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Coating thickness effects on diamond coated cutting tools

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ABSTRACT

Chemical vapor deposition (CVD)-grown diamond films have found applications as a hard coating for cutting tools. Even though the use of conventional diamond coatings seems to be accepted in the cutting tool industry, selections of proper coating thickness for different machining operations have not been often studied. Coating thickness affects the characteristics of diamond coated cutting tools in different perspectives that may mutually impact the tool performance in machining in a complex way. In this study, coating thickness effects on the deposition residual stresses, particularly around a cutting edge, and on coating failure modes were numerically investigated. On the other hand, coating thickness effects on tool surface smoothness and cutting edge radii were experimentally investigated. In addition, machining Al matrix composites using diamond coated tools with varied coating thicknesses was conducted to evaluate the effects on cutting forces, part surface finish and tool wear. The results are summarized as follows. (1) Increasing coating thickness will increase the residual stresses at the coating–substrate interface. (2) On the other hand, increasing coating thickness will generally increase the resistance of coating cracking and delamination. (3) Thicker coatings will result in larger edge radii; however, the extent of the effect on cutting forces also depends upon the machining condition. (4) For the thickness range tested, the life of diamond coated tools increases with the coating thickness because of delay of delaminations.

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1. Introduction

Diamond coatings produced by chemical vapor deposition (CVD) technologies have been increasingly explored for cutting tool applications. Diamond coated tools have great potential in various machining applications and an advantage in fabrications of cutting tools with complex geometry such as drills. Increased usages of lightweight high-strength components have also resulted in significant interests in diamond coating tools. Hot-filament CVD is one of common processes of diamond coatings and diamond films as thick as 50 μm have been deposited on various materials including cobalt-cemented tungsten carbide (WC-Co) [1]. There have also been different CVD technologies, e.g., microwave plasma assisted CVD [2], developed to enhance the deposition process as well as the film quality too. However, despite the superior tribological and mechanical properties, the practical applications of diamond coated tools are still limited.

Coating thickness is one of the most important attributes to the coating system performance. Coating thickness effects on tribological performance have been widely studied. In general, thicker coatings exhibited better scratch/wear resistance performance than thinner ones due to their better load-carrying capacity. However, there are also reports that claim otherwise [3,4]. For example, Dorner et al. discovered, that the thickness of diamond-like-coating (DLC), in a range of 0.7–3.5 μm, does not influence the wear resistance of the DLC–Ti6Al4V [3]. For cutting tool applications, however, coating thickness may have a more complicated role since its effects may be augmented around the cutting edge. Coating thickness effects on diamond coated tools are not frequently reported. Kanda et al. conducted cutting tests using diamond-coated tooling [5]. The author claimed that the increased film thickness is generally favorable to tool life. However, thicker films will result in the decrease in the transverse rupture strength that greatly impacts the performance in high speed or interrupted machining. In addition, higher cutting forces were observed for the tools with increased diamond coating thickness due to the increased cutting edge radius. Quadrini et al. studied diamond coated small mills for dental applications [6]. The authors tested different coating thickness and noted that thick coatings induce high cutting forces due to increased coating surface roughness and enlarged edge rounding. Such effects may contribute to the tool failure in milling ceramic materials. The authors further indicated tools with thin coatings results in optimal cutting of polymer matrix composite [6]. Further, Torres et al. studied diamond coated micro-endmills with two levels of coating thickness [7]. The authors also indicated that the thinner coating can further reduce cutting forces which are attributed to the decrease in the frictional force and adhesion.

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Coating thickness effects of different coating-material tools have also been studied. For single layer systems, an optimal coating thickness may exist for machining performance. For example, Tuffy et al. reported that an optimal coating thickness of TiN by PVD technology exists for specific machining conditions [8]. Based on testing results, for a range from 1.75 to 7.5 µm TiN coating, thickness of 3.5 µm exhibit the best turning performance. In a separate study, Malik et al. also suggested that there is an optimal thickness of TiN coating on HSS cutting tools when machining free cutting steels [9]. However, for multilayer coating systems, no such an optimum coating thickness exists for machining performance [10].

The objective of this study was to experimentally investigate coating thickness effects of diamond coated tools on machining performance – tool wear and cutting forces. Diamond coated tools were fabricated, by microwave plasma assisted CVD, with different coating thicknesses. The diamond coated tools were examined in morphology and edge radii by white-light interferometry. The diamond coated tools were then evaluated by machining aluminum matrix composite in dry. In addition, deposition thermal residual stresses and critical load for coating failures that affect the performance of diamond coated tools were analytically examined.

2. Experimental investigation

The substrates used for diamond coating experiments, square-shaped inserts (SPG422), were fine-grain WC with 6 wt.% cobalt. The edge radius and surface textures of cutting inserts prior to coating was measured by a white-light interferometer, NT1100 from Veeco Metrology.

Prior to the deposition, chemical etching treatment was conducted on inserts to remove the surface cobalt and roughen substrate surface. Moreover, all tool inserts were ultrasonically vibrated in diamond/ water slurry to increase the nucleation density. For the coating process, diamond films were deposited using a high-power microwave plasma-assisted CVD process. A gas mixture of methane in hydrogen, 750–1000 sccm with 4.4–7.3% of methane/hydrogen ratio, was used as the feedstock gas. Nitrogen gas, 2.75–5.5 sccm, was inserted to obtain nanostructures by preventing columnar growth. The pressure was about 30–55 Torr and the substrate temperature was about 683–830 °C. A forward power of 4.5–5.0 kW with a low deposition rate obtained a thin coating; a greater forward power of 8.0–8.5 kW with a high deposition rate obtained thick coatings, two thicknesses by varying deposition time. The coated inserts were further inspected by the interferometer.

A computer numerical control lathe, Hardinge Cobra 42, was used to perform machining experiments, outer diameter turning, to evaluate the tool wear of diamond coated tools. With the tool holder used, the diamond coated cutting inserts formed a 0° rake angle, 11° relief angle, and 75° lead angle. The workpieces were round bars made of A359/SiC-20p composite. The machining conditions used were 4 m/s cutting speed, 0.15 mm/rev feed, 1 mm depth of cut and no coolant was applied. The selection of machining parameters was based upon previous experiences. For each coating thickness, two tests were repeated. During machining testing, the cutting inserts were periodically inspected by optical microscopy to measure the flank wear-land size. Worn tools after testing were also examined by scanning electron microscopy (SEM). In addition, cutting forces were monitored during machining using a Kistler dynamometer.

3. Results and discussion

3.1. Edge rounding and surface morphology

Fig. 1 shows examples of cutting edge images; one is from an uncoated substrate and the other is from a diamond coated tool with the thickest coating tested. Measurement results indicate that the edge radius of the uncoated substrates was about 14 µm in average with less than 1 µm variation. The coated tools have edge radii in 3 ranges: (a) 17–19 µm, (b) 29–32 µm, and (c) 40–45 µm. Thus, the nominal coating thickness was estimated as around (a) 4 µm, (b) 17 µm and (c) 29 µm. In addition, for the uncoated tools, surface roughness, R_a, was about 0.23 µm–0.35 µm, and for coated tools, R_a was from 0.44 to 0.65 µm. The coating surface roughness and diamond grain size, which are related, affect machining in friction coefficient, cutting forces, and part surface finish. For the coatings tested, they are in a similar range, no significant difference was noticed.

3.2. Machining performance

Fig. 2 shows tool wear, flank wear-land width (VB), along cutting time for the 4 m/s and 0.15 mm/rev condition at different coating thicknesses. Results of two replicates are shown. In general, the tools showed a gradual increase of tool wear followed by an abrupt increase of wear-land in one or two passes. It is believed that, during those specific passes, coating delamination occurred and resulted in rapid wear of the exposed substrate material. Tool wear and the onset of coating delamination are dependent on the coating thickness. For the coating thickness range tested, a thicker coating gives a longer tool life. It is also noted that for the 17 and 29 µm-thick coated tools, the wear-land sizes prior to delamination were in a similar range, indicating a comparable abrasive wear resistance. Additionally, surface roughness of machined parts was in a close range between different coating-thickness tools.
Fig. 3 shows examples of worn tool images (from SEM) of two different coating thicknesses: 4 µm and 29 µm. Flank wear-land is noted as the major wear pattern. Moreover, inserts with either thin or thick coatings show similar wear features, a large wear-land once coating being delaminated and noticeable metal deposits. For the thin coating, the delamination area also extended beyond the flank wear-land contact surface.

Cutting forces of all 3 components: tangential ($F_t$), radial ($F_r$) and axial ($F_a$) were analyzed and compared between different coating thicknesses. For the initial cutting (first pass), the average forces are 58 N ($F_r$), 148 N ($F_t$) and 72 N ($F_a$) for 4 µm coating tool, and 72 N ($F_r$), 143 N ($F_t$) and 77 N ($F_a$) for 29 µm thick coating tools. Thus, the cutting force increases due to the edge rounding is considered to be marginal. This may be due to the cutting conditions tested, 0.15 mm/rev feed that is relatively large compared to the edge radius range used.

4. Analytical evaluation

4.1. Deposition residual stresses

Finite element (FE) modeling was used for the simulations of deposition residual stress due to thermal mismatch. The substrate geometry studied here was the same as in the experiments: square-shaped inserts that are 12.7 mm wide and 3.2 mm thick with a 79° wedge angle and a 0.8 mm corner radius. The inserts were modeled in CAD software (Pro/Engineer) according to the actual geometry. The edge radius was incorporated into the models, 15 µm. The diamond coating on the substrate has a uniform thickness at the rake and the relief faces, extending to about 1.6 mm from the substrate bottom. The coating thickness was varied from 5 µm to 30 µm. The CAD models of the tool (substrate and coating) were then imported into FE software, ANSYS, for thermal stress simulations. The element used for analysis was Solid45. Meshing was generated in the coating first using the default setting and the edge area was redefined. The substrate was then meshed using the default setting.

Static structural analysis with thermal strains included was conducted. A uniform deposition temperature of 800 °C was set as the initial condition and a room temperature of 25 °C was set as the final temperature. Linear-elastic material models independent of temperatures were used for both diamond and WC. The elasticity, Poisson’s ratio, and thermal expansion coefficient of diamond [11] and WC [12] used were 1200 GPa, 0.07, 2.5 µm/(m•K), and 620 GPa, 0.24, 5.5 µm/(m•K), respectively. After the model setup, structural analysis was executed to obtain displacement, strain, and stress data. Further, the stress data along the interface was extracted and then transformed into the local polar coordinate along the cutting edge to evaluate the interface stresses including three components that are a function of the location. The procedures were detailed in Renaud et al. [13].

Fig. 4 shows the stress contours ($\sigma_z$ component, one major axis at the tool rake surface) in diamond coated inserts with two different coating thicknesses. It can be noted that the stress in the coating, away from the edge, is about 3.0 GPa in compression, which is consistent with the biaxial stress analysis. Moreover, the stress distribution...
around the tool edge shows considerable stress concentration for the 30 µm coating thickness with a greater tensile stress in the substrate.

Fig. 5 compares the interface stresses around the edge for different coating thicknesses. The abscissa in the figure is the normalized distance (by the arc length of the rounded edge) from 0 to 1, where 0 is the beginning of edge rounding at rake and 1 is the end of rounding at the relief surface. First, high stress concentrations due to thicker coatings can be noted. For the radial normal stress ($\sigma_r$), the maximum increase from 1.0 GPa for 5 µm to 1.4 GPa for 30 µm coating thickness. Such high tensile stresses can be detrimental in brittle fracture due to crack propagations and require greater adhesion strengths. The thin coatings also give smooth stress profiles along the edge. On the other hand, the maximum magnitude of circumferential normal stress ($\sigma_\theta$) increases from 2.7 GPa for 5 µm to 3.7 GPa for 30 µm coating thickness.

4.2. Coating failure under indentation load

In a previous study [14], FE simulations of an indentation cycle on a diamond-coating WC-substrate system, including a cohesive-zone interface, were developed, also using ANSYS. The constitutive law of the cohesive zone model adopted was based on Xu and Needleman's approach [15]. The mechanical relations between the traction and displacement jump across the interface describe the interface behavior, characterized by three parameters, namely, the normal strength of the interface, and characteristic lengths for both the normal and shear modes. In the simulations, the material behaviors were perfect elastic for the diamond coating and elastic–plastic with a hardening rule for the substrate, respectively. Quasi-static structural analysis was performed to simulate the loading–unloading cycle during indentation.

The simulation was used to study the coating thickness effects on coating cracking. The results from the previous work indicate the following. The contact between the indenter and the coating produces a high tensile stress right at the contact circle, which will result in Hertzian ring cracks. On the other hand, the bending of the coating on a compliant substrate will introduce tensile stresses at the bottom surface of the coating, but compressive stresses at the top surface. These two mechanisms may affect failures in an opposite way at different coating thicknesses. The bending effect may vanishes gradually with the increase of coating thickness, therefore, reducing the critical load for ring cracks. Thus, for a thicker coating (greater than 20 to 30 µm), the failure mode is Hertzian ring cracks, and the critical load for cracking decreases with the increase of the coating thickness, Fig. 6. On the other hand, for thin coatings, the radial cracking is more dominant, and the critical load will increase with the coating thickness. The developed simulation was also extended to investigate coating thickness effects on the critical loads for the interface delamination. From Fig. 6, it is observed that as the coating thickness around the tool edge shows considerable stress concentration for the 30 µm coating thickness with a greater tensile stress in the substrate.

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thickness increases, the critical load for delamination increases due to the delay of plastic yielding onset.

Comparing the experiments and analysis, it is suggested that thicker coatings have a greater machining-load capacity and thus a longer tool life before delamination. The greater interface stresses and larger edge rounding due to thick coatings do not seem to significantly impair its performance. However, it also needs to point out that such phenomena (coating thickness effects) may be dependent upon the substrate edge radius and machining conditions.

5. Conclusions

In this study, the coating thickness effects on diamond coated cutting tools were studied from different perspectives. Deposition residual stresses in the tool due to thermal mismatch were investigated by FE simulations and coating thickness effects on the interface stresses were quantified. In addition, indentation simulations of a diamond coated WC substrate with the interface modeled by the cohesive zone were applied to analyze the coating system failures. Moreover, diamond coated tools with different thicknesses were fabricated and experimentally investigated on surface morphology, edge rounding, as well as tool wear and cutting forces in machining. The major results are summarized as follows.

(1) Increase of coating thickness significantly increases the interface residual stresses, though little change in bulk surface stresses.
(2) For thick coatings, the critical load for coating failure decreases with increasing coating thickness. However, such a trend is opposite for thin coatings, for which radial cracking is the coating failure mode. Moreover, thicker coatings have greater delamination resistance.
(3) In addition, increasing the coating thickness will increase the edge radius. However, for the coating thickness range studied, 4–29 µm, and with the large feed used, cutting forces were affected only marginally.
(4) Despite of greater interface residual stresses, increasing the diamond coating thickness, for the range studied, seem to increase tool life by delay of coating delaminations.

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