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ScienceDirect
Manufacturing Letters 5 (2015) 1–6
www.elsevier.com/locate/mfglet

Research Letter

Study of ionic liquid as effective additive for minimum quantity lubrication during titanium machining

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Received 1 October 2014; received in revised form 12 January 2015; accepted 12 April 2015
Available online 18 April 2015

Abstract

The objective of this study is to investigate the effectiveness of ionic liquid (IL), a low melting point salt, as a lubricant additive for minimum quantity lubrication (MQL) implementation during titanium machining. Herein 1-butyl-3-methylimidazolium hexafluorophosphate (BMIM-PF_6), a prototypical IL, has been used as an MQL cutting fluid additive. It is found that IL-based MQL can effectively reduce the tool wear by 60% when compared to dry cutting and 15% more than MQL without BMIM-PF_6. It is also found that IL-based MQL results in the smallest cutting forces, largest saw-tooth/shear band spacing, and best surface finish.

Keywords: Machining; Ionic liquid; Minimum quantity lubrication

1. Introduction

Machining innovations are often needed to improve the cutting performance during the machining of difficult-to-cut materials such as titanium. Effective cooling and lubrication have been the focus of many machining innovations while various cutting fluid delivery methods have been developed to better cool/lubricate the tool–workpiece interface. Under most industrial settings, the cutting area is flooded with cutting fluid which effectively cools both the tool and workpiece. However, it has been noted that flood cooling does not always provide adequate lubrication to the tool cutting edge even with a large flow rate and pressure at which a lubricant is applied. While flood cooling provides adequate cooling, minimum quantity lubrication (MQL) has emerged as a disruptive environmentally conscious machining technology for various machining processes, including turning [1,2]. With a typical flow rate that is four orders of magnitude less than conventional flood cooling (5–50 mL/min), MQL provides the advantage of providing lubrication to the tool–workpiece interface.

For improved MQL performance during machining, numerous efforts have been devoted to enhancing the performance of the MQL fluids, and this is often achieved by coupling the base fluid with various additives. Of them, nanoparticles have found great success in various machining applications, such as turning (MoS_2 in calcium-based grease [3] and Al_2O_3 in ServoCut Type S oil [4]), milling (SiO_2 in ECOCUT SSN 332 [5]), and grinding (MoS_2 in soybean oil [6], carbon nanotube in soybean oil [7], and Al_2O_3 in deionized (DI) water [8,9]), to name a few. Cutting force reduction [5,6,9] and tool life improvement [3,8,9] have been frequently reported. While nanoparticles have proven their effectiveness as an MQL additive, their application, unfortunately, is still limited by environmental concerns as well as cost.

The objective of this study is to investigate the effectiveness of ionic liquid (IL), a type of low melting point salt (<100 °C), as an additive for MQL implementation during titanium machining. As salts in the liquid state, ILs are

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http://dx.doi.org/10.1016/j.mfglet.2015.04.001
2213-8463/

typically composed of an organic cation, the most common being imidazolium, and a weak coordinating anion such as tetrafluoroborate (BF_4) or hexafluorophosphate (PF_6) [10]. Numerous tribological tests have proven ILs as excellent lubricant additives to lower both friction and wear coefficients during pin/ball contact sliding tests using material pairs of steel/steel [11], aluminum/steel [12–15], titanium/steel [10,16,17], and steel/cast iron [18], to name a few. For example, a 70% reduction in the friction coefficient was reported during steel/aluminum sliding when using 1-ethyl-3-methylimidazolium tetrafluoroborate (L102), a type of IL, as a 1% lubricant additive in neat mineral oil [15]. Additionally, a reduction of 60% and 99.5% in the friction coefficient and wear rate, respectively, was observed in titanium/steel sliding contacts using 1-octyl-3-methylimidazolium tetrafluoroborate (L108) when compared to neat mineral oil [10].

Unfortunately, there is still no study regarding the use of IL as a cutting fluid additive for machining applications. In this study, the effects of IL-based MQL on the titanium cutting performance in terms of tool wear, cutting force, chip morphology, and surface roughness have been examined. It is expected that the resulting knowledge will help promote the further study and applications of various ILs as effective MQL additives for advanced machining operations.

2. Materials and methods

The inset of Fig. 1 illustrates the chemical structure of 1-butyl-3-methylimidazolium hexafluorophosphate (BMIM-PF_6), a widely used imidazolium-based, prototypical IL. BMIM-PF_6 is a viscous, colorless, hydrophobic and non-water soluble IL, making it possible to form micro-emulsions suitable for MQL applications. In this study, 1-butyl-3-methylimidazolium hexafluorophosphate (BMIM-PF_6) was chosen as the prototypical IL for MQL machining for its wide acceptance and good lubrication performance in tribological studies [14,17,19,20]. A cutting fluid containing 0.5% (wt%) BMIM-PF_6 (Sigma–Aldrich, St. Louis, MO) was prepared by adding BMIM-PF_6 drop wise in 30 min increments to DI water under constant stirring. The suspension was further stirred for 24 h inside a fume hood to ensure equilibrium is reached. It is assumed that hydrolysis, if occurring, during the preparation of BMIM-PF_6 and water suspension may only produce lowly concentrated CH_3OHF (fluorinated methanol) [21–23]. Furthermore, the reaction between BMIM-PF_6 and water reaches equilibrium after 24 h. As such, it is believed that it is safe to use the BMIM-PF_6 water suspension for the proposed MQL study. While BMIM-PF_6 is used as a prototypical IL additive herein, other ILs should also be explored in future studies.

Since the objective of this exploratory study was to evaluate the effectiveness of ILs as lubricant additives during MQL machining, DI water instead of industrial MQL cutting fluids was chosen as the base cutting fluid. By using DI water, a typical base cutting fluid with an excellent thermal conductivity, the possible physical and/or chemical reaction between the IL and any undisclosed additives from industrial MQL cutting fluids may be minimized.

Commercially pure grade 2 titanium round bars (Titanium Metal Supply, Poway, CA) with a diameter of 19.1 mm (0.75 inches) were turned using uncoated cubic boron nitride (CBN) inserts (Kennametal TPGN160308MT, Latrobe, PA) on a Mikron UCP 600 Vario machining center (GF Agie Charmilles, Switzerland). As shown in Fig. 1, the Mikron milling center was configured for turning operation using an Erickson high-speed milling chuck (Kennametal, Latrobe, PA) to fix the titanium workpiece in the spindle. The cutting insert was mounted to a Kistler 9257B dynamometer (Kistler, Amherst, NY) which was fixed on the work table of the milling center. The machining test was conducted under nominal cutting conditions: cutting speed $V = 2$ m/s, feedrate $f = 0.05$ mm/rev, and depth of cut $DOC = 0.1$ mm. Diamond tools were not favored in

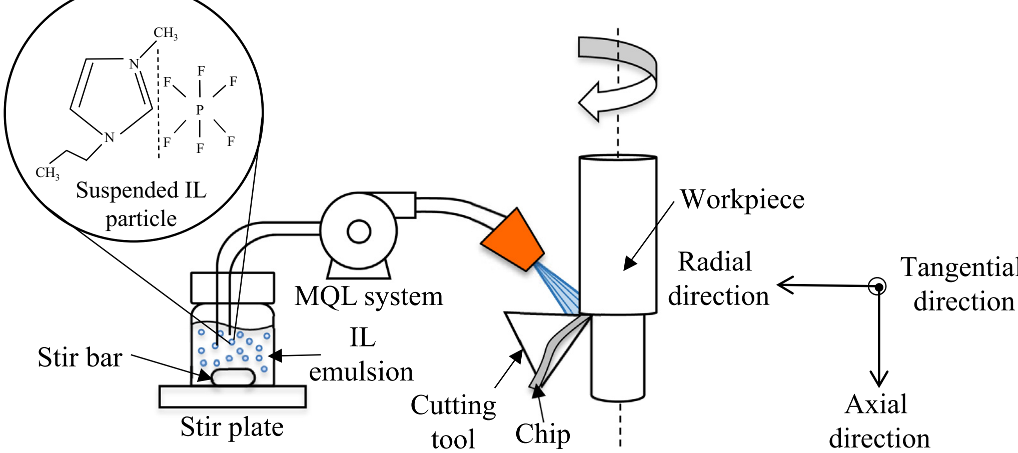

Fig. 1. Schematic of machining and MQL setup.