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Evaluation of ionic liquids as lubricants in micro milling – process capability and sustainability

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ABSTRACT

Ionic liquid has gained much attention from the research community, due to its eco-friendly properties, including low vapor pressure, non-flammability, thermal stability, and high-friction reduction abilities. In this study, a series of experiments were performed to investigate the characteristics of ionic liquids as lubricants in micro end milling, especially the sustainable characteristics. 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide ([EMIM][TFSI]), a low-viscosity ionic liquid, and 1-butyl-3-methylimidazolium iodide ([BMIM][I]), a high-viscosity ionic liquid, were examined and compared with two conventional oils and distilled water. Dry machining was used as a reference case for the testing. The workpiece material is aluminum Al 5052, while tool bit is made of tungsten carbide (WC) with diameter of 200 μm. The performance of each liquid as lubricant was considered through machining data as cutting forces, surface morphology and surface roughness of machined workpiece; and the sustainability was considered through the evaporation rate during machining. Analysis of data showed that micro end milling with ionic liquids, and in particular the high-viscosity lubricant ([BMIM][I]), provided a slightly better machined surface and exhibited extremely low volatility compared with conventional oils or other lubrication conditions.

1. Introduction

Cutting fluids, including air, gases, water-based fluids, and neat oils, have been used in machining for a long time. Cutting fluids have two primary functions: lubrication and cooling. Cutting fluids also facilitate chip removal, as well as protect the tool and workpiece from corrosion. However, despite their various uses, cutting fluids are being used less in today's machining processes, primarily due to the environmental and health hazards that they present. Additionally, the recycling costs of cutting fluids are becoming prohibitively expensive for machining companies (Beng and Omar, 2014; Vollerstsen and Schmidt, 2014). A number of alternative methods have been proposed to replace the traditional use of cutting fluids, including new eco-friendly lubricants (Lovell et al., 2010; Liu et al., 2005; Adhvaryu et al., 2004), dry machining (Sreejith and Ngoi, 2000; Derflinger et al., 1999; Nouari et al., 2003), and minimum quantity lubrication (MQL) (Nguyen et al., 2012; Tasdelena et al., 2008; Park et al., 2010; Mao et al., 2012).

The miniaturization trend of industrial products and micro machining of devices in many fields, such as electronics, biotechnology, and the aerospace industry, has come to the forefront of manufacturing technology in recent years (Byrne et al., 2003; Park et al., 2009; Yoon et al., 2011, 2013; Kang and Ahn, 2007; Chu et al., 2006). Cutting fluid is still required for micro machining; however, the small sizes involved in device fabrication have presented several difficulties (Dornfeld et al., 2006). In the literature, there have been several studies of micro machining with the introduction of new lubricants. Prakash et al. (2002) studied MQL using a vegetable-based oil mist in micro end milling of pure copper. In another study, Nam et al. (2011) used a nano-diamond fluid, a liquid containing nano-diamond particles, as a lubricant in the micro drilling of an aluminum workpiece. Lee et al. (2012) also used nanofluid in their research of micro grinding of steel. Li and Chou (2010) researched micro end milling, using a vegetable oil mist as a lubricant. In these studies, the diameter of the tool bits used in micro milling varied from 600 to 1000 μm. In this study, we investigated micro end milling of aluminum (Al) workpieces, using ionic liquid lubricants and 200-μm-diameter tungsten carbide (WC) tool bits.

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Ionic liquids are liquid salts, consisting of an organic cation and an inorganic anion. Recently, many studies have investigated ionic liquids (Khare et al., 2010a, 2010b, 2012) and their performance in tribology (Liu et al., 2002, 2006; Wang et al., 2004). The global interest in ionic liquids is due to their potential as a green replacement for lubricants in industry, based on their extremely low vapor pressure, non-flammability, and thermal stability (Minami et al., 2007; Reich et al., 2003). In addition to being eco-friendly, ionic liquids also demonstrate the ability to reduce friction and wear. The widely recognized explanation of their superior lubricating performance is the formation of a protective boundary film at the contact area by tribochemical reactions between the ionic liquids and metal surfaces of sliding counterparts during the interaction process (Minami, 2009; Bermudez et al., 2009; Qu et al., 2011; Lu et al., 2009; Kondo et al., 2012). Also, the polar nature of the ionic liquids facilitates their physical adsorption in the boundary lubrication regime (Palacio and Bhushan, 2010). In comparison with conventional oils, ionic liquids have similar or better performance in friction and wear reduction and far better performance in sustainability. For example, almost all of the conventional machining oils have fast evaporation or decomposition rates at room temperature; this leads to environmental pollution and hazardous health effects, as well as the need for the oil lubricant to be supplied on a continuous basis. In contrast, ionic liquids can be considered as non-volatile or extremely low-vapor pressure liquids.

Despite the numerous studies on the tribological performance of ionic liquids, including friction and wear behavior for various material contacts (e.g., steel–steel, ceramic–ceramic, and steel–aluminum), to date, there has been little research on the characteristics of ionic liquids as lubricants in specific machining applications, specifically micro machining. In this study, two ionic liquids, 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide [EMIM][TFSI] and 1-butyl-3-methylimidazolium iodide [BMIM][I], were investigated for their use as lubricants in micro end milling. The properties of the lubricants, as well as their sustainability, were compared with conventional cutting fluids.

2. Experimental setup and design

2.1. Hardware system and tools

Fig. 1 shows the experimental setup of the hardware system. The system used a three-axis stage (404XR150, Packer, USA), with a translation resolution of 1 μm for each axis. The entire system was controlled by a computer numerical control (CNC) program. The 1-mm-thickness workpiece, 30 × 25 mm in size, was mounted on a dynamometer attached to the system's platform. The dynamometer (9256C1, Kistler, Winterthur, Switzerland) measured the cutting force. The micro milling tool was kept in a spindle, driven by compressed air. A high-speed camera (Ultima APX-RS, Photron, USA) was used to record the cutting process during the experiments.

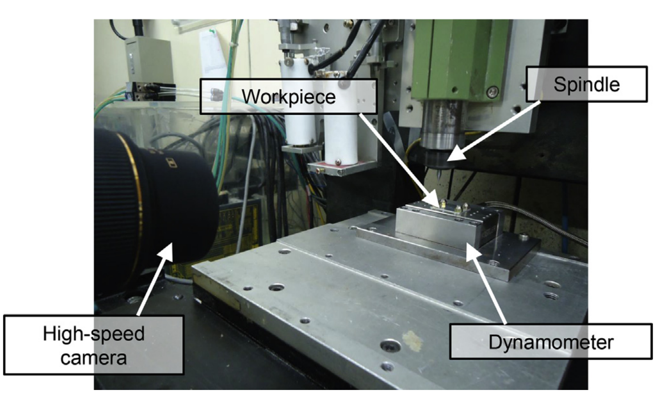

Fig. 1. Experimental set-up of the machining system.

Aluminum (Al) 5052 workpieces were used in this study. Tungsten carbide (WC) micro end-milling tool bits (C-CES 2002-0040, Union, Japan) were used to machine the aluminum (diameter: 200 μm; number of teeth: 3; rotary direction: clockwise).

For each lubrication condition, a rectangular pocket 3.5 × 1.7 mm in size was created by micro end milling of the workpiece surface. To avoid changes in the cutting depth during the experiments, a thin layer of material was first removed from the workpiece surface to create an absolute plane. The workpiece was then machined to create the desired surface. The axial depth of the cut was 10 μm.

Fig. 2(a) and (b) shows the cutting zone and the cutting path of the tool. The cutting area was formed by a series of straight-line passes of the tool bit. The distance between two horizontal tool paths was 100 μm. Hence, the radial depth of cut was 100 μm, except for the first line.

2.2. Lubrication conditions and experimental plan

Two ionic liquids were chosen for these experiments: [EMIM][TFSI], a low-viscosity liquid, and [BMIM][I], a high-viscosity liquid at room temperature. Both of these lubricants have been investigated in previous studies. [EMIM][TFSI] exhibited very low volatility and high thermal stability (Minami, 2009); additionally, this lubricant presented a lower friction coefficient in steel–steel contact, compared with conventional lubricant oil (Lu et al., 2009). The formation of a tribo-film on the steel surface by reaction with [EMIM][TFSI] was observed by Lu et al. (2009). [BMIM][I] was studied in the work of Kondo et al. (2012), which confirmed the formation of an iron-fluoride boundary layer, leading to the reduction of friction and wear of steel–steel sliding contacts. The properties of the ionic liquid lubricants, [EMIM][TFSI] and [BMIM][I], are given in Table 1; their molecular structures are shown in Fig. 3.

Along with these two ionic liquids, five other lubrication conditions were also investigated as a reference; the list consists of two conventional cutting oils, distilled water, and two dry conditions. The two conventional oils chosen for this work were ST-501 (ELE, Korea) and TC#1 (Nabakem, Korea), which are commercial lubricant products used in the manufacturing industry, especially in metal-cutting processes. Distilled water is the simplest type of cutting fluid, and is used in some simple cutting applications as a coolant rather than as a lubricant. Among the two remaining lubrication conditions, the first dry condition refers to the machining process performed without any cutting fluids. Under the second dry condition, the same dry-cutting process described was repeated over the previously machined area. The purpose of this repetition was to compare the lubricant performance in a cutting and deburring (double machining) setting. Herein, for the reminder of the text, this condition is referred to as the 'dry-repeat' condition. Table 2 summarizes the seven different lubrication conditions tested: two ionic liquid lubricants ([EMIM][TFSI] and [BMIM][I]), two conventional oil lubricants, distilled water, and two dry processes (with one of these being the dry-repeat process).

For each test, one workpiece was used and one lubricant was supplied to its cutting zone (except for the two dry conditions). Lubricant was supplied to the surface by dropping a small amount of the liquid onto the workpiece surface, to just cover the cutting zone before cutting began. The amount of lubricant supplied was