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Tribological evaluation of contact-charged electrostatic spray lubrication as a new near-dry machining technique

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ABSTRACT

To minimize lubricant usage and friction at the chip–tool interface, a new near-dry machining technique called “contact-charged electrostatic spray lubrication” (CCESL) is proposed. In this study, the chargeability, penetrability, and wettability of charged lubricant droplets under CCESL conditions were investigated. The atomization and tribological properties of CCESL were compared with those of conventional minimal quantity lubrication (MQL) techniques under various testing-conditions. The experimental results suggest that CCESL improves tribological performance considerably and reduces lubricant consumption compared with conventional MQL. In addition, XPS analysis was used to investigate worn surfaces. The enhanced tribological performance of the new technique is attributed to the formation of a lubricating layer comprising an adsorption film and an oxide layer, which improves the surface quality.

1. Introduction

A negative impact on the environment and waste disposal problems caused by a vast quantity of coolant used in manufacturing processes is becoming significant. The most effective method for minimizing this impact is to decrease the consumption of cutting fluids. By implementing near-dry machining techniques such as minimal quantity lubrication (MQL), cutting fluid consumption can be reduced [1]. With MQL, a small quantity of lubricant mixed with compressed air to form an oil mist is supplied to the cutting point through an external supply nozzle or spindle channel [2]. Many successful results have been reported on the application of MQL in end milling [3,4], turning [5], and drilling [6]. For example, Kishawy et al. [3] investigated the effects of flood coolant, dry cutting, and MQL technologies on tool wear, surface roughness, and cutting forces of high-speed milling aluminum alloy A356. They found that MQL could be a viable alternative to the flood coolant application. MQL not only has the advantage of a significant reduction in cutting fluid consumption but also leaves minimal lubricant residue on the chips, workpiece, and tool holder. In MQL machining, the effectiveness of lubricant droplets depends on their ability to penetrate and wet the chip–tool interface through capillaries to form a thin layer with lower shear strength than the strength of the material in the interface in a short amount of time by either chemical attack or physical adsorption [7,8]. Moreover, Min et al. [9] investigated the lubrication mechanism of MQL cutting. They reported that oxygen in ordinary air plays important role in lubrication. Liao and Lin [10] investigated the MQL mechanism in the high-speed milling of hardened steel. They found that when lubricant droplets penetrate the chip–tool interface in the presence of oxygen, a protective oxide layer is formed. They also found that the content of oxygen in the oil mist is increased because of the increased lubricant surface area resulting from decreased droplet size.

Electrostatic spraying is a spray atomization improvement technique that uses a high-voltage electrostatic field to make the droplets carry a charge. Currently, the technique is widely used in automotive and chemical industries, agriculture, and other related fields. Li et al. [11] investigated the effects of electrostatic spray techniques on energy conservation and emissions reduction in the automotive industry. They found that the technique can significantly reduce engine exhaust emissions due to a decrease in the average size of fuel droplets. Ghanshyam et al. [12] described the application of electrostatic spray techniques in thin film deposition. They pointed out that electrostatic spray deposition has the advantage of high deposition efficiency (up to 80%) as, unlike in the conventional chemical vapor deposition, the droplets are transported by electric forces. Moreover, the uniformity and wettability of atomized droplets increase. Law [13] reviewed the use of the electrostatic spray techniques in agriculture.

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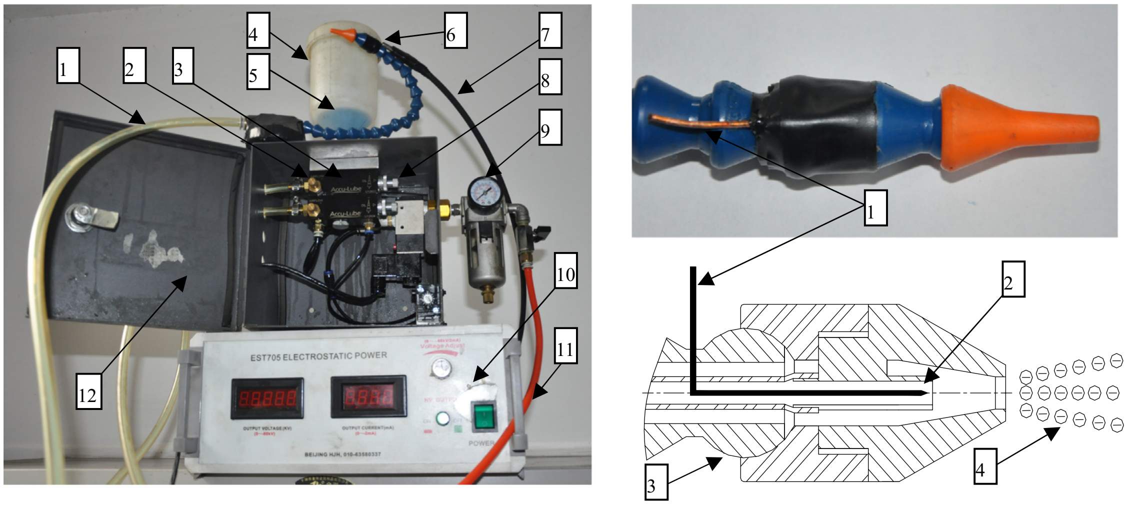

Fig. 1. (a) Proposed CCESL system, where (1) is the air–oil delivery hose, (2) the air adjusting knob, (3) the mixing chamber (4) the oil reservoir, (5) the LB-2000 vegetable oil lubricant, (6) the nozzle for the CCESL system, (7) the high-voltage wire, (8) the oil adjusting knob, (9) the pressure gauge, (10) the negative high voltage power supply, (11) the compressed air hose, and (12) the Accu-Lube precision lubricant applicator. (b) Structure of nozzle for CCESL, where (1) is the needle electrode, (2) the oil hose, (3) the air hose, and (4) the charged lubricant droplets.

He suggested that electrostatic spray techniques can increase the adsorption and penetration rates of droplets on targets and hence reduce material consumption while minimizing waste. Meanwhile, electrostatically assisted machining as a novel method of controlling the cutting zone lubrication and cooling without polluting the environment has been investigated and improved upon by numerous researches [14–16]. To supply a constant and defined amount of cutting fluid, an electrostatic lubrication (EL) technology that uses electricity instead of gas to form the fluid droplets was developed by Reddy and Yang [15]. A detailed comparison has been done with MQL and dry drilling with respect to thrust force, tool wear, hole diameter, and surface finish. The results obtained from these experiments showed the effectiveness of EL technology as a viable alternative to MQL machining. Liu et al. [16] investigated the effects of dry electrostatic cooling (DEC) technology on cutting force and tool life in the hardened steel cutting process. The results showed that the technology utilizing compressed air treated by corona discharge can achieve better lubricating and cooling effects compared with dry cutting, and consequently decreases the cutting force and tool wear.

In this study, a contact-charged electrostatic spray lubrication (CCESL) technique, which is a near-dry machining technique using the synergetic effects between electrostatic spraying and MQL, was developed to further minimize lubricant usage and friction at the chip–tool interface. With this technique, a very small amount of lubricant, negatively charged by the electrostatically contact-charged method, is sprayed into the machining zone using compressed air. To achieve a better lubrication effect, cutting fluids need to penetrate into and wet quickly the chip–tool interface, with oxygen, in a short amount of time. Considering the required conditions, CCESL was developed for improving the penetrability and wettability of lubricant droplets and decreasing their size. The present research work investigates the chargeability, penetrability, and wettability of lubricant droplets under CCESL conditions. Furthermore, the atomization and tribological performance of CCESL are compared with conventional MQL techniques under various testing-conditions. Finally, the lubrication mechanism of CCESL is studied, and the results are expected to help in understanding the lubrication mechanism for the practical application of CCESL in machining.

Table 1
Typical physical properties of LB-2000 lubricant.

Parameter	LB-2000
Appearance	light blue liquid
Density, 25 °C, g/cm^3	0.92
Viscosity, 40 °C, mm^2/	37
Flash point, open up, °C	320
Pour point, °C	-20
Surface tension, 25 °C, N/m	29.5×10^{-3}

2. Experimental

2.1. Structure of the CCESL system

The CCESL system consists of an Accu-Lube precision lubricant applicator (Illinois Tool Works Inc., USA) and an EST705 negative high-voltage power supply (Beijing Huajinghui Technology Ltd., China), as shown in Fig. 1(a). Compressed air to atomize the lubricants was supplied to the nozzle through an air hose. The lubricant supply rate was controlled by means of an oil-adjusting knob. Negative high voltage was supplied to the needle electrode through a voltage-supply wire attached to the oil hose. The structure of the nozzle for the CCESL system is shown in Fig. 1(b). Lubricants were initially charged in the oil hose and were then broken into lubricant droplets by the compressed air. After passing through the nozzle, the charged lubricant droplets came into contact with the surfaces of the friction pair and quickly penetrated into the rubbing interface to form a lubricant film.

For the CCESL system, a vegetable oil lubricant with the designation LB-2000 (manufactured by Illinois Tool Works Inc., USA) was used. This fluid, which is used as a special lubricant in MQL machining, is biodegradable, non-toxic, and insoluble in water. Its performance is comparable to mineral oil [17]. The typical physical properties of LB-2000 are summarized in Table 1.

2.2. Evaluation of chargeability and atomization performance

An experimental setup was developed for measuring the charge-to-mass ratio (CMR) of lubricant droplets under various charging voltages, air pressures, and lubricant flow rates, as shown