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Adhesion analysis and dry machining performance of CVD diamond coatings deposited on surface modified WC–Co turning inserts

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ABSTRACT

This paper investigates the effects of different surface pretreatments on the adhesion and performance of CVD diamond coated WC–Co turning inserts for the dry machining of high silicon aluminum alloys. Different interfacial characteristics between the diamond coatings and the modified WC–Co substrate were obtained by the use of two different chemical etchings and a CrN/Cr interlayer, with the aim to produce an adherent diamond coating by increasing the interlocking effect of the diamond film, and halting the catalytic effect of the cobalt present on the cemented carbide tool. A systematic study is analyzed in terms of the initial cutting tool surface modifications, the deposition and characterization of microcrystalline diamond coatings deposited by HFCVD synthesis, the estimation of the resulting diamond adhesion by Rockwell indentations and Raman spectroscopy, and finally, the evaluation of the dry machining performance of the diamond coated tools on A390 aluminum alloys. The experiments show that chemical etching methods exceed the effect of the CrN/Cr interlayer in increasing the diamond coating adhesion under dry cutting operations. This work provided new insights about optimizing the surface characteristics of cemented carbides to produce adherent diamond coatings in the dry cutting manufacturing chain of high silicon aluminum alloys.

1. Introduction

There is an uprising trend in the dry machining of composite metals such as aluminum–silicon alloys and aluminum matrix composites as the result of the environmental impact of coolants used in traditional wet machining operations. The amount of coolants disposed in the form of mist, waste, and coolant-coated chips have been reported to produce a significant harmful effect to the environment (Adler et al., 2006). The estimated global market of over $1500 million in 2007 (increasing 6% annually) related to equipment used in filtration and separation of cutting fluids (Sutherland, 2008), provides an important reason to companies in seeking new strategies to reduce fluids consumption by using minimum quantity lubrication (MQL) systems or remove them entirely from the machining operation. Additionally, the development of new automated high-speed machine centers and the use of novel composite materials in complex designs, create new challenges for coated cutting tools that need to function under these aggressive machining conditions.

Roy et al. (2009) found that the chemical inertness of CVD diamond coatings is the key factor to enhancing the performance of cutting tools in the dry machining of Al–Si alloys, outperforming uncoated tools along AlON, TiC, TiB_2, TiN, and Al_2O_3 coated tools. Particularly, aluminum alloys are very abrasive and extremely difficult to dry machine with conventional TiN PVD coated materials due to the formation of built-up layer (BUL) or built-up edge (BUE) over the rake surface of the tool as concluded by Gangopadhyay et al. (2010).

Köpf et al. (2006) discussed the initial substrate pretreatments required to deposit adherent diamond coatings in WC–Co tools for the machining of non-ferrous metals and fiber reinforced plastics. However, the machining performance of diamond coated tools is not yet robust due to a non-optimized adhesion between the carbide tool and the deposited diamond film. The insufficient diamond adhesion with the cutting tool substrates would render them inadequate or lead to unpredictable behavior and even

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possible catastrophic failure during dry cutting operations. Moreover, the adhesion and machining performance of CVD diamond coated tools need to be optimized based upon considering the particular manufacturing chain in terms of the substrate condition, surface pretreatments, workpiece materials, and cutting operation conditions (Uhlmann and Koenig, 2009).

Carbides enriched with 3–13 wt% of cobalt binder provide high fracture toughness and are the most common substrate materials in coated tools used for dry machining applications. However, when diamond is deposited on these substrates, the diamond (carbon) solubility of 0.2–0.3 wt% in cobalt degrades the adhesion of the film by forming a graphitic layer at the interface at the conventional CVD deposition temperatures of ∼800 °C, which prevents diamond nucleation.

Several studies have been reported on enhancing the growth mechanisms and behavior of adherent diamond films deposited on different kinds of substrates, however, the majorities do not take into account the practical substrate surface conditions encountered when using commercial carbide tools existing in the market. It has been shown by Li and Hirose (2007) that film and substrate operate as a "composite" system and the interface between them plays an important role in the durability of the coating. In order to optimize the final performance of diamond coated tools under the harsh conditions developed during dry machining operations, the resulting tribological interface must be understood as a system in terms of the fundamental coating adhesion and the wear mechanisms at the cutting edge of the tool.

A systematic study between the shape and characteristics of the WC–Co cutting tool, the CVD diamond deposition process, and the dry machining parameters, was proposed by Chou et al. (2010) as an optimal approach to achieve adherent diamond coatings for dry drilling applications. Haubner and Kalss (2010) concluded that the lifetime of diamond coating tools is influenced by the interaction of many factors. As a consequence, an optimization of diamond coated tool performance is needed for particular manufacturing applications.

With the aim to analyze the dry cutting behavior of CVD diamond coated tools in specific manufacturing chains, this study utilized different surface pretreatments applied to commercial WC–Co 6% turning inserts to modify their surfaces prior to the diamond deposition.

Substrate pretreatments were focused on providing a surface that facilitates the diamond film interlocking effect and at the same time eliminates the effect of the cobalt by increasing nucleation density, both of which are reported to improve film adhesion and tool life. Two chemical etching methods and a CrN/Cr buffer interlayer were evaluated in the present study. The pretreated tools will exhibit differences in their substrate surface textures and integrity, providing different interfacial characteristics with a direct effect on the diamond adhesion and dry machining performance.

The wear behavior and adhesion improvement of diamond by using a Cr–N interlayer was evaluated by Glozman et al. (1999), using a fretting test rig and compared with indentation and scratch tests. Tribological and mechanical properties of HFCVD diamond coatings deposited on WC–Co substrates with different Cr interlayers were measured by indentation techniques and correlated with the substrate roughness and hardness by Chou et al. (2008). Fluidized Bed modified Cr/CrN interlayers on WC–Co substrates were proposed by Polini et al. (2010), as a mechanism to enhance the diamond film nucleation by forming a highly adherent diamond coating and evaluated by dry 'pin-on-disk' tribological tests.

Of particular interest is the behavior of the CrN/Cr interlayer when compared with chemical etching as diamond adhesion improvement methods in dry machining conditions. In the present study, diamond coatings were deposited using the same growth characteristics and thicknesses (25–30 μm) than the commercial microcrystalline diamond (MCD) tools found in the market. The adhesion characteristics of the diamond coated tools were evaluated by indentation techniques and Raman spectroscopy, and compared with the diamond wear failure under a particular dry turning machining operation on A390 aluminum workpiece. It was found that chemical etching methods surpassed the effect of the CrN/Cr interlayer in increasing the diamond coating adhesion during dry cutting operations. The wear failure mechanism of the CrN/Cr interlayer on the diamond adhesion is discussed, thus, providing insights about the use and optimization of these interlayers to increase the dry machining performance of WC–Co diamond coated tools.

2. Materials and experiments

Commercial tungsten carbide–6 wt% cobalt square positive angle turning inserts (WC–6%Co/SPG-422) were used as tool substrates for further MCD coating depositions. Different surface pretreatments were selected in order to evaluate the most reported common technical approaches, which have been claimed to be able to overcome the detrimental effect of the cobalt binder, including the removal of the cobalt at the surface by chemical etching (Zhang et al., 2000) and by pre-depositing an inter-diffusion barrier layer (Polini and Barletta, 2008) to suppress the interaction between cobalt and carbon.

2.1. Chemical etching

WC–Co inserts were first cleaned in an acetone ultrasonic bath for 10 min, followed by an ultrasonic rinse for 5 min in methanol to remove any contamination from previous processes. After that, samples were ultrasonically treated with Murakami's solution (1:1:10 $KOH + K_3[Fe(CN)_6] + H_2O$) for 10 min and then rinsed with deionized water. In Method E-1, Murakami's step was followed by immersion of the samples in an ultrasonic bath containing 10% HNO_3 + 90% H_2O_2 for 60 s. Method E-2 included the initial etching with the same Murakami's solution followed by immersion in an ultrasonic bath containing 3 ml of H_2SO_4 and 88 ml of H_2O_2 for 60 s. After chemical etching, samples were ultrasonically rinsed with deionized water and dried with nitrogen gas.

2.2. Cobalt inter-diffusion barrier interlayer

A buffer interlayer was deposited to prevent the diffusion of carbon into the underlying cobalt binder phase and to act as a stress relaxation layer to reduce the thermal expansion coefficient mismatch between the diamond and the substrate material as concluded by Sarangi et al. (2008). In this work, as-received WC–Co (6%) inserts were coated with an initial layer of CrN (1.5 μm) followed by a top layer of Cr (1.5 μm) using a commercial cathodic-arc Physical Vapor Deposition (PVD) system. Then, the interlayers were further roughened to promote diamond nucleation and interlocking of the diamond film. Two methods were used to nucleate the diamond: Method I-1 is an additional step of media blasting on the top Cr surface during 1 min with 50 μm diamond particles at a pressure of 40 psi as reported by Xu et al. (2007); Method I-2 is an additional surface scratching process to the Cr interlayer during 60 min in the ultrasonic bath containing a solution of 2.4 g of 50 μm diamond powders dispersed in 50 ml of methanol.

The surface roughness of the substrates and the morphology before and after each surface pretreatment were measured by a Vecco Wyko-NT9100 white-light interferometer and a Hitachi S-800 Scanning Electron Microscope in conjunction with an Energy Dispersed Spectroscopy (EDS) system attached to the SEM. The cross section before and after each treatment was prepared by dicing the inserts with a refrigerated diamond saw, then followed by