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A synergistic approach towards the application of nanofluids in machining with laser micro-textured cutting tools

Sarvesh Kumar Mishra*, Sudarsan Ghosh, Sivanandam Aravindan

Department of Mechanical Engineering, Indian Institute of Technology-Delhi (IIT Delhi), Hauz Khas, New Delhi, India, 110016

**Corresponding Author Email: mishra.sarvesh8@gmail.com*

Abstract
The present work investigates the interaction of nanofluids on micro-textured cutting tools and their influence in turning of Ti6Al4V alloy. Microhole texture has been fabricated on the WC/Co cutting tool rake face using Nd: YAG nanosecond laser. Three different types of nanofluids, namely MoS_2 (lamellar nanofluid), Al_2O_3 (oxide-based nanofluid), and MoS_2-Al_2O_3 (hybrid nanofluid) have been prepared and characterized for physicochemical properties. The nanofluid interaction has been studied on polished textured WC/Co surfaces for understanding the adsorption behavior of different nanofluids. The metal cutting tests have been conducted for turning of Ti6Al4V alloy with textured tools under the nanofluid environment. Cutting forces and the apparent coefficient of friction were measured and correlated with the adsorption behavior of the nanofluids on the micro-textured surfaces. The hybrid nanofluids resulted in the lowest contact angle and offered the least surface energy with the textured surfaces. The enhanced wettability of the hybrid nanofluids decreased the main cutting force and the apparent coefficient of friction by 20% and 25%, respectively.

Keywords: Nanosecond laser texturing; Ti6Al4V machining; Tool wear; Textured tools; Hybrid nanofluids.

1. Introduction

Laser texturing of the cutting tools is projected as one of the next-generation technologies for the manufacturing of high-performance cutting tools. The surface modification with laser ablation methods and consequent functionalization of the tool rake/flank surface or cutting edges are rigorously studied nowadays. Since the first experimental trials on the laser textured cutting tools in 2007 [1], there is a continuous quest to find the most effective texturing method, cutting parameters, cooling the environment for metal cutting operations. The application of textured cutting tools has been investigated for machining of steels, aluminum, and titanium alloys. Titanium alloys are considered as one of the most difficult to cut material because of various physical, mechanical, and thermal properties [2]. Even after decades of research, the machining of Ti-alloys is still considered one of the most challenging tasks. Inferior thermal properties, low elastic modulus, high strength, and high heat generated at the secondary interface are the major contributors to the low machinability. The conventional cutting tools suffer from rapid crater and flank wear because of the severity of thermal interaction at rake face and intense rubbing at the flank face respectively.

Textured cutting tools have been used for machining of Ti-alloys under dry, flood, and MQL environments [3–5]. Under dry cutting conditions, laser textured cutting tools do not offer any significant machinability improvement. Under the influence of poor thermal properties, the textures act as micro-cutters and undercut the sliding chips owing to the interface-multipoint micro-cutting (IMP-µC) mechanism [3,6]. Hence, the textured cutting tools under dry cutting conditions are not highly encouraged for machining of Ti-alloys. Flood cooling offers the advantages of micro-pool formation at the secondary interface in the presence of textured microholes [7]. The mechanism of micro-pool formation leads to improved machinability. With the strict environmental regulations and conscious efforts towards the eco-friendly aspects, the use of cutting fluids are being obliterated [8].

Minimum quantity lubrication (MQL), nanoMQL, and cryogenic machining techniques have proven their capability to replace the conventional flood cooling [9,10]. The past research has investigated the application of nanofluids for titanium machining with plain cutting tools [11,12]. Recently, water suspended Al_2O_3 nanoparticles were used as cutting fluid for Ti6Al4V machining using textured tools [13]. Hard nanoparticles puncture the nanofluid droplets upon impact to the cutting tools and get entrapped into the textures. This action reduces the efficacy of the nanofluids to reduce the cutting forces and tool wear. The combined effect of soft-hard hybrid nanofluids has been prolific in the improvement of the grindability of IN718 alloys [14]. The physical synergy between soft MoS_2 and hard CNT has been stated as offered lubrication advantages and reduced friction and surface roughness. In another study to combine the surface modification and advanced cooling/lubrication strategies, tribological tests have been performed over textured tool steel under TiO_2 based nanofluids [15]. Textured surfaces under nanofluid lubrication reduced friction coefficient, wear, and sliding temperature.

The advanced cooling strategies and innovative cutting tools have instigated a new dimension of metal cutting research. There is a vital need for an in-depth investigation combining the cooling and tool modification strategies for machining of difficult-to-cut Ti-alloys. The effect of nanofluids has not been explored much to consider the combinatorial success of nanofluids and surface texturing. Some preliminary investigations, limited to sliding tribology, have been performed. To the best of authors' knowledge, no research is available, which has tried to address the interaction of hybrid nanofluids with textured surfaces. As an attempt to address the research gap, the present study entails the application of soft lamellar (MoS_2), hard oxide (Al_2O_3), and hybrid (MoS_2-Al_2O_3) nanofluids for machining of Ti6Al4V with textured tools.

2. Materials and methods

Straight grade carbide (WC/6Co) cutting tools (WIDIA: CNMA120408-THM F) were used for metal cutting tests. The rake face of the cutting tools was laser textured using nanosecond (Nd: YAG) pulsed laser. Laser texturing has been carried at 25 mJ pulse energy, frequency 20 kHz, and wavelength 1064 nm, according to the author's previous work [3]. The microhole textures were fabricated with diameter $60 \pm 5\ \mu m$, pitch $100\ \mu m$, and depth $30\ \mu m$. Machining of Ti64V alloy is performed on CNC turning centre (Leadwell CNC: Fanuc series OiMate, Taiwan). The cutting forces were measured using a piezoelectric dynamometer (9129AA: Kistler, Switzerland) and charge amplifier (5070B). Machining tests have been conducted with five replicates for each experimental condition. The average values of the main cutting force and the apparent coefficient of friction have been used for the comparative performance of various nanofluids. The machining performance of the nanofluids has been compared with the results obtained under machining with base fluid (DI water) environment.

MoS_2 (APS 90 nm, Sigma Aldrich) and Al_2O_3 nanoparticles (APS 40 nm, Reinste nano) were used for preparing DI water-based nanofluids. Nanoparticles are mixed in DI water in the presence of 0.05 wt.% SDBS (sodium dodecyl benzene sulphonate) as a surfactant. The fluids have been continuously stirred for 30 min using a magnetic stirrer and ultrasonicated for 15 min. In the previous studies, it has been confirmed that the only addition of surfactant in base water doesn't influence the metal cutting results [13]. TEM and TEM-EDS analysis of nanofluid have been performed using JEOL-JEM 1400 (USA) to confirm the size of nanoparticles, nanoparticle distribution, and its chemistry.

The nanoMQL flow conditions (flow rate: 250 ml/h, and air delivery pressure 8 bar) were selected after initial trials for Ti6Al4V turning. The MQL system comprises of twin siphon nozzle, external mixing chamber, air inlet, a fluid inlet, and flow controller. The nozzle to cutting tool tip distance has been fixed to 52 mm. The nanofluid jet sprays over the tool tip and the rake face of textured tools. Nanoparticles impacting the textured rake face can influence the wettability behavior of nanofluids. Adsorption behavior of the nanofluids with the polished cutting tool surfaces was characterized by contact angle measurement using the DSA100 goniometer. The liquid volume for the contact angle measurement was 2μL and the measurement time was 5 sec. The static contact angle has been measured using the sessile drop method. The average contact angle values have been used for the prediction of the wetting behavior of nanofluids.

3. Results and discussion

3.1 Nanofluid characterization

The nanoparticles were mixed in 1:1 proportion and characterized for their physicochemical interaction and adsorption behavior (Fig. 1). TEM analysis shows the clustering of the alumina nanoparticles because of small particle size and high surface energy (Fig. 1a). The flaky structure of MoS_2 nanoparticles has also been revealed from the analysis (Fig. 1b).

In hybrid nanofluid, the alumina clusters are evident to be joined at multiple branches of the MoS_2 flakes (Fig. 1c). It has been observed that MoS_2 flakes have been surrounded by alumina nanoparticles at multiple locations. MoS_2 flakes connected to alumina nanoparticles have a branching of the aggregated nanoparticles. This physical interaction gives rise to the distribution of alumina nanoparticles around MoS_2 nanoparticles. This branching of smaller nanoparticles on the MoS_2 flakes can be considered as one of the advantages of the hybrid nanofluids.

TEM micrographs confirm the nature of soft-hard nanoparticle agglomerate for the hybrid nanofluid used in the present case. The presence of the chemical elements in hybrid nanofluid is confirmed from TEM-EDS analysis. The peaks of Al and Mo elements present in the EDS spectra (Fig. 1d) could be used to ascertain the preparation of the hybrid nanofluid. The physico-chemical interaction of different nanofluids may influence the crystalline nature of the nanoparticles. To confirm the same, selected area electron diffraction (SAED) analysis has been conducted on the hybrid nanoparticles. The crystallinity of the hybrid nanofluid is retained, as revealed from the SAED pattern in Fig. 2.

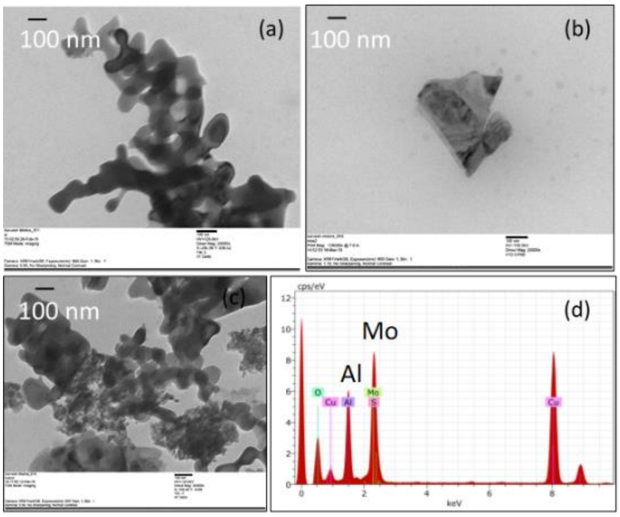

Fig. 1 TEM results for (a) alumina nanoparticles, (b) MoS2 flakes, (c) hybrid Al_2O_3-MoS_2 nanofluid, and (d) TEM-EDS for hybrid nanofluid

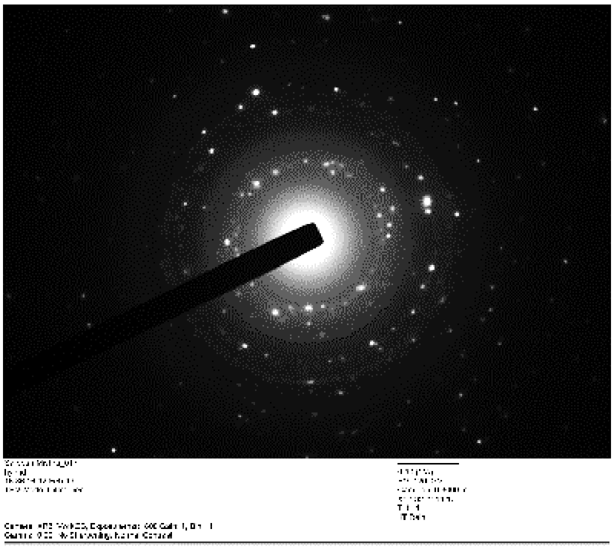

Fig. 2 SAED pattern revealing the retained crystallinity of the nanoparticles in the hybrid nanofluid

The physico-chemical interaction of the nanoparticles has a greater influence on the adsorption properties of the nanofluids.

Hybrid nanofluid resulted in a lower contact angle on the textured tool surface (Fig. 3). Contact angle values for base fluid and hybrid nanofluid are $61.72° \pm 3.2°$ and $32.1° \pm 1.2°$, respectively. The lower contact angle is attributed to the low surface energy of the fluid-substrate pair resulting in increased spreadability of the hybrid nanofluid. Water droplets have a higher specific heat capacity and the addition of nanoparticles enhances the thermal conductivity and heat capacity of the nanofluids. Better spreadability and enhanced thermal properties of nanofluids could be beneficial in reducing friction and frictional heat from the secondary interface.

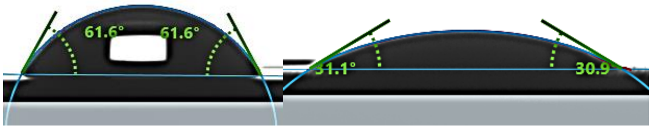

Fig. 3 Adsorption behavior of the hybrid nanofluid compared to the base fluid

3.2 Metal cutting results

The main cutting force and the apparent coefficient of friction are plotted in Fig. 4. The cutting force and the apparent coefficient of friction are reduced for turning under hybrid nanoMQL fluid by 20.1% and 24.9%, respectively. The reduction during turning under hybrid nanofluid is higher than the corresponding single nanoparticle-based nanofluids. Alumina nanoparticles possess high refractory nature but poor lubrication effects, whereas MoS_2 nanoparticles could offer lubrication. MoS_2 nanoparticles lose their lubrication effect at a higher temperature. During titanium machining, high machining temperature dissociates MoS_2 to MoO_3 (Equation 1) and reduces the lubricating effects [14].

$$2\,MoS_2 + 7\,O_2 \rightarrow 2\,MoO_3 + 4\,SO_2 \qquad (1)$$

The hard alumina nanoparticles resulted in a lower friction coefficient than that of soft MoS_2-based nanofluids. The hard alumina nanoparticles can offer a ball-bearing effect to the sliding chips and bear the chip load over the tool rake face. This effect can reduce local friction over several asperity contact zones unless the alumina nanoparticles get entrapped inside the textures [13]. Entrapment of nanoparticles inside textures and loss of ball bearing effect do not offer tribological advantages during machining. Similar results have been reported for high-speed machining of titanium alloy and the entrapment of the nanoparticles has been confirmed experimentally [13].

Hybrid nanofluids have a better network of soft and hard nanoparticles, as shown with the help of the TEM image (Fig. 1). The presence of hard and soft nanoparticles can form a thin lubricating film over the tool-chip interface. The combined action of hard and soft nanoparticles is beneficial in reducing both friction and cutting forces. Hybrid nanofluids can sustain the chip load and high cutting temperature (due to the presence of alumina nanoparticle), and offer better lubrication (due to the presence of MoS_2 surrounded by the alumina nanoparticles). The high spreadability of hybrid nanofluids could be an influential factor for improved machinability of Ti6Al4V alloy. Higher spreading of fluid over the rake face helps in improved heat transfer from the tool-chip interface. Reduction in heat lessens the chance of material adhesion and sticking friction.

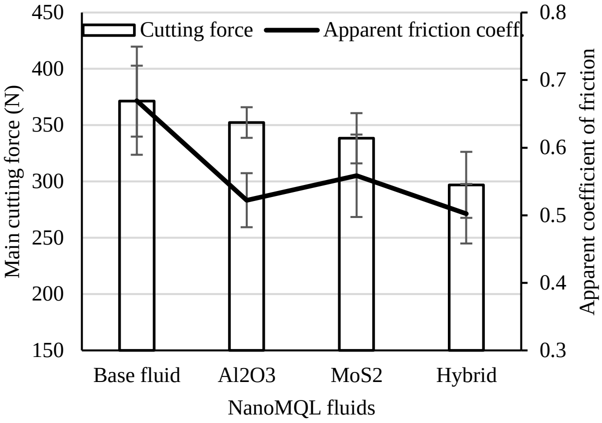

Fig. 4 Variation of cutting forces and apparent friction coefficient for tested nanofluids at (cutting speed 120 m/min, feed 0.12 mm/rev and depth of cut 1 mm)

4. Conclusions

In the present study, an experimental study has been conducted on the application of the hybrid nanofluid during turning of Ti6Al4V alloy. Water-based Al_2O_3, MoS_2, and Al_2O_3-MoS_2 nanofluids have been prepared. Physical structure and physico-chemical interaction of nanofluids have been characterized. Spreadability study of the nanofluids on the laser textured WC/Co cutting tools have been performed to augment the adsorption behavior prediction. The following inferences are withdrawn:

- A hybrid nanofluid has been prepared, which resembles a physical synergy between hard and soft nanoparticle.
- Alumina nanoparticles cluster around the MoS_2 flakes at multiple branches in hybrid nanofluids.
- The hybrid nanofluid reduces the contact angle drastically compared to base fluid and single nanoparticle-based fluid. CA value of hybrid nanofluid $32.1° \pm 1.2°$ has significantly increased the wetting behavior of nanofluids.
- The combined action of hybrid nanofluid (hard and soft nanoparticles) has better performance than a single constituent alone.
- The physical synergy between the hybrid nanoparticles and adsorption behavior over laser textured surfaces have lowered the main cutting force and the apparent friction coefficient by 20.1% and 24.9%, respectively.

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