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Performance of supercritical carbon dioxide sprays as coolants and lubricants in representative metalworking operations

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ABSTRACT

This paper investigates the cooling and lubrication properties of supercritical carbon dioxide ($scCO_2$) sprays as potential substitutes for aqueous emulsions and straight oils used in the metalworking industry today. Sprays of rapidly expanding $scCO_2$ act to cool and lubricate machining and forming processes by delivering a mixture of dry ice and lubricant deep into the cutting/forming zone. In this work, experiments with turning, milling, drilling, thread cutting, and thread forming were performed with $scCO_2$ and other metalworking fluids (MWFs) to evaluate their relative performance with respect to tool wear and machining torque. Observations reveal that $scCO_2$–MWFs are more effective in removing heat from the tool-workpiece interface than conventionally delivered (flood) aqueous MWFs as well as other gas-based MWF sprays. In addition, $scCO_2$–MWFs delivered in lubricant-expanded phase, where $scCO_2$ is used to increase volume of lubricant in the spray field, are shown to provide better lubricity than straight oils and oil-in-air minimum quantity lubrication (MQL) sprays. As a result, $scCO_2$–MWFs can reduce tool wear and improve machining productivity in a wide range of manufacturing operations leading to appreciable improvements in the economics of manufacturing. Also given that CO_2 is a recovered waste gas that is non-toxic, $scCO_2$–MWFs can improve the environmental and worker health performance of manufacturing operations.

1. Introduction

Metalworking fluids (MWFs) are essential coolants and lubricants used in material removal and deformation processes to improve manufacturing productivity by increasing process throughput and tool life. MWFs are ubiquitous in the machine tool industry, with estimates of world-wide annual consumption reported by Cheng et al. (2005) to be in the billions of liters. Typically formulated as either as straight-lubricants, or more typically as aqueous (water-based) emulsions/solutions, MWFs have high life cycle costs from their acquisition, maintenance, and disposal, with estimates ranging between 10 and 17% of total metals manufacturing costs as reported in Klocke and Eisenblätter (1997). Straight-lubricants, such as mineral oils, fatty oils, esters, chlorinated paraffins or a combination of two or more of these compounds, are generally used in friction dominated processes such as grinding, forming and thread tapping.

Aqueous MWFs can contain over a dozen chemicals such as extreme pressure (EP) additives, surfactants, biocides and defoaming agents. Aqueous MWFs are widely used in chip forming processes such as turning, milling and drilling. They are highly effective in transporting chips out of the cutting zone and dissipating heat from the bulk of the workpiece and tool. However, aqueous MWFs create health risks for workers, such as dermatitis, infection, and cancer. Biological growth within MWFs, along with the buildup of metal particles and oils, deteriorates manufacturing performance and ultimately necessitates disposal. Disposal of untreated MWFs can lead to significant oxygen depletion and nutrient loading in surface waters, further posing environmental risks. Aqueous wastes can also carry heavy metals from manufacturing (e.g., cobalt and lead) into the environment.

Recent research has sought to develop environmentally-benign MWFs with higher performance in manufacturing, thus enabling faster machining without undermining part quality and tool life. Substitutes to aqueous MWFs have been investigated over the past two decades. Minimum quantity lubrication (MQL) technology is one of the most prominent alternatives to conventional MWFs. MQL delivers sprays of lubricants or emulsions in compressed air at about 0.6–1 MPa pressure. Developed in the 1990s, MQL has since

Abbreviations: MWF, metalworking fluid; $scCO_2$, supercritical carbon dioxide; NDL, no dissolved lubricant; DL, dissolved lubricant; XL, expanded lubricant; HRP, heat removal potential; HRE, heat removal efficacy; LE, lubrication efficacy.

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been researched as a feasible means to deliver lubrication to a variety of machining operations on a number of engineering materials as discussed in a comprehensive review of the technology provided by Weinert et al. (2004). In practice, oil-in-air MQL has found acceptance only in certain niche applications such as crankshaft oil-hole drilling and machining of aluminum engine and transmission prismatics because of its limited capability to remove heat in processes such as rough turning and milling, grinding and deep-hole drilling. From an environmental standpoint, MQL has been shown to have lower environmental impact than aqueous MWFs in a comparative life cycle assessment by Fratila (2010).

Liquid nitrogen (LN_2) has been researched as another alternative to aqueous MWFs in applications involving high heat generation and high cutting temperatures. Despite its limited lubrication potential LN_2 has demonstrated the potential for reduced tool wear and improved surface finish relative to aqueous MWFs as reported by Wang and Rajurkar (2000), and relative to MQL as demonstrated by Pusavec et al. (2011) in the machining of recalcitrant materials such as Ti6Al4V and Inconel with poor thermal diffusivities. However, insufficient heat removal at the tool-workpiece interface (due to poor cutting zone penetration) arising from rapid vaporization of LN_2 as reported by Nguyen et al. (2007), and thermal warping from non-uniform cooling of the workpiece have restricted use of LN_2 to certain specific material-process combinations in the industry. Although using larger flow rates of LN_2 can alleviate warping, large flows may be an impractical solution for large components due to high supply costs and high environmental impacts associated with separating and liquefying nitrogen which are outlined in Li et al. (2010).

El Baradie (1996) showed that high-pressure gases could be effective coolants and since then alternative MWFs such as carbon dioxide gas, cooled compressed air, and oxygen have been explored in research. However, these alternatives have found relevance only in certain niche applications and cannot be extended to real-world production-line manufacturing. Considering the limited market adoption of MQL (an excellent lubricant system) and LN_2 (an excellent cooling system), it can be hypothesized that a widespread alternative to conventional MWFs will need to serve *both* as a heat removal agent and as a lubricating agent, without a trade-off between those two functions. Presently, only flood application of aqueous MWFs at high flow rates has the capability to deliver both cooling and lubrication to a satisfactory level, which is why their use in the industry remains widespread despite their costs and adverse health and environmental effects.

Clarens et al. (2006) proposed an alternative MWF based on supercritical carbon dioxide ($scCO_2$). Carbon dioxide is a reclaimed material that is non-toxic and has excellent solubility for aliphatic and most aromatic hydrocarbons such as vegetable oils above its critical point (critical temperature = 31.2 °C, critical pressure = 7.38 MPa) as shown by Hyatt (1984). It allows for precise control of solvent concentration through pressure and temperature control and, as such, $scCO_2$ has been utilized as a solvent in pharmaceutical and polymer industries, dry-cleaning, semiconductor devices cleaning and automotive component coating as discussed in DeSimone (2002). Tom and Debenedetti (1991) show that the rapidly propagating mechanical perturbation resulting from the rapid expansion of $scCO_2$ and oil produces a homogenous and finely dispersed spray of dry ice and frozen oil particles a few microns in size. As a result it can be hypothesized that $scCO_2$–MWF sprays can provide sufficient heat removal *and* lubrication to replace conventional MWFs in a greater variety of machining operations than MQL or LN_2.

In this paper we examine the efficacy of $scCO_2$–MWFs over a wide range of metalworking processes to assess their candidacy as an alternative to conventional MWFs. We first hypothesize that $scCO_2$–MWFs perform as well as or better than conventional MWFs in the heat removal function. To test this hypothesis, we perform titanium turning, compacted graphite iron (CGI) milling and A390 aluminum drilling experiments to evaluate flank wear. Arsecularatne et al. (2006) establish flank wear to be determined by temperature-based phenomena, such as diffusion, adhesion and delamination, and thus flank wear serves as a pragmatic measure to evaluate the heat removal efficacy of MWFs in the tool-workpiece combination examined in this study. Second, we hypothesize that $scCO_2$–MWFs can produce a better lubricating medium than straight lubricants or aqueous MWFs. To test this hypothesis, we perform thread cutting and thread forming experiments on 1018 steel and 2024 aluminum, respectively. Thread cutting and thread forming have been chosen because they are friction dominated and cannot be performed without a good lubricant such as straight oil.

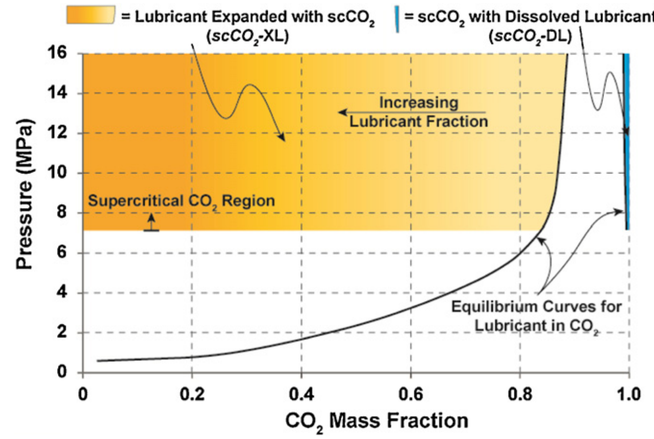

Fig. 1. Solubility curve for soybean oil in CO_2 at 35 °C (adapted from Ndiaye et al., 2006 and Clarens et al., 2009) showing the two phases of $scCO_2$–MWF delivery when a lubricant is present in $scCO_2$.

In Section 2, we describe the experimental setup and materials used in this research. Section 3 discusses the experimental results and their relationship to the hypotheses listed above. Section 4 concludes with a summary of the key findings regarding $scCO_2$–MWFs as a potential alternative to aqueous MWFs.

2. Experimental investigations: methods and materials

2.1. $scCO_2$ delivery

$scCO_2$–MWFs can be delivered as a rapidly expanding solution of either $scCO_2$ and a lubricant, or only $scCO_2$. Fig. 1 shows the solubility curve for CO_2 and soybean oil. The shaded area on the right indicates the phase with $scCO_2$ containing dissolved lubricant ($scCO_2$-DL) and the shaded area on the left indicates the phase where $scCO_2$ is dissolved in the lubricant ($scCO_2$-XL). Table 1 lists the characteristics of these two phases as applied in this research, along with the possibility of not including oil in the supercritical carbon dioxide ($scCO_2$-NDL). In this research the lubricant used is a vegetable oil (soybean or canola). Fig. 2 shows images of the $scCO_2$-DL (left) and $scCO_2$-XL (right) sprays being expanded at identical pressures through nozzles of same diameter. The notable difference in quantity of oil in $scCO_2$-DL and $scCO_2$-DL phases can be seen from the difference in spray lengths, where a longer spray indicates higher oil content leading to a larger number of agglomerates of frozen oil and dry ice.

The custom-built apparatus shown in Fig. 3 was used for the delivery of $scCO_2$–MWFs. Food-grade CO_2 from a commercially available compressed CO_2 cylinder was further pressurized above its critical pressure using a pump, and heated to a specified