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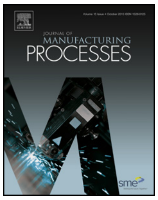

Technical Paper

Graphene oxide colloidal suspensions mitigate carbon diffusion during diamond turning of steel

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ABSTRACT

Diamond-based cutting tools are preferred by the manufacturing community to machine high-value, hard-to-cut materials, especially for applications with stringent surface roughness requirements. However, these tools are not an economically viable option to machine any of the transition metals or their alloys. This is due to the extreme rates of tool wear caused by chemical diffusion of carbon from the diamond tool into the transition metal/alloy workpiece. In this paper we report the use of carbon-rich, graphene oxide colloidal suspensions, as a cutting fluid, to address this critical diamond tool wear issue. Our machining tests conducted on a low-carbon steel alloy reveal that the use of graphene oxide colloidal suspension results in a ~74% reduction in the tool wear over that seen under the dry machining condition. It also results in a ~50% reduction in the cutting temperatures and a ~20 to 30% reduction in the cutting forces, when compared against the dry machining condition. The trends seen in the cutting temperatures, cutting forces and the X-ray photoelectron spectroscopy (XPS) data collectively point to the possibility of the graphene oxide platelets serving as a barrier to the carbon diffusion reaction. These findings have the potential to make diamond a cost-effective tool material for machining transition metal-based materials such as ferrous and titanium alloys that have wide-spread engineering applications.

1. Introduction

The hardness of diamond makes it an ideal tool material for high-value, ultra-precision machining and grinding operations that influence a multi-billion dollar industry spanning key societal areas such as healthcare, defense, aerospace and transportation. The main benefits of using diamond tools include the ease of cutting hard-to-machine materials and the ability to generate low surface roughness values on the ensuing workpiece surface [1,2]. While diamond tools can machine a wide variety of materials, they are not economically viable for machining any of the transition metals or their alloys [3,4]. This is due to the accelerated tool wear problem caused by the chemical diffusion of carbon from the diamond tool into the transition metal/alloy workpiece [4]. Techniques that mitigate this carbon diffusion rate could make diamond a cost-effective tool material to machine transition metal-based alloys such as ferrous and titanium alloys that have wide-spread engineering applications.

Researchers have attempted to reduce diamond tool wear by manipulating the machining environment while cutting ferrous alloys. Their experiments have included techniques such as cryogenic cooling of the workpiece holder [5], intermittent cutting [6], and even the creation of a gaseous carbon-rich (methane) environment [7]. While these techniques were successful in reducing tool wear, the costs of maintaining these special environments were not nearly worth the increase in tool life [5–7]. Given the widespread use of cutting fluids by the manufacturing industry, the use of carbon-rich colloidal suspensions as cutting fluids for diamond tools is likely to offer a more economical solution.

Graphene colloidal suspensions have recently been demonstrated to be an excellent cutting fluid for high-performance micro-machining applications involving cubic boron nitride tools [8,9]. In these studies, the presence of graphene was seen to improve both the cooling as well as the lubrication performance of the carrier fluid [8,9]. These improvements were attributed to both the thermal conductivity of the graphene platelets as well as to their ability to provide lubrication by effectively penetrating the tiny interface between the tool and the workpiece. However, the effectiveness of using such graphene-based colloidal solutions for machining applications involving diamond tools is largely untested.

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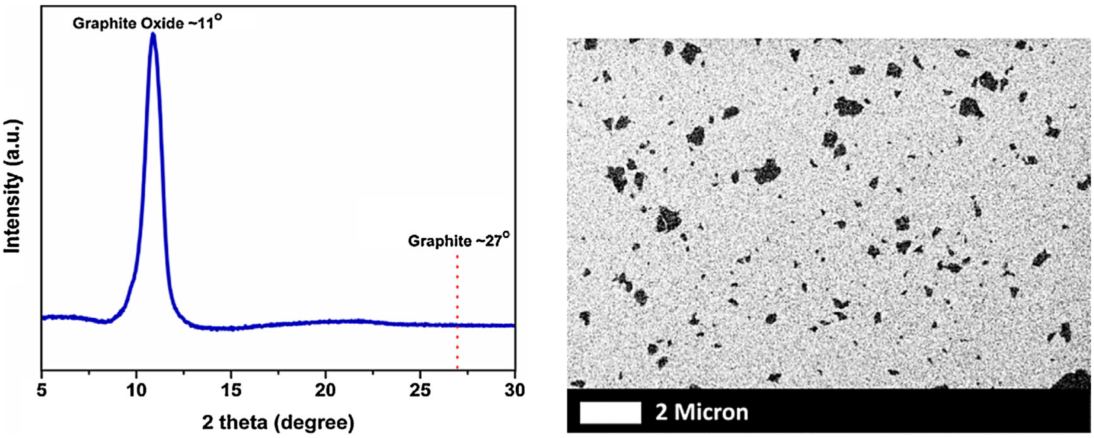

(a) (b)

Fig. 1. Graphene oxide platelets using modified hummers method (a) XRD (b) Scanning electron microscope image of ultrasonicated graphene oxide platelets.

The objective of this research is to study the effect of carbon-rich, graphene oxide colloidal suspensions on the tool wear seen while machining ferrous alloys using diamond tools. To this end, micro-machining tests were conducted on a low-carbon steel alloy by using a polycrystalline diamond tool. The findings reveal that the presence of the graphene oxide platelets (GOPs) significantly reduces the diamond tool wear. In addition to reducing the temperature and the cutting force encountered during machining, the experimental evidence points to the possibility of GOPs serving as a barrier to the carbon diffusion reaction.

The remainder of this paper is organized as follows. Section 2 presents the details about the manufacturing of the graphene oxide colloidal suspensions followed by Section 3, which presents the details of the machining setup. The results from the machining studies and an interpretation of these findings are presented in Sections 4 and 5, respectively. Finally, Section 6 presents the specific conclusions that can be drawn from this study.

2. Graphene oxide colloidal suspensions

The manufacturing of the graphene oxide colloidal suspensions first involves the production of graphite oxide (GO) as a precursor, and its subsequent exfoliation using a solution-phase ultrasonication technique. Graphite powder (325 mesh, >44 μm) was obtained from Asbury Carbons (Microfyne) and used to produce graphite oxide via a modified Hummer's method [10]. The X-ray diffraction data shown in Fig. 1a reveals that the modified Hummer's method completely oxidizes the graphite resulting in a diffraction peak shift from the graphitic ~26.8° to graphite oxide at ~10.8°. This corresponds to an increase in d-spacing from ~0.34 nm to ~0.81 nm between the individual graphite layers [11,12]. The resulting graphite oxide was then dispersed in de-ionized (DI) water since it is commonly used as a diluent for cutting fluids [8]. Graphite oxide was seen to disperse well in DI water and had a yellowish-brown color as described in literature [10]. The graphite oxide was then exfoliated in-solution by subjecting it to ultra-sonication for ~2 to 3 h (Sonics Vibracell VC 750, Sonics and Materials Inc., USA). The exfoliated graphene oxide platelets (GOPs) were seen to have a lateral dimension in the 100 nm–1 μm range and to be made of 3–4 layers (Fig. 1b).

In order to synthesize the colloidal suspensions, GOPs were mixed with Castrol Clearedge 6519 semi-synthetic cutting fluid (at 12.5% dilution in DI water). The resulting solution had a GOP weight loading of 0.2%. Dynamic light scattering (DLS) technique was used to measure the in-solution hydrodynamic diameter of the GOP colloidal suspension. As seen in Fig. 2, the DLS data shows a bi-modal size distribution with the hydrodynamic diameter of the Castrol Clearedge droplets and the GOP sheets being ~30 nm and ~230 nm, respectively. During SEM characterization (Fig. 1b), the graphene oxide platelets are spread out on the silicon wafer and thus display the fullest extent of their 2-dimensional area. The fact that the hydrodynamic diameter of the platelets is recorded to be slightly lower that the size-scales seen in the SEM image (Fig. 1b) could imply that the GOPs are wrapping themselves around the oil droplets in the emulsion.

3. Machining setup

Turning was chosen as the machining process of interest to evaluate the performance of the GOP colloidal suspensions [8,9]. The turning experiments were conducted on a three-axis Mikrotools^{TM} DT-110 computer numeric control machine, equipped with a NSK spindle capable of rotating at 80,000 rpm and having a positional accuracy of ± 1 μm on all three axes. As depicted in Fig. 3, the spindle-workpiece combination (items A and B in Fig. 3) was mounted on the Y–Z plane of the machine (item C in Fig. 3). The diamond turning-tool (item D in Fig. 3) was mounted on top of a Kistler^{TM} 9256C1 dynamometer (item E in Fig. 3) used to measure the cutting force. The tool and dynamometer combination was mounted on the X-axis of the machine (item F in Fig. 3). During the

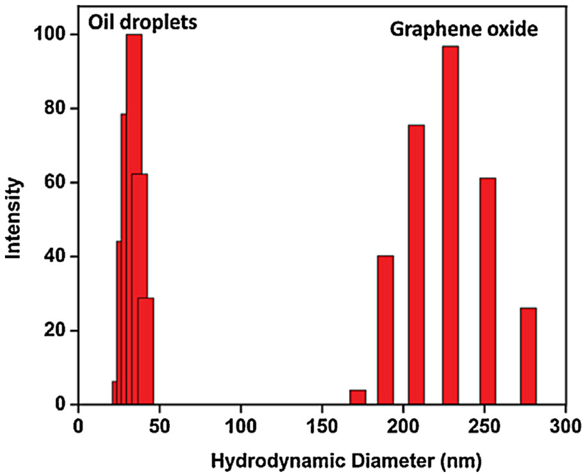

Fig. 2. Dynamic light scattering data of graphene-oxide platelet suspension in Castrol Clearedge semi-synthetic cutting fluid showing bi-modal distribution.