Nanocrystalline diamond coating tools for machining high-strength Al alloys

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Abstract

Diamond coating tools have been increasingly used for machining advanced materials. Recently, a microwave plasma-assisted chemical vapor deposition (CVD) technology was developed to produce diamond coatings which consist of nano-diamond crystals embedded into a hard amorphous diamond-like carbon matrix. In this study, the nanocrystalline diamond (NCD) coating tools were evaluated in machining high-strength aluminum (Al) alloy. The conventional CVD microcrystalline diamond coating (MCD) tools and PCD tools were also tested for performance comparisons. In addition, stress distributions in diamond coating tools, after deposition and during machining, were analyzed using a 2D finite element (FE) thermomechanical model.

The results show that catastrophic failures, reached in all except one machining conditions, limit the NCD tool life, which is primarily affected by the cutting speed. In addition, coating delamination in the worn NCD tools is clearly evident from scanning electron microscopy (SEM) and force monitoring in machining can capture the delamination incident. At a high feed, coating delamination may extend to the rake face. Furthermore, SEM observations of coating failure boundaries show intimate coating-substrate contact. Though the NCD tools are inferior to the PCD tools, they substantially outperform the MCD tools, which failed by premature delamination.

Keywords: Coating delamination; Diamond coating; Machining forces; Nanocrystalline diamond; Tool wear

1. Introduction

Diamond coatings, owing to their extreme properties comparable to or even exceeding synthetic polycrystalline diamond (PCD), processed by high pressures and high temperatures, have been frequently explored for cutting tool applications. Hot-filament chemical vapor deposition (CVD), in which the gas phase activation is controlled by heating the filament, is one of primarily used processes because of the relatively low equipment cost and mature fabrication technologies. Thin film CVD diamond over 50 µm thick has been deposited on various materials including tungsten carbides (WC).

Investigations of CVD diamond coating tools have been frequently reported. There are, however, mixed results of the CVD diamond tool performance. In a few applications, CVD diamond-coated tools show a tool life comparable to PCD tools in machining. Oles et al. tested diamond coating tools with different pre-deposition treatments in machining of high-Si Al alloys [1]. The results showed that the CVD diamond tools can meet or even exceed the PCD tool in tool life. However, the part surface finishes produced by the CVD diamond tools are poor than the finish by the PCD tools. Shen evaluated CVD diamond tools from a variety of sources in industrial machining settings and reported large variations of machining results and that a few types
of diamond coating tools have the performance comparable to the PCD tools [2,3]. Belmonte et al. showed that thick CVD diamond tools (~0.3 mm film) can top PCD tools and have greater flank-wear resistance in machining hard-metal, WC [4]. Karner et al. investigated CVD diamond tools in a broad range of production processes [5]. In turning copper armature, the CVD diamond tools doubled the tool life of PCD tools. On the other hand, several studies reported that the wear resistance of CVD diamond tools is still distant to the PCD counterparts, though some argued that CVD diamond tools have potential economic benefit because of multiple cutting tips. Schafer et al. assessed CVD diamond coatings on high-speed steel substrates in machining AlSi10Mg alloys and concluded that the CVD diamond tools had much poor performance than the PCD tools [6]. In machining silicon-carbide (SiC)–Al matrix composites, Andrewes et al. reported that the PCD tools perform significantly better than the CVD diamond tools, over three times [7]. D’Errico and Calzavarini indicated that majority of diamond coating tools, obtained from five different manufacturers, have shorter tool lives than the PCD tools in machining Al based composites [8]. Davim reported that in machining SiC–Al matrix composites, PCD tools have a much longer tool life, over 10 times, than the CVD diamond tools and can be used at much higher cutting speeds, over five times used for the diamond coating tools [9]. Polini et al. also tested CVD diamond tools with varied coating parameters in dry turning of alumina-reinforced Al matrix composites [10]. The authors noted that the majority of the tested CVD coating tools have shorter tool lives than PCD tools.

Several diamond coating tool studies further discussed coating tool wear. Andrewes et al. indicated that both abrasion and adhesion are the wear mechanism with the former dominant during the initial cutting but the latter detrimentally limiting the CVD diamond coating tools [7]. Karner et al. showed that flaking of diamond films at the flank surface is the major wear mechanisms of CVD diamond coating tools [5]. D’Errico and Calzavarini examined coating failure boundary and observed the coating detachments and gaps between the coating and the substrate [8]. Chou and Liu also demonstrated that coating delaminations at the tool flank can be of catastrophic nature and is the tool-life limiting factor for CVD diamond coating tools [11]. High stresses and/or degraded adhesion during machining may result in coating failures and subsequent rapid wear of the exposed substrate.

In CVD processing, the coating-substrate system returns to the room temperature from a deposition temperature. The largely mismatched thermal strains between the diamond coating and substrates generate high stresses in the coated tool system as well as the stress discontinuity at the interface. Diamond coatings bear a compressive residual stress and the carbide substrates receive a stress in tension [12]. Residual stresses in diamond coatings have been widely studied using different techniques [13–16]. The residual stresses in diamond coatings depend upon substrate materials, surface treatments, and deposition temperatures, etc., and can be as high as 6 GPa in compression [17]. Such a high level of residual stresses has a compound impact to the coating performance [18].

Recently, a microwave plasma-assisted CVD technology was developed to increase the diamond growth rate, and by using nitrogen gas, this process can produce ultrafine diamond grains in the order of 10 nm [19]. The produced diamond coatings consist of nano-diamond crystals embedded into a hard amorphous diamond-like carbon matrix and have high hardness and low surface roughness [20]. This technology has been applied to fabricate nanocrystalline diamond (NCD) coating tools. The objective of this research was to evaluate the newly developed NCD tools in machining high-Si Al alloys. Machining performance such as tool wear and process variables such as cutting forces were evaluated in a range of machining conditions. Tool wear conditions were examined in details by scanning electron microscopy (SEM). In addition, the conventional CVD diamond coating tools and PCD tools were also evaluated for comparisons. Moreover, to investigate the stress field in diamond coating tools, finite element (FE) modeling was applied for thermal and mechanical simulations, both after the deposition and during machining.

2. Experimental set-up

2.1. NCD coating processing

For NCD coating tool fabrications, the substrates used were 6 wt.% cobalt fine-grain tungsten carbides of square-shape inserts (SPG422), 12.7 mm wide and 3.2 mm thick. The NCD film was produced by a high-power microwave plasma-assisted CVD process using an in-house fabricated reactor. A gas mixture of methane in hydrogen was used as the feedstock gas. Nitrogen, maintained at a certain ratio to methane, was inserted to the gas mixture to obtain nanocrystalline microstructures by preventing cellular growth. The pressure was about 90 Torr the substrate temperature was 800 °C, and the deposition rate was roughly 1 μm/h. All conditions were fixed to produce NCD tools with consistent quality. The coating thickness at the rake surface was about 30 μm, comparable to commercial CVD diamond coating tools. The coating was uniform over the rake face and the thickness at the flank surface linearly diminished to nil at about 0.9 mm from the substrate bottom. Commercial CVD diamond coating with 30 μm film (named MCD for its micro-crystal sizes) and PCD tools of the same shape and size (SPG422) were evaluated as well. A separate study showed that the grain sizes of the MCD and PCD tools are 3–5 μm and 10–20 μm in average, respectively [21]. On the other hand, the NCD tool has ultrafine grains [21].

2.2. Machining experiment

In machining, a 25.4 mm thick steel tool-holder was used together with the NCD tools to form 0°, 11°, and
15° of the rake, relief, and lead angles, respectively. The workpieces were solid round bars made of A 390 alloy (18 wt.% Si), composition in Table 1. Outside diameter turning using the NCD tools was carried out in a precision computer-numerical-control (CNC) lathe (Hardinge Cobra 42) in dry. Machining conditions included four combinations of two cutting speeds: 3 m/s and 10 m/s, two feeds: 0.2 mm/rev and 0.8 mm/rev, and fixed 1 mm depth of cut. The commercial CVD diamond coating and PCD tools were also tested at the most aggressive condition, i.e., 10 m/s and 0.8 mm/rev. A triaxial piezoelectric force sensor (Kistler 9257B) with a data acquisition system was used to continuously monitor three components of cutting forces during machining, i.e., tangential, radial and axial, respectively. Tool wear, in flank wear-land width (VB), was periodically measured off-line by optical microscopy. Note that, during machining, the work materials deposited and covered the tool flank wear-land, partially or entirely. In order not to alter the tool conditions in the continued machining experiment, the wear-land size was estimated without the material removed, if any. In the end of the machining test, the tools were chemically cleaned using a 10 vol.% hydrofluoric acid solution to remove the adhered work materials. The exposed wear-land was also measured and compared to the with-deposit measurements. After the completion of machining testing, the worn tools were also studied by SEM, before and after the deposit cleaning, to examine the wear mechanisms at different machining conditions.

3. Tool stress study

To evaluate the stress field in a diamond-coated tool, after the deposition and during machining, a simplified 2D FE model using ANSYS software was developed for thermal and mechanical analyses with the plane strain condition assumed, detailed in [22]. For deposition-stress simulations, static structural analysis with thermal strains considered was conducted. A deposition temperature of 800 °C was set as the uniform initial condition and a room temperature of 25 °C as the final temperature. Linear-elastic material models were applied to both the diamond and WC.

To simulate the stress distributions in the tool during machining, the thermal and mechanical contact loads were first estimated based on the cutting mechanics analysis using measured data from the machining test including cutting forces, cutting chip thickness, and the chip-tool contact length. The measurements were input in the cutting analysis [23], orthogonal cutting approximation, to estimate the heat flux and heat partitioning as well as the normal and shear stresses at the tool rake face. Then, transient heat conduction analysis was performed, with the partitioned heat flux at the tool-chip contact, to obtain the temperature distributions in the diamond coating tool. The substrate bottom was approximate as the room temperature and other surfaces adiabatic. Next, a static structural analysis was continued, carrying final temperatures from the thermal analysis and initial stresses from the deposition simulations. The machining contact stresses at the rake face, also estimated from the cutting mechanics analysis, were applied as the mechanical boundary conditions. The final stress distributions in the diamond coating tool were simulated and the stresses at the coating-substrate interface were analyzed and compared for different machining conditions.

4. Results and discussion

Fig. 1 compares flank wear vs. cutting time at four different machining conditions. For all except the low-speed and low-feed condition, abrupt wear growths occurred during the last cutting pass and consistently showed catastrophic coating failures as the tool life limit. It is also observed that the cutting speed is dominant to the tool life. For the most aggressive machining condition (10 m/s and 0.8 mm/rev), the tool life was about 2.6 min. with a flank wear-land of 0.6 mm. On the other hand, for the 3 m/s and 0.2 mm/rev condition, coating failures were not noted after about 16 min. of cutting time with a VB less than 0.1 mm.

Fig. 2 shows SEM images of the worn NCD tools after the machining test. For the low-speed low-feed condition, the cutting edge has minor traces of wear. The other three machining conditions resulted in larger worn surfaces and coating failures were evident with clear wear-land boundaries. The work material deposited and adhered around
the tip is another wear-related feature, with the least amount in the mild machining and the most in the aggressive condition, covering the most of the wear-land. Fig. 3 shows the details of the worn NCD tools. For the low-speed high-feed conditions, it is observed that the exposed substrate extended beyond the wear-land contact zone, Fig. 3b. For the high-speed high-feed condition, the work material deposited at the wear-land appears to experience severe plastic deformation during machining. The tool used in the low-speed and low-feed machining seems to retain an undamaged cutting edge.

The worn NCD tools after cleaning the metal deposits are shown in Fig. 4. At the rake surface, the crater wear is not observed, and for the high-feed conditions, the coating delamination extended to the rake face considerably. With the deposit removed, the wear-land contact can be clearly identified and coating delamination extended beyond the contact zone, implying that delamination occurred first followed by consequent massive WC/Co wear and increased wear-land contact. On the other hand, coating thinning due to the gradual wear process is not observed, again indicating that the material loss was substantial followed by the severe nose wear. Fig. 5 shows an example of high-magnification views around the coating failure boundaries, 10 m/s and 0.8 mm/rev. The coating-substrate interface appears to be intact without visible gaps or flaking and the interface contact remains completely intimate, implying good coating interface.

Fig. 6 compares cutting forces at different machining conditions. As expected, the feed has dominant effects on cutting forces, mainly the tangential and radial components. The cutting speed effect on cutting forces is marginal with the tangential component more noticeable and the other two components little affected. Before the coating failure, machining forces were stable, then followed by rapid increasing during the tool failure pass for the high-speed conditions. For the low-speed high-feed machining, sharp force increasing was not observed during the tool failure pass, even with large flank wear growing. Fig. 7 is an example of the force signal changes during the coating failure pass at the high-speed low-feed condition. The large magnitude variations are clearly evident and associated with the coating delamination, with the axial component being the most noticeable. The abrupt decreasing of the machining forces was due to the loss of materials and decreased intimate contact, and the rapid development of wear-land contact resulted in the subsequent force climbing. Both the worn tool features from SEM and machining force data point out that the coating delamination is the major tool wear mechanism and triggers the catastrophic failure.

For different diamond tools, the flank wear development during machining is shown in Fig. 8. The aggressive
machining conditions, 10 m/s and 0.8 mm/rev, caused rapid tool wear. For the conventional CVD diamond coating tool (MCD), premature coating failures led to a drastic tool wear growth, reaching about 1.0 mm VB at just 1.2 min. of cutting time. On the other hand, the NCD tools had better wear resistance and the tool wear was close to the PCD tool till around 2 min. cutting time. However, rapid wear of the NCD tool then developed and the wear-land size became larger than the PCD tool wear. Fig. 9 compares machining forces of different diamond tools. It is noted that initial forces were in similar ranges for all three different diamond tools.

Majority of surveyed literature in Section 1 reported that CVD diamond-coated tools are still distant to PCD
tool performance. In this study, the machining results also indicate that the conventional CVD diamond tools (MCD) have a much lower tool life than PCD tools in machining A390 alloy. On the other hand, the NCD tools were able to maintain low wear comparable to PCD tools before delamination causes catastrophic wear. The NCD tools substantially outperformed the MCD tools possibly due to the following reasons. The nanoindentation test shows that the NCD tools have a much greater hardness than the MCD and PCD tools, about 81 GPa vs. 57 and 50 GPa, respectively [21]. The high hardness will benefit the abrasive wear resistance. In addition, the NCD tools have the lowest elastic modulus among the three types of diamond tools, 684 GPa vs. 1027 and 1019 GPa of the MCD and PCD tools, respectively [21]. Since the thermal strain mismatch is proportional to the elasticity, the low elasticity of the NCD tools implies a lower deposition-induced residual stress that may reduce the adhesion problem.

Fig. 10 is a typical stress contour in a diamond coating tool after the deposition, showing the normal stress parallel...
to the substrate top surface. The area away from the edge has a uniform compressive stress around 4.0 GPa in the coating and 0.7 GPa of tension in the substrate. However, around the edge, the stress concentrations are considerably high. The plot also shows the distortion caused by the residual stresses, about 1.7 \mu m deflection in the thickness direction at the center of the insert.

Fig. 11 plots three components of stresses around the cutting edge. \( \sigma_r \) and \( \sigma_\theta \) are the normal stresses in the radial and tangential directions (with respect to the round edge), respectively, and \( \tau_{r\theta} \) is the shear stress in the tangential direction. The stresses plotted are at the coating–substrate interface and around the edge, also extended to the flat area of the top surface (coordinate 0 is where the edge curve begins and negative values are toward the rake face). Severe stress concentrations around the cutting edge can be quantified. For the radial normal component, high tensile stresses were developed, about 1.8 GPa. The high tensile stresses can be detrimental in brittle fracture by crack propagations and require greater adhesion strength. On the other hand, the tangential normal stresses around the edge are highly compressive, maximum 4.5 GPa. The large compressive tangential stresses have been viewed beneficial to abrasive wear reductions, however, buckling could be another mechanism risky to the coating failure [24]. The tangential shear stresses have values in a range from −1.0 GPa to 0.8 GPa.

Fig. 12 shows stress evolutions from the deposition to machining at 10 m/s and 0.2 mm/rev. The stress changes resulted from the combined thermal and mechanical loads in machining. The plots also illustrate the decoupled effects of the thermal and mechanical loads from machining. The curve of “thermal” means that only the contact heat flux was imposed. While “thermomechanical” indicates that
both the heat flux and contact stresses were applied. The elevated machining temperatures caused stress relief and result in reduced radial normal stresses, from maximum 1.8 GPa to about 0.3 GPa. Mechanical contact-loading from machining was compressive, and thus, further reduced $\sigma_r$ to about maximum 0.1 GPa, and the location of the maximum stress shifted toward the flank surface. From the results, it can be inferred that the thermal effect is more dominant to the stress reversal conditions. For the tangential normal and shear stresses, a similar trend is also observed. Fig. 13 shows machining parameter effects on the stress modifications, $\sigma_r$ and $\sigma_\theta$, respectively. As observed in Fig. 12, machining loading generally lowers the magnitudes of the radial and tangential normal stresses, considered as a stress reversal pattern. Comparing to the tool wear results, Fig. 1, the stress reversal pattern seems to be correlated to the tool life; e.g., the high-speed and high-feed machining had the largest stress reversal and the shortest tool life.

5. Conclusions

Nanocrystalline diamond coatings were produced using a microwave plasma-assisted CVD process and deposited on common tungsten carbide tools. The NCD tools were
investigated in machining high-Si Al alloy at a range of machining conditions with tool wear and cutting forces examined and analyzed. In addition, commercial CVD diamond coating and PCD tools were also tested and compared against the NCD tool performance. Moreover, an FE model was developed to study the stress modifications in diamond coating tools after the depositions and during machining conditions with tool wear and cutting forces. The results are summarized as follows.

1. Catastrophic failures, reached in all except one machining conditions, limit the life of the NCD tools. The cutting speed has a dominant effect on the tool life.
2. Coating delamination of the NCD tools is clearly evident by SEM. In addition, machining force monitoring can capture the delamination event.
3. At a high feed, coating delamination extends to the rake-face contact. Furthermore, SEM observations of coating failure boundaries indicate intimate coating-substrate contact.
4. The NCD tools substantially outperform the MCD tools, which also failed by the delamination. The NCD tool wear was close to the PCD tool before rapid wear development caused by delamination.
5. The diamond coating tools can have a deposition stresses of 4 GPa in compression and stress concentrations at the cutting edge are high.

(6) Further machining loading causes the stress reversal pattern which seems to correlate with the tool wear; the larger the stress reversal, the shorter the tool life.

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