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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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Keywords: ionic liquids; lubricants; near-dry; MQL; machining; tribology

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

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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, pyridynium, 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 ($BMIMPF_6$), 1-methyl 3-butylimidazolium tetrafluoroborate ($BMIMBF_4$) 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.

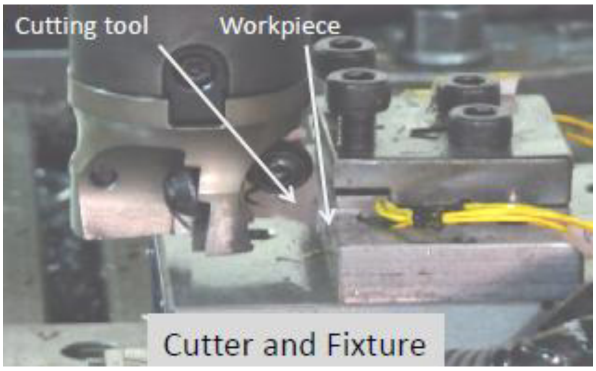

Fig. 1 Experimental set-up for interrupted orthogonal cutting (milling)

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

The MQL unit used in the experiments was of Botti Lubrostar make which supplied compressed air at 5 kg/cm^2 pressure and the oil flow levels used were in the range 15 - 72 ml/hr. Three replicates were conducted for each condition of the experimental plan (Table 1) and the average value was considered for comparison. The machining force measurement was conducted with a Kistler 5210 dynamometer with 6 channels summing. The surface roughness values of the machined workpieces were measured using Surfcom 130 2D profilometer supplied by Zeiss using a cutoff value of 0.8 mm (average of 6 readings per sample, with 5 mm evaluation length for each reading).

3. Results and Discussion

Preliminary experiments were conducted to study the effect of oil flow rate on peak cutting (F_{xmax}) and thrust (F_{ymax}) force and surface roughness (R_a) in MQL machining with pure vegetable oil. The air pressure was kept constant at 5 kg/cm^2 while the volume flow rate was varied from 15 – 72 ml/hr. Data acquired at lower air pressure (2 kg/cm^2) are not presented or analyzed since a clean spray did not form under this condition; the lubricant was instead dripping from the nozzle tip. The effect of volume flow rate of vegetable oil on peak cutting and thrust force components is shown in Fig. 2 while the effect of oil flow rate on workpiece surface roughness is shown in Fig. 3. It is observed that while the surface finish improved with increase in oil flow rate, the cutting force and thrust force reduced initially, but increased again when the oil flow rate was further increased beyond 39 ml/hr. Accordingly, oil flow rates of 39 ml/hr and 72 ml/hr have been chosen for the main experimental plan (Table 1).

In peripheral down milling the cutting tool enters the workpiece with maximum engagement and the chip thickness reduces progressively until the tool exits the workpiece. Correspondingly, the recorded machining forces signal shows a sharp peak as the tool enters the workpiece followed by a relatively more gradual decline to zero, sometimes interspersed with one or more minor peaks, as the tool exits the workpiece material. A detailed analysis of the cutting force signals was performed and it revealed two distinct trends when considering either the peak values of machining forces (mainly representing forces during tool entry) or the average machining forces (representing the average forces during each cutting cycle, from tool entry to tool exit).

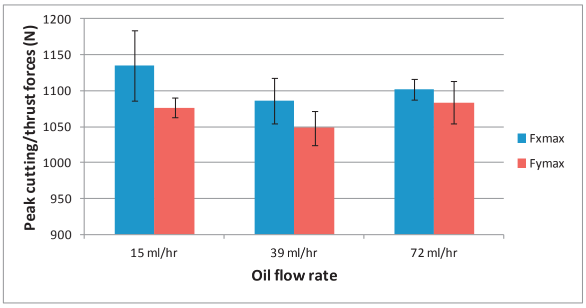

Fig. 2. Influence of oil flow rate on peak cutting (F_{xmax}) and thrust (F_{ymax}) forces in MQL machining with pure vegetable oil. Error bars represent ± 1 standard deviation.

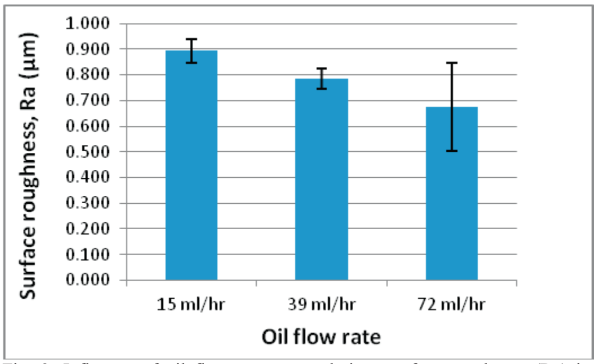

Fig. 3. Influence of oil flow rate on workpiece surface roughness (Ra) in MQL machining with pure vegetable oil.

Each of these considerations is discussed separately below, followed by discussion of measured surface roughness of machined workpieces.

3.1 Analysis of peak cutting forces

The mean values of peak cutting force observed during machining with different cooling/lubricating conditions are shown in Fig. 4 while the mean values of peak thrust force are shown in Fig. 5. It is observed from Figs. 4 and 5, that the peak cutting and thrust forces are higher for machining with compressed air jet, MQL machining with vegetable oil and flood cooling when compared to dry cutting, though the MQL conditions with vegetable oil perform better than dry cutting with compressed air jet.

Among the 3 vegetable oil + ionic liquid emulsions, the cutting and thrust forces for $BMIMPF_6$ and BMIMTFSI are higher when compared to $BMIMBF_4$. Further, the ionic liquid experimental condition employing $BMIMBF_4$ yields lower thrust forces than dry machining, while the conditions employing $BMIMPF_6$ and BMIMTFSI yield higher cutting force than dry machining.

3.2 Analysis of average cutting forces

The mean values of average cutting and thrust forces observed during machining with different cooling/lubricating conditions are shown in Figs. 6 and 7, respectively. Contrary to the trends observed for peak force values, the average forces are higher for dry cutting as compared to machining with flood cooling. The average cutting and thrust force values for MQL machining with pure vegetable oil are in the same range as dry cutting with compressed air jet, which suggests that under the severe contact and boundary lubrication conditions existing at the tool chip interface, pure oil may be unable to penetrate the tool-chip and tool-workpiece interfaces for long enough to significantly affect the entire cutting duration. However, the addition of 1%Wt. of ionic liquid $BMIMBF_4$ to vegetable oil lowers the cutting and thrust forces significantly. A similar effect was observed under MQL application of vegetable oil with $BMIMPF_6$ additive in the case of thrust force only. In the case of peak as well as average machining forces the MQL conditions employing ionic liquid BMIMTFSI as additive yielded cutting and thrust forces that were either comparable to dry machining or higher.

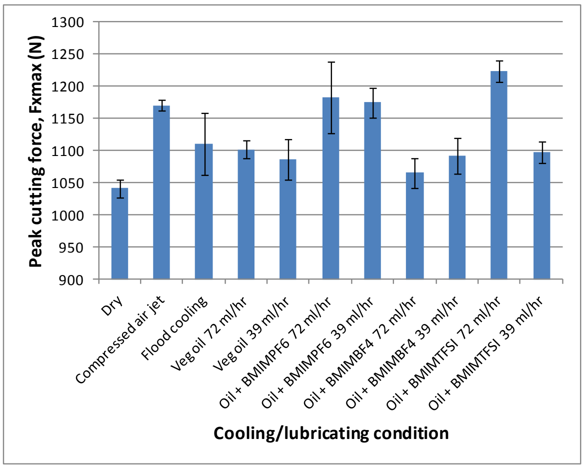

Fig. 4: Variation of mean values of peak cutting forces (F_{xmax}) in orthogonal milling under different cooling and lubrication conditions.

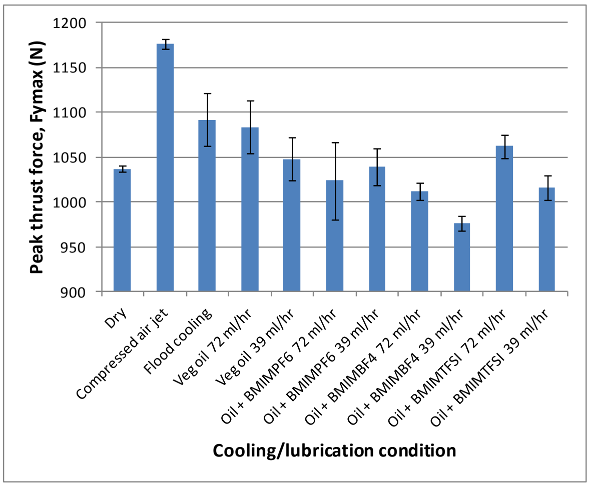

Fig. 5: Variation of mean values of peak thrust forces (F_{ymax}) in orthogonal milling under different cooling and lubrication conditions.

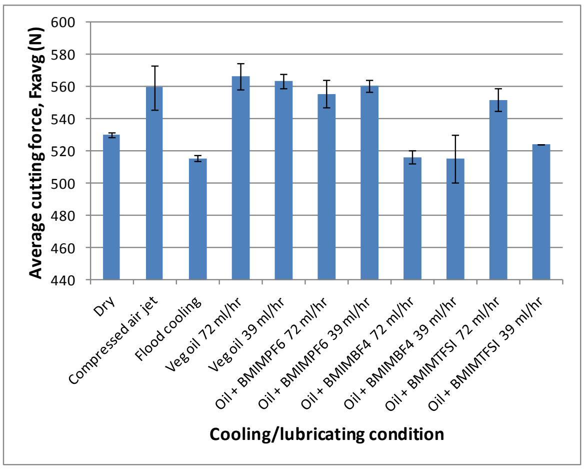

Fig. 6: Effects of different cooling and lubrication conditions on mean values of average cutting forces (F_{xavg}) in orthogonal milling.

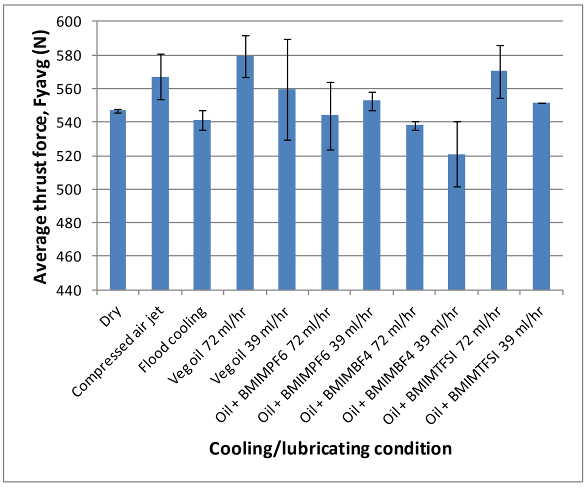

Fig. 7: Effects of different cooling and lubrication conditions on mean values of average thrust forces (F_{yavg}) in orthogonal milling.

Further, increasing oil flow rate generally tended to increase peak and average thrust forces during MQL machining with vegetable oil, as well as MQL machining with $BMIMBF_4$ and BMIMTFSI additives. The trend was generally reversed or neutral in the case of MQL machining with $BMIMPF_6$ additive.

3.3 Analysis of workpiece surface roughness

The average workpiece surface roughness (R_a) values in machining with different cooling/lubricating conditions are shown in Fig. 8. The workpieces which were machined in MQL conditions with vegetable oil containing ionic liquid as additive had significantly improved surface roughness as compared to workpieces machined under dry, compressed air jet, or MQL with vegetable oil machining environments. The surface roughness values achieved in MQL machining with ionic liquid additive were found to be comparable to those obtained through machining under flood cooling condition. The only exception is the case of MQL machining with BMIMTFS additive at the higher oil flow rate (72ml/hr).

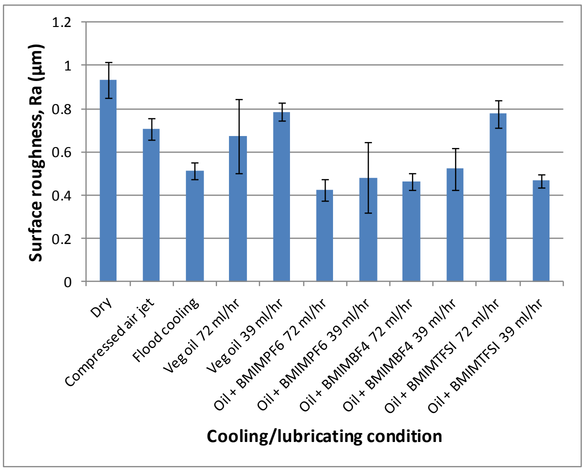

Fig. 8: Variation of workpiece surface roughness (R_a) values under different cooling and lubrication conditions during orthogonal milling.

As also indicated in Fig. 3, during MQL machining with vegetable oil the machined surface roughness improves with increasing oil flow rate. However, in the case of MQL machining with vegetable oil containing ionic liquid additive no significant effect of oil flow rate was observed on machined surface roughness for $BMIMPF_6$ and $BMIMBF_4$ additives, while the surface roughness improved with decreasing lubricant flow rate in the case of BMIMTFSI ionic liquid, showing a correspondence with similar trends for peak and average machining forces for MQL machining with BMIMTFSI.

4. Conclusions

It is observed from the analysis of peak as well as average cutting and thrust forces and average surface roughness of the machined workpieces that the presence of even minute quantity of ionic liquid (1% concentration by weight), delivered as an additive with base vegetable oil in MQL mode, significantly affects the tribology of the machining process, as compared to dry cutting, conventional flood-cooled cutting, and machining with neat vegetable oil applied in MQL mode. Further studies are currently in progress to expand the knowledge base on the working principal of ionic liquids as metalworking fluids so that they can be suitably designed for specific applications, machining processes, cutting parameters and tool-workpiece material pairs.

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