Deposition of Diamond/β-SiC Composite Interlayers for Improved Machining Performance of Diamond Coated Cemented Carbide Cutting Tools

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Abstract. Diamond/β-SiC composite films and diamond film with composite interlayers were synthesized on cemented carbide substrates and hard metal cutting tools. Diamond top layers and the interlayers were deposited in one single process by hot filament chemical vapor deposition (HFCVD) technique using a gas mixture of hydrogen, methane and tetramethylsilane (TMS). Two different kinds of interlayers have been employed, namely, gradient interlayer and interlayer with constant composition. The gradient composite film, featuring a cross-sectional gradient with increasing diamond/β-SiC content from film-substrate interface to the top of the film, showed the best film adhesion. Turning test was carried out using diamond coated and uncoated cutting tools to machine aluminum alloy. It was confirmed that the diamond films with gradient interlayer showed best adhesion to the hard metal cutting tools. Diamond coated cutting tool with gradient composite interlayer showed also higher wear resistance than uncoated cutting tool. The tool lifetime of such diamond coated cutting tool was 10 times higher than that of uncoated cutting tool. Moreover, diamond coated cutting tools performed non-sticking machining, which led to much higher surface quality of machined surface than uncoated insert.

Introduction

With the rapid development of automobile and aerospace industries, materials with high strength to weight ratio, such as aluminum alloy, titanium alloy and fiber enhanced composite materials, are highly needed. The requirement of dry machining has given a real challenge in such materials. Diamond coated cemented carbide cutting tools are considered to be an ideal cutting material for cutting or milling non-ferrous materials, because they possess outstanding mechanical properties including high hardness, low friction coefficient and high wear resistance.[1, 2] However, it has been proven difficult to deposit adherent diamond films on different technologically relevant substrates.[3] Moreover, other obstacles such as low fracture toughness, unsuitable nucleation procedures, and unfavorable gas compositions add more complexities to this topic and limit its further application.[4, 5]

This poor adhesion is caused by a fatal combination of two phenomena. Firstly, Co, which acts as a binder phase in the WC–Co substrates, shows a strong catalytic effect during diamond deposition. The catalytic effect is characterized by a preferentially promotion of the formation of graphite at the substrate interface.[6] Secondly, during the cooling process, thermal stresses are generated in the film owing to a mismatch in the thermal expansion coefficients between diamond coating and WC–Co substrate.[7] To solve the above problem, different strategies involving substrate surface pretreatments and coating of different interlayers have been applied.[8-11] Regarding the adjustment of the thermal expansion coefficient normal to the substrate, the deposition of a composite interlayer with diamond as one of the components represents an optimal solution. In this context, the combination of diamond and SiC allows for a reduction in residual stress in the film, which, in turn, improves the diamond film adhesion.[12, 13]
In this study, hot filament chemical vapor deposition (HFCVD) was utilized to synthesize diamond/β-SiC composite films on cemented tungsten. Compared to uncoated diamond film, the cutting performance of different composite films was studied. Here we describe the method possesses three distinct advantages over common methods. Firstly, diamond top layer can be in situ deposited on the composite interlayer. Secondly, the distribution of diamond and SiC in the composite films can be controlled by adjusting the gas composition. Thirdly, the composite film exhibits in contrast to a pure diamond coating a higher adhesion.

Experiment

The diamond/β-SiC composite film, and diamond films with and without interlayers were synthesized by hot-filament chemical vapor deposition (HFCVD). WC-6 wt. % Co is chosen as the substrate. Prior to deposition, the substrates were treated with Murakami solution (10 g K$_3$[Fe(CN)$_6$]+10 g KOH+100 mL H$_2$O) followed by an acid solution (10 ml 98% H$_2$SO$_4$ + 100ml 33% H$_2$O$_2$) to remove cobalt from the surface. Subsequently, the substrates were ultrasonically seeded for 30 min by employing a dispersion containing nanodiamond (5 nm, 0.05 wt.% in ethanol). After seeding, the substrates were rinsed in water and dried with N$_2$. For the deposition of composite films (sample C), the flow rates of H$_2$, CH$_4$ and TMS were maintained at 500 sccm, 5 sccm, and 35 sccm, respectively. Diamond top layers were in situ deposited on the diamond/β-SiC composite interlayers. The detailed structure and the deposition conditions of the films are summarized in Table 1. For sample A, the composite interlayer was deposited with constant parameters. After the deposition on the interlayer, the TMS flow was turned off, leaving only H$_2$ and CH$_4$ in the chamber, for the deposition of diamond top layers on the composite interlayer. For sample B, a gradient interlayer was achieved by gradually decreasing the TMS flow rate, followed by the deposition of pure diamond layer.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Film description</th>
<th>TMS flow rate</th>
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<tr>
<td>A</td>
<td>1 µm composite interlayer + 3 µm top diamond layer</td>
<td>35 sccm for 1 h, then turned off</td>
</tr>
<tr>
<td>B</td>
<td>2 µm gradient interlayer + 2 µm top diamond layer</td>
<td>35 to 0 sccm in 4 h</td>
</tr>
<tr>
<td>C</td>
<td>4 µm composite film</td>
<td>35 sccm for 4 h</td>
</tr>
<tr>
<td>D</td>
<td>4 µm pure diamond film</td>
<td>0 sccm</td>
</tr>
</tbody>
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The turning test was performed on a CNC-Universal-Lathe (Typ TND 360, Traub, Germany). Diamond coated and uncoated (as-received) indexable insert (CCGT 12040404-ALX-TK 1210) were used as cutting tools. The workpiece materials are aluminum alloy (AlZn5.5MgCu, EN AW-7075) rods with length of 600 mm and diameter of 150 mm. The diamond coated insert was fixed on a tool holder (HERTEL, Germany, RCLNR 2525M12 F6 N26) and continuously cutting the outside of the rod. The machining parameters used are cutting speed (Vc) of 800 m/min and feed (f) of 0.4 mm/turn with depth of cut (ap) as 1 mm.

Results and Discussion

Figure 1 shows a photograph of the diamond coated indexable insert. The surface of the insert was homogenously covered by diamond films. Figure 1a shows the cross-sectional image of diamond film with diamond/β-SiC composite gradient interlayer. Figure 1b and c shows the high magnification and low magnification SEM images of the coated cutting edge. All the cutting edges are coated by dense microcrystalline diamond film. Diamond films were coated not only on the rake face and the cutting edge, but also on the flank face of the cutting tools (see Figure 1c).
Diamond coated and uncoated inserts were utilized in dry machining the aluminum alloy workpiece using the same cutting parameters. The diamond coated insert was fixed on a tool holder and continuously cut the outside of the rod. After 15 min machining, the major cutting edge of uncoated and coated inserts were checked. The edges of the uncoated and coated inserts including the rake and flank faces are shown in Figure 2. For the uncoated insert and the diamond coated insert without interlayer, aluminum sticks to the whole worn areas and builds up aluminum on the cutting edge (similar like Figure 2C2). This leads to the rough machined surface shown. In order to observe the wear of the cutting edge, these inserts were cleaned in a 30% KOH solution to remove aluminum build-up from the cutting edge. The edge of the insert is apparently worn out as shown in Figure 2A. A width of a flank wear was measured to be approx. 0.04 mm. For the diamond coated insert without interlayer (Figure 2D, sample D), a large film delamination and notch wear is observed, indicating quite poor film adhesion. For the diamond coated insert with composite interlayer (Figure 2A, sample A), the cutting edge is clean without aluminum build-up. No film delamination is observed. However, a notch wear is observed in a small area. In this area, diamond coating peels off, and WC–Co substrate is exposed. This indicates that the film adhesion is better than the diamond film without interlayer, but it is still not sufficient for the machining application. For the diamond coated insert with gradient interlayer (Figure 2B, sample B), however, no film delamination is found at the cutting edge, indicating sufficient film adhesion. The aluminum does not build up on the cutting edge, resulting in a smooth machined surface. In addition, the cutting edge of the composite film is shown in Figure 2C1 and Figure 2C2. No peeling off or delamination was found in Figure 2C1, but aluminum buildup is observed (see Figure 2C2). This might be due to the existence of SiC phase on the film surface. SiC possesses worse mechanical and thermal properties than diamond, and similar properties of hardness and thermal conductivity like WC–Co substrate. These results are in agreement with the Rockwell C adhesion test and residual stress discussed [13]. In conclusion, the composite interlayers are helpful to improve the diamond film adhesion, and the best diamond film adhesion was achieved by depositing gradient interlayer.

The diamond coated insert with gradient interlayer is utilized to machine aluminum alloy with the same parameters till 193 min. The width of the flank wear of the diamond coated insert and uncoated insert is plotted against cutting time in Figure 3. With increasing cutting time, the uncoated insert is more quickly worn than the diamond coated insert. The flank wear grows slowly on the diamond coated insert. There are three wear regions with increasing cutting time. The initial wear region involves in removal of surface asperities (by fracture or polishing) which corresponds to the first 15 min of machining using diamond coated insert. After the initial wear, the flank wear size is proportional to the cutting time, which is called steady wear region. The wear increasing rate is relatively constant from 15 min till 193 min for the diamond coated insert, indicating that our testing region belongs to the steady-state wear region. Finally, there is an ultimate wear region when the flank wear rate increases and then the tool loses its cutting ability, which is not shown here.
Lifetime of a cutting tool is expressed as cutting time till the tool failure. The criterion for tool failure is considered as the width of flank wear which is broader than 0.055 mm. To achieve this criterion, the uncoated insert machines approx. 18 min, whereas the diamond coated insert machines 193 min. Thus, the wear resistance ability (or tool lifetime) of the diamond coated insert is 10 times higher (or longer) than that of the uncoated insert.

During the machining process, cutting tools are subjected to extremely arduous conditions, high surface loads, and high surface temperatures. Tool wear can be generated by mechanical (thermo-dynamic wear, mostly abrasion) and chemical (thermo-chemical wear, diffusion) interactions between the tool and the workpiece.[14]

The basis of utilizing diamond films as a cutting tool material is the sufficient film adhesion. Without interlayer, the diamond coating delaminates severely only after 15 min machining, suggesting that the tool lifetime of the diamond coated insert without interlayer can be maximum 15 min. For the diamond coated insert with gradient interlayer, the cutting tool could still be used after 193 min machining. Therefore, the adhesion of diamond coatings is drastically improved by using diamond/β-SiC gradient interlayer.

The wear resistance of diamond coated insert is 10 times higher than that of uncoated insert. This is due to the different mechanical and thermal properties of diamond, β-SiC, WC–Co and aluminum alloy. The hardness of WC–Co is more than 10 times higher than that of aluminum alloy, whereas the hardness of diamond is more than 55 times higher than that of aluminum alloy. The Young’s modulus of diamond is also much higher than that of WC–Co and aluminum alloy. These indicate that diamond is very hard to be deformed and very resistant to various kinds of shape change. Furthermore, the toughness of the diamond coating with diamond/β-SiC composite film could be further improved by deposition together with β-SiC to avoid brittle fracture. The thermal conductivity also plays an important role during machining. It is known that heat is generated in the friction process between the cutting tool and machined materials. The thermal conductivity of diamond is 20 times higher than that of WC–Co. The diamond coating transfers the heat more quickly than WC–Co that the diamond coated cutting tool undergoes less thermally induced damage. These advantages of diamond result in not only longer tool lifetimes, but also higher surface quality of workpiece.
Conclusion

Diamond/β-SiC composite films and diamond film with composite interlayers were synthesized on WC–Co substrates and hard metal cutting tools, respectively. Diamond films were deposited in situ on the composite interlayers. Two different kinds of interlayers were employed, namely, gradient interlayer and interlayer with constant composition. The gradient interlayer featured a cross-sectional gradient with increasing diamond/β-SiC content from film-substrate interface to the top of the film. Turning test was carried out using diamond coated and uncoated cutting tools to machine aluminum alloy. It was confirmed that the diamond films with gradient interlayer showed good adhesion to the hard metal cutting tools. Moreover, diamond coated cutting tools performed non-sticking machining, which led to much higher surface quality of machined surface than uncoated insert. Diamond coated cutting tool with gradient composite interlayer showed also higher wear resistance than uncoated cutting tool. The tool lifetime of such diamond coated cutting tool was 10 times higher than that of uncoated cutting tool.

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References


