10^6 \cdot \frac{v_{pl}}{v_s} \quad (1)$$

where Q is the material-removal rate, A_c is the contact area, v_s is the wheel velocity and v_{pl} is the plunge velocity into the wheel.

When grinding ductile materials, the specific energy, **e**, increases as h_{max} decreases due to the 'size effect', where smaller grit penetration leads to a greater degree of rubbing and plowing [10]. This has been experimentally validated in numerous materials, including WC-Co [1]. In contrast, in brittle materials specific energies are nearly constant over a wide range of h_{max} values, which is explained by a constant energy per area of plowed surface [13], and rising only at small values of h_{max}.

Several experiments performed at various feedrates on WC-Co showed anomalous size-effect behavior, where specific energies were constant at $e \sim 50\,J/mm^3$ over a very wide range of h_{max} values, rising only at very small h_{max} values. This is anomalous, and more consistent with brittle materials.

WC-Co consists of hard WC particles (90%+) held in a soft cobalt matrix. Swarf consists of chips exhibiting ductile flow, albeit shorter and blockier. Much contemporary WC-Co consists of WC particles which are smaller than one micron, which may be more conducive to plowing and chip removal rather than breaking. In addition, most WC-Co is ground in 100% oil, whereas most literature gives tests done in water-based coolant.

To quantify this, the feedrate and wheel speed can be altered and the specific energy can be analyzed as a function of maximum chip-thickness [10] in the form of the grinding Aggressiveness [11,12], $Aggr_g$, defined for plunge grinding as:

$$Aggr_g = 10^6 \cdot \frac{Q}{A_c} \cdot \frac{1}{v_s} = 10^6 \cdot \frac{v_w}{v_s} \cdot \sqrt{\frac{a_e}{d_s}} \quad (2)$$

where v_w is the feedrate, a_e is the depth of cut and d_s is the wheel diameter.

The G-ratio, the unit volume of material ground per unit volume of wheel worn away, typically increases as $Aggr_g$ decreases due to the smaller forces on the grits. However, when grinding WC-Co, several studies have shown anomalous behavior, where this trend reverses, with low values of G-ratio at higher wheel speeds and longer contact lengths [4,6,7,14,15], without explanation.

One possible explanation is that at low values of $Aggr_g$, rubbing energies – or, in particular for WC-Co, plowing energies–dominate, leading to higher specific energies and, in turn, higher wheel-surface temperatures. This may lead to bond degradation.

3. Experimental

Experiments were performed on two production grinders when flute-grinding sub-micron-grade WC-Co endmills using either resin- or hybrid resin/metal-bonded diamond grinding wheels in 100% oil coolant. Specific energy, **e**, was calculated by measuring voltage and current with Hall-effect transducers in three phases and subtracting out idle power to calculate grinding power, *P*, and dividing by the material-removal rate, *Q*. Power was measured at various feedrates and wheel speeds. Wheel wear, Δh, was estimated via the 'No Dress Test' [16] by measuring the change in part dimension from the first part in the bottom of the flute. Truing was performed with large-grit, hard-grade SiC wheels. Conditioning was performed after truing and periodically in-cycle with soft-grade Al_2O_3 abrasive sticks of various grain sizes at various feedrates. In some tests, a commercially popular scrubber nozzle (~1.6 mm diameter, 40° fan angle) was used, ~6 mm from the wheel normal to the wheel surface, powered by a constant-displacement, low-flowrate (maximum 30 liters/minute), high-pressure (maximum 70 bar) pump. Scanning electron-microscope (SEM) photos were taken of diamond grinding wheels after truing, after sticking and after grinding.

4. Results

Fig. 1 shows SEM photos of a wheel: (a) after truing, (b) after truing and sticking, and (c) after truing, sticking and grinding.

For the trued wheel (a), the surface is flat and there are no visible diamond grits. There are numerous rings, which appear to be cavities left by diamond grits removed during truing and filled in with bond material. Luo et al. [5] found that the majority of grit-pullout during grinding was the diamond separating from the coating, rather than the coating-diamond combination separating from the bond, and this also appears to be the case in truing.

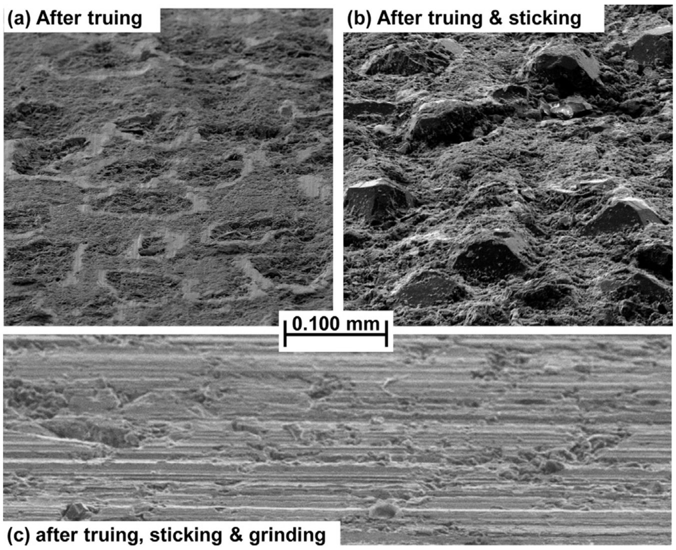

Fig. 1. SEM of trued (a), stuck (b) and ground (c) wheel surface.

For the stuck wheel (b), the surface is irregular and exposed diamonds are visible. For the wheel after grinding (c), the appearance changes significantly, with no visible diamond grits.

Considering that ground WC-Co is comprised of a surface layer of extruded cobalt [2] and that high-ductility materials are typically more prone to loading, it was postulated that loaded regions would be disproportionally comprised of cobalt. Therefore, EDS was used to determine the chemical composition of the loaded material. Seventy EDS samples were taken at various points on loaded regions of two wheels.

Surprisingly, the loaded material was not disproportionately cobalt. Samples gave values ranging from 40% to 85% tungsten and only 4% to 9% cobalt, reflecting the material composition.

Tests were done with various stick grit sizes under various sticking feedrates. Sticks were soaked in coolant before use. The maximum grinding power, *P*, was taken for each flute ground after truing. The results are shown in Fig. 2.

After grinding 11 parts (Fig. 2a, red line), the increase in grinding power due to loading was around 65%. After sticking, using non-aggressive sticking conditions ($Aggr_{sc} = 40$) with grits in the conditioning stick, d_{cs}, 45% larger than the diamond grits, d_d (320-mesh diamond, 220-mesh stick, $d_{cs}/d_d = 1.45$), the drop in power was minimal and power continued to increase.

The test was then repeated (Fig. 2a, black line) with a freshly trued-and-stuck wheel under the same conditions. The power again increased at the same rate. The wheel was stuck with the same large stick-grit size ($d_{cs}/d_d = 1.45$), but more aggressively ($Aggr_{sc} = 210$). Here the power drop was greater. The test was then repeated (a, blue line) with the same aggressive conditions ($Aggr_{sc} = 210$), but now with a finer stick grit size (400-mesh stick, $d_{cs}/d_d = 0.8$). Power dropped to its original level.

Testing was then done on a different process (b) using similar, aggressive parameters ($Aggr = 250$, $d_{cs}/d_d = 0.8$). After six parts (24 flutes), the aggressive, small-grit sticking parameters dropped power to its original level. A second sticking after six additional parts also dropped power to its original level. However, after the first and second stickings, the power rose more quickly (~+21%/part vs. ~+15%/part). This trend – of power increasing more rapidly in subsequent stickings – was also seen in all other sticking tests (not shown). Finally, sticking was done with a very fine grit (2000-mesh, $d_{cs}/d_d = 0.2$). However, the wheel became heavily loaded with Al_2O_3 grits and the wheel had to be 'restuck' with a 400-mesh stick to remove the loaded 2000-mesh Al_2O_3 grits.

Scrubber nozzles, also called cleaning nozzles, have proven successful in removing loading of ductile materials. No evidence exists for their efficacy in removing loading of WC-Co. In spite of that, high-pressure scrubber systems have become more popular. Users have reported to the author that they 'think it provides a