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Enhancement of surface finish using water-miscible nano-cutting fluid in ultra-precision turning

C.Y. Chan, W.B. Lee*, H. Wang

State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong Special Administrative Region, P.R. China

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ABSTRACT

This paper presents an experimental study on the enhancement effect of the low viscosity cutting fluid enriched with nano-droplets (NDCF) in ultra-precision turning. Unlike the conventional method in which the enhancement is done by adding nano-metric particles, no suspension particles are mixed to produce the NDCF in this paper. Instead, the NDCFs are produced by atomisation of the cutting fluid that circulates in a closed-loop treatment device. The atomisation process is found to reduce the viscosity of the NDCF significantly by the formation of nano-droplets (NDs). The reduced viscosity of the NDCFs could be increased by diluting them with water. The bench tests on wetting properties reveal that the NDCF demonstrates two distinct properties: a very linear spreading rate and a relatively low contact angle. These two properties assist the NDCF in penetrating deeper into the tool–chip and tool–work interfaces and hence provides a better lubrication effect at these interfaces. In this paper, the ultra-precision cylindrical turning experiments reveal that the droplet size of the NDCF is a more important factor than viscosity on affecting the surface finish in ultra-precision machining.

1. Introduction

To promote the performance of machine tools and to regulate the machining conditions, different kinds of cutting fluids have long been used in machining. The cutting fluids are found to improve the machining quality by their cooling effect (through the reduction in localised heating zone, thermal expansion and distortion of the work-piece) and by their lubrication effect (in the reduction of cutting force, extension of tool life, etc.).

Sharma et al. [2] have reviewed various cooling techniques in literature, including cryogenic cooling, minimum quantity lubrication/near dry machining (MQL/NDM), high-pressure coolant, air/vapour/gas coolant, etc. Among them, dry machining (DM) and near-dry machining (NDM) have received substantial attention in recent years because of the ever-growing popularity in promoting the concept of sustainable manufacturing [3] and green cutting or machining [4]. The central task of DM/NDM is to reduce the usage of cutting fluids [5,6].

A great spectrum of conventional coolant and lubricant can be applied in machining by the supply system of MQL/NDM. Tai et al. [7] summarised their work on the evaluation and comparison of different oil-based lubricants. For the purpose of ecological and environmental protection, Liu et al. [4] developed the use of water vapour as a coolant and lubricant which is deemed to be a "greener" approach that could also reduce the processing cost.

While the MQL/NDM method aiming at reducing the usage, the other branch of research has been dedicated to boost the performance of cutting fluid through modification or enhancing, among which nano-fluids with the addition of nano-particles are overwhelmed. Das et al. [8] in their work defined nano-particles enhanced cutting fluid (NPCF) as usual heat transfer fluids that contain suspended ultra-fine particles of nano-metric size. The materials used for nano-particles are Al_2O_3, CuO, etc. The heat transfer properties of such modified NPCFs have been further studied in the experimental work on convective heat transfer [9,10]. The dynamic spreading properties of NPCFs composed of liquid suspensions of nano-particles were studied by Kondiparty et al. [11] and the phenomenon of inner contact line was discovered which does not exist in fluids without nano-particles. In the recent work of Park et al. [12], the NPCF incorporated with the MQL technique has been introduced in balling milling in which exfoliated graphite nanoplatelets (xGnP) was reported to be used. Khandekar et al. [13] also reported their work on NPCF for better metal cutting performance by adding 1% Al_2O_3 nanoparticles in their cutting fluid.

According to the research work reported, the classification of cutting fluids [1] can be extended with the introduction of NDCFs as shown in Fig. 1. In this paper, the general purpose soluble oil is treated without adding nano-particles which provides a novel means to modify cutting fluids by breaking up the cutting fluid

* Corresponding author. Tel.: +852 27 666577; fax: +852 27 64 7657.
E-mail address: mfwblee@polyu.edu.hk (W.B. Lee).

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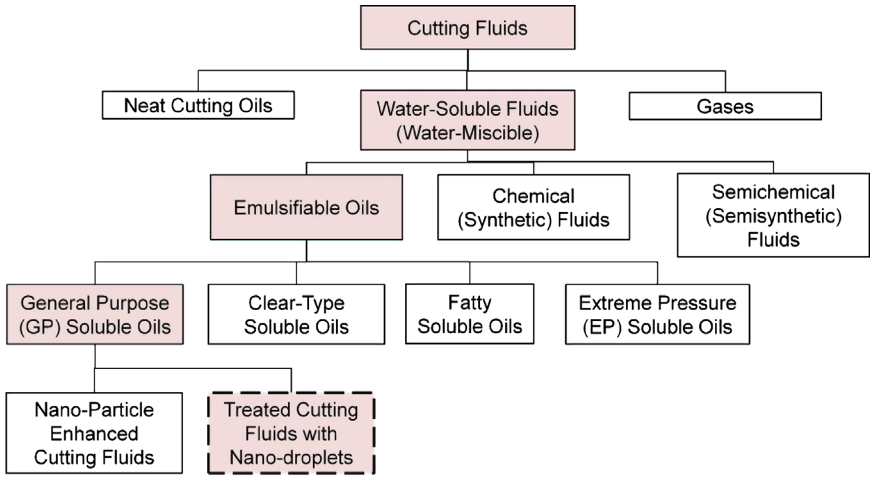

Fig. 1. Extended classification of cutting fluids with nano-cutting fluids based on the classification by Baradie [1] (the colour shaded blocks denote the category of the developed nano-cutting fluids in this paper).

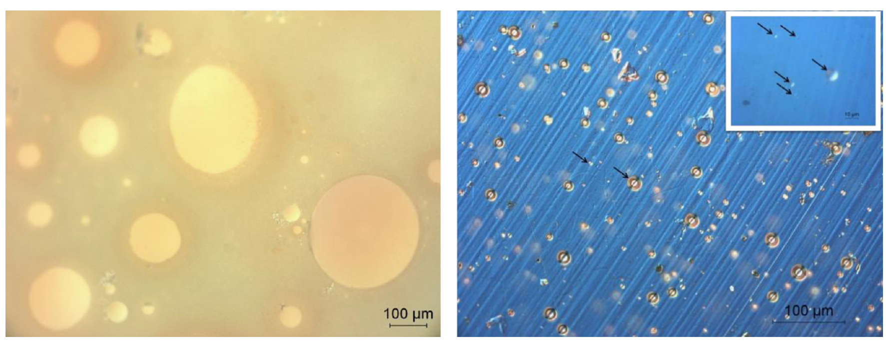

Fig. 2. Optical microscopic images of (a) general purpose (GP) soluble oil with 5% mineral oil concentration before ND treatment and (b) GP soluble oil after ND treatment (the nano-metric oil droplets are indicated by arrows).

into nano-droplets (NDs). Without the chemical and nano-particle additives, the developed NDCF is more attainable and environmental friendly. Also, it will reduce and even will avoid the possible pitting and fretting damage on the machined surface due to the scratching and/or bombardment of fast removing nano-particles. This paper presents an experimental investigation on the enhancement effect of the NDCF on the machined surface finish, chip morphology with bench test and cylindrical turning trials in comparison with the conventional cutting fluids.

2. Experiments

2.1. Preparation of nano-cutting fluid samples

The starting cutting fluid was a miscible mixture of 95% water and 5% mineral oil (JAEGER SW-105). As typical general-purpose soluble oil, the milky fluid contained mineral oil droplets of 0.005 mm to 0.2 mm diameter [1]. The NDCF was produced by passing the fluid through a cutting fluid treatment equipment called Super Nano Mixer SMA, designed and fabricated by Sohbi Nanodevice LLC. The equipment can significantly reduce the droplet size by three orders, i.e., from micro-metric size down to nano-metric (Fig. 2). The NDCF was then characterised under Olympus BX60 optical microscope. As indexed by arrows in Fig. 2(b), soluble mineral oil with nano-droplets can be unambiguously identified without traceable aggregation or coarsening by coalescence or Ostwald ripening. In contrast, the starting cutting fluid (Fig. 2(a)) contained droplets with diameters ranging from tens to hundreds of micro-metres, which appeared to be translucent white by scattering visible light [14]. The difference in optical transparency of the starting cutting fluid and the NDCF is a useful tool and indicator of the size of droplets in the cutting fluids. The optical images in Fig. 2 are found to be consistent with the observation reported by Leong et al. [15]. The mean particle sizes of their transparent nano-emulsions are below 40 nm.

Experiments were designed to further reveal the enhancement effect of the NDCFs in ultra-precision machining. Eight samples were prepared for the comparison study, in which Sample 1 was pure water (denoted by “PW”) and Sample 6 was the as-treated water-miscible cutting fluid with nano-droplets (denoted by “ND”). Samples numbered 2–5 were the diluted mixture of the two, with volume ratios ND:PW of 1:1, 2:1, 3:1 and 4:1, respectively. Sample 7 was the untreated water-miscible cutting fluid (JAEGER SW-105) with 5% mineral oil concentration and Sample 8 was the diluted solution of Sample 7 with 2.5% mineral oil concentration. The description of the cutting fluid samples is tabulated in Table 1.

2.2. Bench test

In this paper, the contact angles of the prepared cutting fluid samples were measured with the static sessile drop method on a Sindatek Contact Angle Meter (Model 100SB) with the MagicDroplet software package (Fig. 3). The static sessile drop method was employed to measure contact angle with a goniometer and an optical system to acquire the droplet profile on a solid substrate. The substrate surface of polymethyl methacrylate (PMMA) was prepared with the arithmetic surface roughness of 7.0 nm and the