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Investigation of ionic liquids as novel metalworking fluids during minimum quantity lubrication machining of a plain carbon steel

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Abstract

Metalworking fluids are a major cause of health hazards for operators apart from being sources of environmental pollution, thus necessitating research in dry and minimum quantity lubrication (MQL) machining. Ionic liquids are a relatively new family of environment-friendly chemicals that have significant potential to be employed as lubricants in MQL machining. This paper presents the results of preliminary studies in which three ionic liquids based on the 1-methyl 3-butylimidazolium cation were applied as additives to vegetable oil in MQL machining of AISI 1045 steel under interrupted orthogonal cutting conditions. The results show that the presence of even minute quantities of ionic liquids can significantly affect the machining process through reduction in cutting forces and surface roughness of the machined workpiece, as compared to dry cutting, conventional flood-cooled cutting, and MQL machining with neat vegetable oil.

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1. Introduction

The critical need for achieving sustainability in manufacturing is now well established [1-2], necessitating significant research efforts in sustainable manufacturing [3]. Machining is an important category of manufacturing processes which has significant relevance to industrial sustainability not only due to its direct economic influence [4-5] but also due to its indirect influence on surface integrity and life of critical components [6-7]. The most significant environmental, economic and operator health related issue in machining is the conventional profligate use of cutting fluids, which are generally applied as a flood directed towards the cutting tool tip [8-10]. Hence, significant research has been undertaken to advance sustainable dry [9], near-dry/minimum quantity lubrication (MQL) [10] and cryogenic machining [11].

In the case of near-dry/MQL machining, which is the primary focus of the authors' work, a very small amount of lubricating medium is supplied to the cutting zone in atomized

form along with air or gas stream, and the lubricant is consumed in the cutting process itself. Further, in keeping with the overall focus on sustainability it is desired that the lubricating medium should be as environmentally friendly, and non-hazardous for operators, as possible. Mineral oils, synthetic chemicals, and vegetable oils have been extensively investigated as the lubricating media in MQL systems [12-15]; however, these generally suffer from limitations on environmental performance in the former cases and machining performance and stability in the latter case. Ionic liquids are a promising and relatively new family of environment-friendly chemicals [16] with the potential to be applied as advanced lubricants in severe tribological environments [17-18], and this paper presents a first attempt to study the effects of applying ionic liquids in MQL machining.

Ionic liquids are salts with melting point lower than 100°C. Further, salts with melting point lower than 25°C are known as room temperature ionic liquids. Ionic liquids usually consist of an organic bulky, asymmetric cation that includes

Nitrogen or Phosphorus, and an organic or inorganic anion. Due to the large size difference between anion and cation, and consequent asymmetric distribution of charge, crystal lattice energy is lowered and thus these materials have low melting point. The combination of the large unsymmetrical cation and the relatively smaller anion controls the properties of the resulting ionic liquid. Even though a very large number of such combinations are theoretically possible, commonly used cations which have been explored include phosphonium, imidazolium, pyridinium, pyrrolidinium, sulfonium and ammonium, while commonly used anions include halides, tetrafluoro-borate, hexafluoro-phosphate, bis(trifluoro methyl-sulfonyl)imide, etc. [16].

Ionic liquids have been explored for many engineering applications, including lubrication in conventional tribological conditions involving sliding/rolling at relatively lower contact pressures and temperatures [19-22]. There is also some limited work in the literature indicating the beneficial effects of applying ionic liquids as lubricants in challenging tribological environments involving relatively higher contact stresses and temperatures [17-18, 23], indicating the potential to apply them in machining operations.

Libardi et al. [17] have attempted to evaluate the potential for using ionic fluids as lubricants in manufacturing with the aid of fundamental rheological studies, while Schwab et al. [18] have attempted to patent the application of ionic liquids as lubricants in metal forming operations, where the general severity of tribological conditions begins to approach that encountered in conventional metal cutting [24]. Recently, Pham et al. [23] have observed beneficial effects on surface roughness, but not on cutting forces, when using ionic liquids as lubricants in micromachining of Aluminum alloy Al 5052, where the cutting forces and resulting stresses, temperature, etc. are very low as compared to conventional machining and comparable to those found in tribometer type testing. However, to the best of the authors' knowledge there is no published work exploring the application of ionic liquids as lubricants in conventional metal cutting.

Thus, there is a critical need to explore the tribological potential and lubrication action of ionic liquids in metal cutting with the aim of further advancing environmentally friendly near-dry/MQL machining. This paper presents the results of a preliminary study involving interrupted orthogonal cutting (milling) operations performed on AISI 1045 steel under dry and MQL conditions, with conventional flood-cooled cutting serving as the basis for comparison. In cutting under MQL conditions, neat vegetable oil was used as cutting fluid and then results were compared to cutting with vegetable oil to which 3 candidate ionic liquids were added in 1% concentration by weight.

2. Methodology and Experimental Setup

In order to study the effects of ionic liquids as additives to base oil on tribological conditions in metal-cutting application, orthogonal milling operations were performed on a CNC vertical milling machine. The experimental set up is shown in Fig. 1. The workpiece material chosen was a plain carbon steel of AISI 1045 grade in annealed condition with

average carbon percentage of 0.45% and mean hardness of 230 HBN. The workpiece dimensions were 48 mm x 14 mm x 6 mm and peripheral down milling was carried out on the face measuring 48 mm x 6 mm with a side and face milling cutter of 50 mm diameter, positive radial rake angle of 5° and axial rake angle of 0°.

Uncoated tungsten carbide inserts of ISO designation TPUN 160308 and carbide grade P30 were used in the experiments. A fresh cutting edge was used for each experiment. The experiments were conducted under different cooling conditions, viz. dry cutting, dry cutting with air jet, flood cooling and minimum quantity lubrication (MQL). In MQL machining canola oil (rapeseed oil) was employed as the lubricating medium. The cutting tests were conducted with neat vegetable oil as MQL fluid, and were then repeated with vegetable oil in which three ionic liquids, 1-methyl 3-butylimidazolium hexafluorophosphate (BMIMPF₆), 1-methyl 3-butylimidazolium tetrafluoroborate (BMIMBF₄) and 1-methyl 3-butylimidazolium bis(trifluoromethyl-sulfonyl)imide (BMIMTFSI) were added (1%Wt). The ionic liquids were synthesized using quaternization, and subsequently, the anion metathesis method, and were mixed with the base oil using sonication.



Fig. 1 Experimental set-up for interrupted orthogonal cutting (milling)

Table 1: Values of parameters used for interrupted orthogonal cutting (milling) experiments

Parameter	Value
Cutting speed	150 m/min
Feed	0.3 mm/rev.
Depth of cut	0.8 mm
Compressed air pressure	5 Kg/cm ²
MQL oil flow rate	39 ml/hr, 72 ml/hr
Cooling conditions:	Dry cutting
	Dry cutting with compressed air jet
	Flood cooling
	MQL with vegetable oil
	MQL with vegetable oil + 1%Wt ionic liquid BMIM BF ₄
	MQL with vegetable oil + 1%Wt ionic liquid BMIM PF ₆
	MQL with vegetable oil + 1%Wt ionic liquid BMIM TFSI

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