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Development of finite element based model for performance evaluation of nano cutting fluids in minimum quantity lubrication

Rukmini Srikant Revuru[a,*], Vamsi Krishna Pasam[b], Ismail Syed[b], Uday Kumar Paliwal[c]

[a] Dept. of Technology, University of Northern Iowa, Cedar Falls, IA, USA
[b] Dept. of Mechanical Engineering, National Institute of Technology, Warangal, Telangana, India
[c] Dept. of Mechanical Engineering, Lokmanya Tilak College of Engineering, Mumbai, Maharashtra, India

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ABSTRACT

Traditionally, cutting fluids are used to improve the performance of machining. However, due to the hazardous effects of these fluids on workers' health and ecology, their usage has been often discouraged. As a solution, application of micro/nano cutting fluids in minimum quantity lubrication (MQL) has been proposed in the literature. Many of the works on MQL deal with experimental investigations, which are costly and cannot be generalised for other conditions. Works that apply numerical models like FEA to MQL are limited. In the present work, the performance of micro and nanofluids was compared. Two different solid lubricants — boric acid and molybdenum disulphide were dispersed in the coconut oil. Different machining parameters like cutting forces, cutting temperatures and surface roughness were studied while applying the formulated fluids in MQL. After observing the superior performance of nanofluids at the given cutting conditions, a finite element based model has been developed to predict forces and cutting temperatures. The model was compared with the experimental values and found capable of predicting the values within 8% accuracy. The validated model was used to predict the values for other cases.

Introduction

Cutting fluids are widely used in machining to cool and lubricate the machining zone. Though the conventional cutting fluids generally satisfy the purpose, they pose a threat to the workers' health [1,2] and ecosystem [3]. Hence, the use of cutting fluids needs to be minimized/eliminated to move towards sustainable manufacturing. Different approaches towards sustainable manufacturing like cryogenic cooling, minimum quantity lubrication (MQL), vegetable oil based coolants, dry machining, etc. have been cited in literature. Among the available alternatives, MQL is widely accepted as a viable solution due to the ease in application and superior performance. In MQL, small quantities of cutting fluids are applied thus eliminating the need for recycling and disposal [4]. Typically, less than 500 mL/h of the fluid is used in MQL, compared to the conventional flood cooling method, which uses over 120 L/h. Academic research has, therefore, focussed on different compositions of fluids in MQL with different objectives in mind. MQL with vegetable oils has recently gained prominence due to its co-friendly and sustainable nature and biodegradability [5]. Vegetable oils carry slight polar charge unlike the mineral oils. This polar charge increases the adhesion between metallic surface and the vegetable oil [6]. Vegetable oil molecules create a thick, strong and durable film layer of lubricant. This lubricating film gives the vegetable oil a greater capacity to absorb pressure, making it a good choice as a lubricant [7,8]. Vegetable oil has a higher boiling point, smoke point and greater molecular weight resulting in less loss from vaporization and misting compared to mineral oils [9]. Further, these oils are renewable, economical, easily available and environmentally benign. Vegetable oils have good lubricating properties and help to reduce the friction in chip-tool interface. In addition, vegetable oils pose less problems to the workers because of higher smoke point compared to their mineral oil counterparts [10,11]. Due to the various advantages offered, vegetable oils are fast replacing the mineral oils in cutting fluids.

Kelly and Cotterell [12] used vegetable oil as MQL lubricant during drilling of cast aluminium silicon alloys. It was reported that MQL with vegetable oil resulted in lesser feed forces, torques and surface roughness at high cutting speeds and feed rates. Ozcelik et al. [13] reported the experimental study of sunflower and canola oil based cutting fluids with different percentages (8 and 12%) of EP

* Corresponding author.
E-mail address: rukmini.revuru@uni.edu (R.S. Revuru).

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additives in turning of AISI 304L stainless steel with respect to surface roughness, cutting force, feed force and tool wear. Experiments conducted at dry cutting conditions resulted in rapid tool wear and fracture. High percentage of extreme pressure additives in vegetable-based cutting fluids resulted in higher surface roughness values. Canola oil based cutting fluid with 8% EP additives gave the best performance. Higher rate of EP additive in sunflower and canola-based cutting fluids reduced cutting and feed forces during turning of AISI 304L austenitic stainless steel, However, the increment of EP rate affected surface roughness values negatively. It was concluded that vegetable-based cutting fluids could replace mineral and semi-synthetic cutting fluids in turning [14].

Ojolo et al. [15] used different vegetable-based cutting fluids (groundnut oil, coconut oil, palm kernel oil and shea butter oil) during turning of mild steel, aluminium and copper. It was reported that groundnut oil based cutting fluid showed the best performance among the considered oils. Xavior and Adithan [16] used coconut oil during turning of AISI 304 stainless steel to study the progression of tool wear and surface roughness. The performance of coconut oil was compared with an emulsion and neat cutting oil. They found that coconut oil had reduced the tool wear and improved the surface finish. Paul and Pal [17] investigated the performance of karanja oil, neem oil and conventional cutting fluid in MQL for machining mild steel. The results were compared with dry machining. Lesser cutting temperatures were observed with neem oil. It was pointed out that lesser viscosity of neem oils helps in the capillarity of the oil to reach the tool/chip interface.

Since MQL uses very small quantities of the cutting fluid, it is highly desirable to use fluids with enhanced properties. In this context, nanofluids have gained prominence as a viable solution. Nanofluids are suspensions with solid nanoparticles dispersed uniformly in a fluid. Different solid particles lubricants like CuO, Al_2O_3 and graphite have been experimented by researchers to form nanofluids for MQL [18,19]. Nano fluids possess enhanced thermal and tribological properties compared to the base fluids like oil or water [20]. Khandekar et al. [21] investigated the performance of 1% Al_2O_3 in conventional cutting fluid and observed a reduction of about 50% and 30% in cutting force compared to dry machining and conventional cutting fluid, respectively. It was also observed that surface roughness decreased by about 54.5% and 28.5% compared to the above cases. Vasu and Reddy [22] studied vegetable oil-based MQL with different volume fractions of $A1_2O_3$ (aluminium oxide) nano particles used as the cutting fluid in machining Inconel 600 alloy. Surface finish, temperature dissipation of the work piece, cutting forces and tool wear rate were studied for different percentages of inclusions. It was reported that higher percentages of inclusions led to better results.

Choice of nanoparticles is critical in deciding the effectiveness of the nanofluids. While metallic oxides improve the high thermal properties, addition of solid lubricants like graphite and molybdenum disulphide can lead to lesser friction. The solid lubricants are used in their pure form or mixed with a medium as lubricant in machining. Solid lubricants like molybdenum disulphide, boric acid and graphite were found to enhance the lubricating properties of the base fluid [23]. It was reported that lesser the size of the particles, better is the performance of the fluids in machining. This prompts the possible use of nano-solid lubricants in machining. Krishna et al. [24] studied the application of nano solid lubricant suspensions in coconut oil and SAE-40 oil as lubricant in machining AISI 1040 steel. It was reported that nano boric acid suspensions in coconut oil demonstrated better performance compared to SAE-40 oil based suspensions. Padmini et al. [25] investigated various vegetable oils with varying concentration of nano boric acid and found that cutting temperatures and tool wear decreased significantly with 0.5% nano boric acid suspensions in vegetable oils at the given cutting conditions.

In general, due to the high cost of nanoparticles, many researchers concentrated on particular set of machining conditions to arrive at conclusions. Hence, for a new set of conditions, it is required to be studied again. As experimentation involves many resources, it is advantageous to postulate a model that represents the behaviour of the system and use the model to understand the system. Different mathematical models or numerical models like finite element modelcan be found in literature for the machining process [26]. Mathematical models can be mainly found on prediction of temperatures [27], forces [28] and tool wear [29]. Usually the models are built for dry machining or flood lubrication. Such models for MQL are not found in literature [26].

Though different works are reported on application of nanofluids in MQL, the specific advantage due to the size of particles can be well demonstrated when the performance is compared with microfluids. However, such works are rare in literature, the works either deal with microfluids or nanofluids. Further, the experiments are usually carried under constant cutting conditions and the behaviour is not studied at different cutting conditions. Further, the available mathematical models in literature deal with either dry machining or flood lubrication. Models on MQL are not commonly found. The present work compares the performance of micro/nano cutting fluids based MQL and based on the results, a model is formulated to bridge the gap in literature.

Materials and methods

In the present work, the performance of microfluids and nanofluids were compared while turning AISI 1040 steel ona precision lathe at different cutting speeds. The micro/nano particles of boric acid (mBA-micro Boric acid and nBA-nano Boric acid) and molybdenum disulphide ($mMoS_2$ — micro molybdenum disulphide and $nMoS_2$ — nano molybdenum disulphide) were procured from the market. The average particle size at nano level was 80 nm and the micro particles had particle size of 150 μ, as per the vendor's specification. The cutting fluids were prepared by dispersing nano particles and micro particles of boric acid/ molybdenum disulphide with coconut oil in different ratios as shown in Table 1. The fluids were sonicated for 60 min to prevent agglomeration of the particles [30]. The prepared nanofluids were characterised using zeta potential test for stability.

The formulated cutting fluids were supplied at uniform flowrate of 10 mL/min to the surface behind the chip. Usually, cutting fluids can be applied in any of the three directions: on the rake face, behind the chip or on the flank face (Fig. 1). While the application of flank face helps in reducing the friction between the tool and newly machined surface, the other two are useful to reduce the friction at tool/chip interface. However, applying on the rake face is usually not advantageous due to the flow of the chip [31]. Hence, application of the fluid behind the chip was selected in the study. The fluids reach the tool/chip interface through capillarity.

Cutting forces were measured using piezo-electric dynamometer (Kistler, Model-9272). The resultant of the cutting force was considered for analysis. Cutting temperatures were measured with a thermal imaging system (Fluke Ti200) that uses the IR radiation to produce a real time thermal image. Since it is difficult to accurately measure the temperatures at the secondary shear zone, due to the flow of the chip, the temperatures were measured at a nodal point, 1 mm away from the tip in both horizontal and vertical directions. Since the present work concentrates on comparing the performance of the fluids, the comparison is done using the nodal temperatures. Surface roughness (R_a) of the machined parts was measured using a surface roughness tester (Mahrsurf M400).