International Journal of Machine Tools & Manufacture 49 (2009) 966–970

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

An investigation of graphite nanoplatelets as lubricant in grinding

Matthew Alberts [a], Kyriaki Kalaitzidou [a,b,*], Shreyes Melkote [a]

[a] G.W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, United States
[b] School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, United States

ARTICLE INFO

Article history:
Received 20 April 2009
Received in revised form
8 June 2009
Accepted 10 June 2009
Available online 21 June 2009

Keywords:
Surface grinding
MQL
Graphite nanoplatelets
Solid lubrication

ABSTRACT

Cooling and lubrication are very critical to ensure workpiece quality in grinding due to the high friction and intense heat generation involved in the process. Liquid lubricants have traditionally been used in flood form or minimum quantity lubrication (MQL), raising however, major environmental and economic concerns. The focus of this study is to evaluate the performance of graphite nanoplatelets as a lubricant in surface grinding. The role of graphite's characteristics such as form, size and concentration; and the effect of the carrying medium and the graphite's application method are determined based on an experimental study. The results indicate that graphite nanoplatelets significantly reduce the grinding forces, specific energy, and improve surface finish during surface grinding of hardened D-2 tool steel. A comparison with results obtained in conventional MQL grinding is also provided. The proper selection of graphite, carrying medium and application method can lead to a low cost, nontoxic and simple alternative to solid lubrication or MQL grinding.

1. Introduction

Surface grinding, an abrasive material-removal technique, generates significant heat and high cutting forces, especially at the workpiece–wheel interface. Cooling and lubrication are necessary to protect the workpiece and wheel from damage such as thermal burn, residual stresses, phase transformations and microcracks [1]. Conventionally, liquid coolants in flood form are employed in grinding. However, issues such as restricted accessibility of coolants in the grinding zone [2] and ineffective heat transfer [3] limit their value in grinding. Additionally, many of these fluids are health hazards raising major environmental concerns [4], and cumbersome to recycle and manage, which significantly increases the total manufacturing cost [5]. A few vegetable-based cutting/grinding oils have been developed, but do not perform as conventional cutting fluids [6].

An alternative to flood cooling is minimum quantity lubrication (MQL) or use of solid lubricants. Dry grinding is not an option because it results in workpiece damage, poor surface finish and accelerated wheel wear due to insufficient chip removal. MQL grinding can produce results very similar to flood cooling if the coolant in MQL does not evaporate due to the grinding heat before it reaches the workpiece–wheel interface [7]. Solid lubricants for grinding should satisfy the following requirements: be able to sustain the high temperatures present in the grinding process, be nontoxic, easy to apply and be cost effective [8].

Materials that have been employed as solid lubricants in surface grinding are graphite [8–11], molybdenum trioxide [8] and molybdenum disulfide [11–13], and calcium and barium fluoride [8]. Graphite and molybdenum disulfide are the most common ones, owing their lubrication properties to their layered morphology and crystal structure [14]. Their morphology consists of a hexagonal arrangement of carbon atoms which form stable planar lattices due to strong covalent bonds. Parallel planes stay together due to weak inter-layer bonding, mainly van der Waals forces. The tangential frictional force present during the grinding process breaks these weak electron bonds causing inter-layer slip with a low friction coefficient [14].

In addition to the morphology and crystal structure of the solid lubricant particles, the way the particles are introduced at the workpiece–wheel interface, and their size and quantity also play a dominant role in the lubrication achieved during the grinding process. One approach is to add the solid lubricant in powder form directly to the grinding zone using an automated feeder [12]. Although the resulting lubrication is sufficient, there is still a need for flushing action and tool cleaning making solid lubrication less attractive than conventional liquid-lubrication methods. Instead of powder form, a thick paste of the solid lubricant made from water-soluble oil and general purpose grease has also been used [8]. However, it yielded significantly lower forces: wheel loading due to ineffective removal of the lubricant paste and the formed chips is the major limitation of this application method. Finally, a third application method is to disperse the particles in water-based oils and perform grinding under MQL conditions [13]. The

* Corresponding author at: MaRC Rm 438, 817 Ferst Drive, Atlanta, GA 30332-0405, United States. Tel.: +404 385 3446; fax: +404 894 9342.
E-mail address: kyriaki.kalaitzidou@me.gatech.edu (K. Kalaitzidou).

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doi:10.1016/j.ijmachtools.2009.06.005

solid lubricant used was molybdenum disulfide with an average particle size of 250 nm at concentrations of 5 and 20 wt% with respect to the oil. The results are very encouraging but the required amount of nanomaterial significantly increases the overall cost.

The above-mentioned studies indicate the great potential of using solid lubricants for low cost and environment-friendly grinding under the condition that the proper material and application method are identified. This study focuses on investigating the effect of graphite nanoplatelets in solid lubrication grinding and aims at developing an application method that eliminates the use of any oils or toxic organic lubricants. Specifically, the role of graphite size, concentration and nature on the forces, specific energy and surface finish in surface grinding are evaluated.

2. Materials and methods

2.1. Graphite nanoplatelets

The graphite nanoplatelets with the trade name xGnP™ (XG Sciences, East Lansing, Michigan) were used in this study. They are made from synthetic, acid-intercalated graphite based on a microwave exfoliation method [15]. Two different types of exfoliated graphite nanoplatelets, xGnP, are used in this study with the only difference being their diameters. Both types have an average platelet thickness of ~5–10 nm and their diameter is either 1 μm (for the xGnP-1 type), or 15 μm (for the xGnP-15 graphite type) shown in Fig. 1a. Each platelet consists of 10–15 graphene sheets, as indicated in Fig. 1b showing two neighboring platelets, which are kept close together by van der Waals forces and they can easily slip relative to each other under the application of shear loads [16]. The material is highly crystalline, has a large surface area of ~60 m^2/g, is nontoxic and costs 5–10 $/lb depending on the platelet diameter. Two other types of graphite platelets supplied by Timcal (Houston, TX) were also used for comparison purposes. These include TimrexSFG-15 and TimrexKS-4, both synthetic, with average diameters of ~15 and ~4 μm, respectively, and corresponding surface areas are 9.5 and 26 m^2/g, respectively.

2.2. Grinding experiments

The experimental study conducted investigated the effects of graphite type, concentration and size on the forces, specific energy and surface finish in surface grinding of hardened D-2 tool steel (62 HRC). The graphite was dispersed in isopropyl alcohol (IPA), a common low-cost and relatively nontoxic organic solvent with boiling point ~80 °C. A sonicator (Misonic Sonicator 4000, probe diameter 12.7 mm) was used at 35% amplitude for 30 min to disperse the graphite in the solvent. The resulting solution was used immediately for grinding in order to avoid agglomeration and/or precipitation of the graphite platelets. The graphite–IPA dispersion was introduced into the grinding process by (i) spraying the workpiece–wheel interface using two common hand pump spray bottles with a combined flow rate of 200 ml/min, or (ii) spray coating the workpiece surface prior to grinding.

For comparison purposes, graphite was also dispersed in a common cutting fluid called Trim SC200, which is a semi-synthetic, water-based emulsion with boiling point 102 °C, and applied to the grinding zone using the same method as the graphite–IPA dispersion. Furthermore, xGnP was compared to the Timcal graphite. Note that the latter graphite type is typically recommended for use as a lubricant in concentrations of 5–40 wt% with grease as the carrying medium. The solid lubrication results were compared to results obtained for dry and MQL (just Trim SC200 fluid without graphite) grinding. The experimental parameters that were investigated and their corresponding range are summarized in Table 1.

A Kistler 9257B 3-Component Dynamometer was used to measure the normal and horizontal grinding forces. The specific grinding energy was calculated from the measured force data as the ratio of the grinding power (= horizontal force × peripheral velocity of the grinding wheel) to the volumetric removal rate. The surface finish was characterized using microscope white light scanning interferometer-based surface texture measuring instrument (ZYGO New View 200). The surface grinder utilized was equipped with a 304.8-mm-diameter, 25.4-mm-wide aluminum oxide grinding wheel (32A46-HVBE). The dynamometer was placed in the center of the magnetic chuck on the grinder and a 152 mm × 101 mm × 12.7 mm block of hardened D-2 tool steel (62 HRC) was bolted to it. The wheel rotational speed was set to

Table 1
Summary of the experimental parameters studied and their investigation range.

Parameter	Investigation range
1. xGnP concentration	0–2 wt%
2. xGnP diameter	1 and 15 μm
3. Graphite source	xGnP and Timcal
4. Carrying medium	IPA and Trim SC200
5. Application method	Spraying, coating

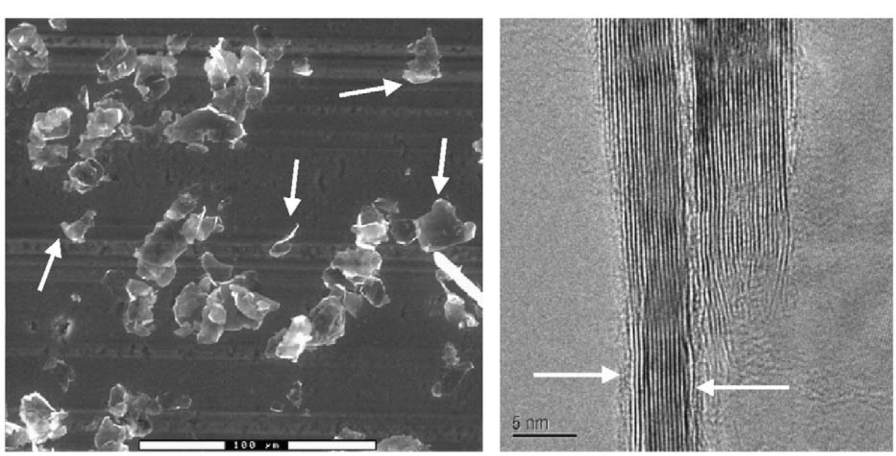

Fig. 1. (a) ESEM micrograph of xGnP-15 (scale bar:100 μm) and (b) TEM side view of xGnP-1 (scale bar:5 nm) [15].