Comparing the adhesion of aluminum to nanocrystalline diamond and tungsten carbide: Consequences for micromanufacturing

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ABSTRACT

Tungsten carbide (WC) micro end mills exhibit a high wear rate, and when cutting soft materials such as aluminum, the chips tend to adhere to the cutting tool increasing the cutting force and leading to clogging and eventually tool failure. Diamond has outstanding properties such as high hardness, high thermal conductivity, chemical inertness, extremely low friction, low wear, and low adhesiveness, making it an ideal coating for cutting tools. However, it has been a challenge to grow uniform, conformal diamond films on WC tools with good adhesion due to the presence of cobalt which suppresses the diamond nucleation and reduces adhesion between the tool and diamond film. We present results for nanocrystalline diamond (NCD) films deposited onto WC micro end mills. Improved growth methods led to a high density of diamond nucleation sites at the surface, and enhanced tool performance cutting Al. We discuss the dramatic reduction of adhesion between Al and the tool that is observed when the diamond coating is present. To understand the origin of this behavior in more detail, atomic force microscopy was used to measure the work of adhesion for Al when in contact with both bare WC and NCD. It was observed that adhesion between Al and diamond is far lower than for Al and WC, illustrating that the macroscopic reduction of adhesion during micro machining is manifested at the nanoscale single asperity level.

INTRODUCTION

Tungsten carbide (WC) micro end mills exhibit a high wear rate, and when cutting soft materials such as aluminum, the chips tend to adhere to the cutting tool increasing the cutting force and leading to clogging and eventually tool failure [1]. Diamond has outstanding mechanical properties, making it an ideal coating for cutting tools. In particular, low adhesion between the tool surface and the workpiece material is desirable since chips of workpiece material are prevented from adhering to the tool which can rapidly eliminate a path for chips to evacuate the cutting zone, and result in a spike in the cutting forces [2].

Methods have been developed to grow uniform, conformal nanocrystalline diamond (NCD) films on WC using a tailored surface pretreatment. This approach has led to enhanced tool performance when machining 6061-T6 Al. Here we review the performance improvements and discuss their correlation with the low adhesion between Al and NCD. To understand the origin of this behavior in more detail, atomic force microscopy (AFM) was used to measure the work of adhesion for Al when in contact with both bare WC and NCD. It was observed that adhesion between Al and diamond is far lower than for Al and WC, illustrating that the macroscopic reduction of adhesion during micro machining is manifested at the nanoscale single asperity level.

EXPERIMENTAL PROCEDURE

Commercially available, 300 µm diameter, 2-flute WC end mills (PMT part TS-2-0120-S) were used for the machining tests. For the AFM-based adhesion measurements, polished WC-Co inserts were coated with NCD. The WC contains 6-8% cobalt (Co) binder located at the WC grain boundaries. NCD films were grown using a three step synthesis process that involved etching, seeding, and diamond synthesis which is described in detail by Heaney *et al.* [3]. Coatings as thin as 60 nm have been grown with NCD grain sizes <35 nm (Fig. 1a), resulting in conformal coatings that preserve the sharp cutting edge radius needed for these tools (Fig. 1b).

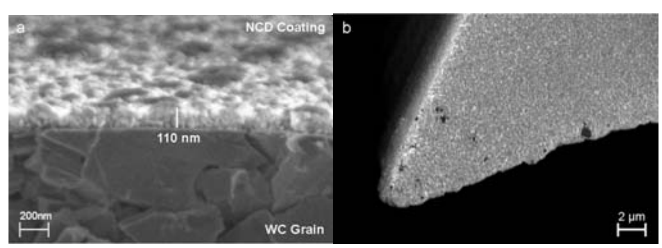

Fig. 1. SEM images of a typical NCD coating on WC. (a) Cross-sectional view. (b) on the micro end mill cutting tip.

For the machining experiments, high-speed spindles with electric drives and composite bearings were used on CNC milling machines (HAAS TM-1 and Atometric G4 Ultra) and operated at 40,000 rpm with a tool feed rate of 500 mm/min. This corresponds to a maximum chip load applied to the cutting tool of 6.25 µm per tooth. These rather harsh conditions were chosen to heighten the contrast in

• corresponding author

performance between coated and uncoated tools. Forces acting on the workpiece were measured by a three-axis force dynamometer (Kistler 9256C2). A humidity control system was used to maintain a constant relative humidity of approximately 85% at the tool-workpiece interface.

The tests consisted of dry machining a single full-width channel 5 mm long and 100 μm deep, in 50 mm x 50 mm x 4.8 mm 6061-T6 aluminum block. Both uncoated and coated tools were run in the same test batch to ensure compatibility between tests. Tool cutting and thrust forces were calculated based on the measured global x and y force using a methodology described in detail elsewhere [4].

For AFM measurements, a Veeco Metrology Dimension 3100 AFM was used. Cantilevers were coated with pure 30 nm Al films and were tested in contact with the WC-Co inserts and with NCD films for comparison. Pure Al has much lower hardness than the Al alloy used in the machining tests. However, the difference in hardness is due to dislocation structure and low percentages of impurities. The single-asperity adhesion we seek to measure is an effect that is primarily governed by the chemical bonding interactions between Al and C. While small effects may be missed by working with pure Al, the dominant effect of switching from WC-Co to C can be determined by these experiments.

Force-separation measurements were obtained by ramping the tip into and out of contact with the samples while ensuring that the maximum force during the measurements was limited to avoid tip damage.

RESULTS

The machining results are described in detail elsewhere [4]. Briefly, cutting and thrust forces were significantly reduced (by an order of magnitude) for NCD-coated tools as compared with uncoated tools and the cutting and thrust forces were more closely balanced. Analysis of the force data indicates that the reduction in forces is due to lower frictional forces between the tool and workpiece, and to the absence of chip adhesion in the flutes. The chips produced by the uncoated tools tended to be long and continuous, indicative of adhesion and welding of the chips while on the tool surface. The diamond-coated tools produced more uniform segmented chips.

Further inspection of end mills via SEM reveals large portions of adherent aluminum on the cutting edges and the flutes of the uncoated tools (Fig. 2a). These uncoated tools often exhibit either complete tool fracture, or partial fracture of a cutting flute. In contrast, the diamond-coated tools are free of aluminum, and are structurally sound after machining (Fig. 2b). They display no evidence of tool fracture on either the tool cutting edge or flank edge. Correspondingly, the channels created by a diamond-coated cutting tool exhibit a highly patterned, uniform and often smoother bottom surface, while the uncoated tool produced a sporadic and rougher surface finish, suggesting a significant amount of heat generated during the cutting process. Increased tool deflection and burr formation were also associated with the uncoated tools.

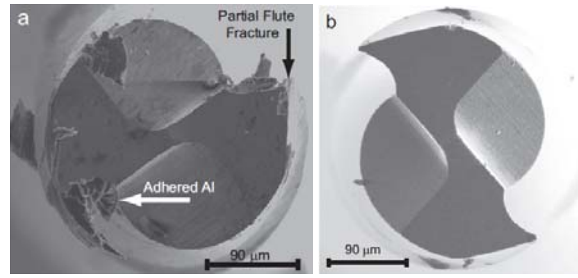

Figure 2. SEM images representative of tool condition after machining: (a) uncoated tool showing adhesion of Al and partial tool fracture and (b) diamond-coated tool showing no observable adhesion of Al or tool wear.

The AFM results demonstrate that the room temperature adhesion between Al and NCD is far less than that for Al and WC (Fig. 3). Using the same Al-coated AFM tip, we found the adhesion force to be ~40% lower on average for the NCD surface. Some evolution of the pull-off force was observed, which may be due to changes in the tip shape and composition throughout the measurements. However, the difference in adhesion for the NCD and WC was well outside this variation. These results indicate that at the level of elastic single-asperity contact at room temperature, the intrinsic interfacial bonding forces are much lower between Al-NCD than for Al-WC. This is an important and potentially significant factor in determining the adhesion that results during the machining process. The low adhesion between diamond and Al is consistent with values determined from first principles calculations [5, 6].

During machining, there will be many other factors that can affect workpiece adhesion, including friction (which can affect the temperature as well as the deformation of the workpiece material) and surface roughness. However, the AFM observations provide an important link between interfacial bonding and macroscopic machining behavior.

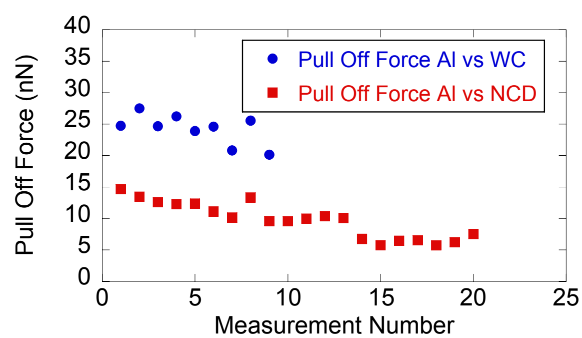

Figure 3. Pull-off (adhesion) force measured between an Al tip and a WC substrate and then a NCD substrate.

CONCLUSIONS

NCD coatings on micro end mills greatly improve tool performance and in particular reduce adhesion of Al to the tool surface. AFM measurements demonstrate that the low adhesion between Al and diamond surface can be observed at the level of nanoscale single asperities and indicates that the resistance to adhesion may be largely due to an intrinsic lack of affinity of Al for diamond, unlike WC.

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