Journal of Manufacturing Processes 25 (2017) 70–76

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Performance of cutting nanofluids in tribological testing and conventional drilling

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ARTICLE INFO

Article history:
Received 5 March 2016
Received in revised form 3 June 2016
Accepted 4 November 2016
Available online 28 November 2016

Keywords:
Nanoparticles
Boelube
Drilling
Extreme pressure (EP)
Cutting fluid

ABSTRACT

Extreme pressure (EP) testing of cutting fluids modified by diamond and molybdenum disulfide (MoS_2) nanoparticles were carried out as a possible predictor of behavior of these fluids when used in conventional drilling. EP tests showed that nanofluids containing 2–4% MoS_2 nanoparticles increased the load carrying capacity up to 16%

while significantly reducing the transfer of material from the softer stainless steel balls to the harder tungsten carbide ball. In contrast, nanofluids containing up to 1% diamond nanoparticles reduced the load carrying capacity by 10%. In conventional drilling tests, the MoS_2 nanofluid exhibited 25% longer drill bit service life and a steadier and lower cutting force and torque. Also, the built-up edge (BUE) on the drill bits tested with nanofluids containing MoS_2 nanoparticles was easily scraped off from the cutting edges. Dispersion of diamond nanoparticles in the baseline fluid did not enhance the machining performance in drilling tests.

1. Introduction

Hundreds of thousand holes are drilled in various components in engine, wing and fuselage of a modern airplane. The production of these components often involves manufacture and assembly of difficult-to-cut alloys and materials such as nickel and titanium-based alloys, aluminum, stainless steel, and multi material combinations with different physical properties. Drilling through these parts in a single-shot process to produce high quality holes with acceptable tool wear is of great significance in cost reduction and minimized cycle time in the production of aircraft parts and structures. Among many parameters that affect the outcome of drilling and other machining processes is the effectiveness of the cutting fluid [1,2].

The significance of the cutting fluid in drilling and other machining processes is due to the severe tribological conditions involving high contact stresses at the tool/chip interface. The real area of contact in these situations becomes nearly equal to the apparent area of contact at the plastic zone of the tool-chip interface. The newly formed chip surface sliding over the tool face has an unoxidized surface which is chemically active with the tool surfaces and edges. The frictional heat and the plastic deformation result in high contact temperatures. As a result, chemical and mechanical interactions between the tool, the workpiece, and the cutting fluid as a means of affecting them are crucial in machining [3].

The ideal cutting fluid can control the severity of the contact interactions in machining by lubricating the chip-tool and tool-workpiece interfaces, removing heat from the workpiece and cutting zone, and flushing away chips from the cutting area while inhibiting corrosion. At low and moderate cutting speeds such as those encountered in conventional drilling and tapping, lubrication and cooling are the key functions of a cutting fluid. The cutting fluid in these operations removes heat from the contact zone and reduces the friction at the chip/rake face and chip/flues interfaces which lowers the torque and axial force, reduces tool temperature, and prevents marring the machines surface. This results in longer tool life and higher workpiece quality [4].

Nanofluids which are engineered colloidal suspension of solid nanoparticles in a base fluid present the opportunity for improvement in lubrication and heat transfer. In early works, the enhanced thermal conductivity of nanofluids for increased cooling rates in microelectronics and transportation industries with high thermal load requirements was the focus of research and development. The enhanced thermal properties of nanofluids promised thermal man-

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http://dx.doi.org/10.1016/j.jmapro.2016.11.001
1526-6125/

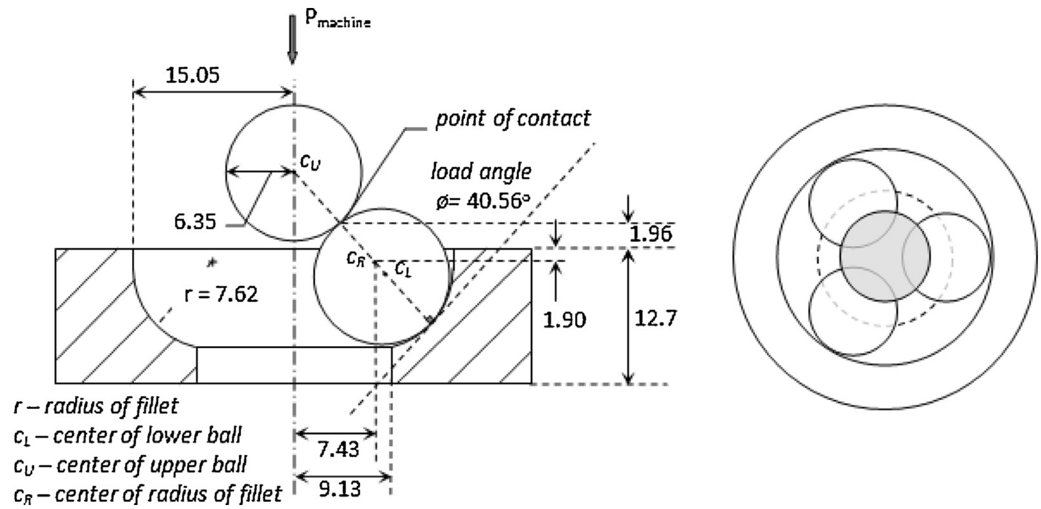

Fig. 1. Ball configuration in the four-ball tester.

Table 1
Nanoparticles and their dispersion characteristics.

Materials	Average particle size (APS) as individual particles in powder (nm)	Dynamic APS in nanofluid after shaking (nm)[a]	Dynamic APS in nanofluid after sonication (nm)[a]
MoS_2 nanoparticles	70–100	800	550
Diamond nanoparticles	3–5	500	250

[a] Determined by light scattering spectroscopy.

agement solutions requiring reduced coolant inventory, pumping power, and emission [5,6]. Recent advances in nanotechnology and nanoparticle synthesis have provided the opportunity for creating nanoparticles with desired structures and morphologies for other applications including tribological applications and nanolubricants [7–10]. The capacity to enhance heat transfer and lubrication using the nanofluid technology presents an opportunity for cutting fluids for improving part quality, tool life, and higher machining efficiency [11–13].

In this paper, both extreme pressure testing and conventional drilling using nanofluids containing diamond and MoS_2 nanoparticles are conducted and the correlation between the tribological testing and the actual machining process is evaluated and discussed. The use of MoS_2 nanoparticles is because molybdenum disulfide has a layered and two-dimensional structure with weak van der Waals forces between its molecular layers which makes it an efficient solid lubricant. The efficacy of MoS_2 nanoparticles for tribological applications has been demonstrated in the literature [14,15]. Also, to enhance the base fluid's heat transfer, diamond nanoparticles (detonated nanodiamond) whose high thermal conductivity has been shown to significantly enhance the thermal conductivity of water-based nanofluids was utilized [16].

2. Experimental

The assessment of effectiveness of cutting nanofluids were carried out in two phases, namely tribological studies by extreme pressure testing and cutting process studies by conventional drilling.

2.1. Nanofluid preparation

Boelube 70104, a long chain alcohol-base machining lubricant which is water-insoluble liquid at room temperature, was the control lubricant throughout this study [17]. Boelube-based dispersions were prepared by addition of nanoparticles to the base fluid, shaking, and sonication for approximately 15 min at 20 W output. In order to prevent significant heating, the container of fluid sample was placed in a bath of iced water. Table 1 shows the dimensional characteristics of nanoparticles used in this study. The MoS_2 and detonated nanodiamond particles were purchased from Nanostructured & Amorphous Materials Inc. of Houston, Texas. The aggregation of individual particles in the powder and in the dispersions resulted in a significantly larger dynamic average particle size (APS) in the fluid state. The sonication reduced the dynamic APS, but it did not reduce it to the APS of the individual particles. The selected nanoparticle concentrations for MoS_2 were 2% and 4% by weight and for diamond were 0.5% and 1% by weight as suggested in other investigations [10,11].

2.2. Tribological evaluation

2.2.1. Materials and procedures

A four-ball tester with a maximum rotational speed and normal load of 10,000 rpm and 10,000 N, respectively, was utilized. Through the system's computer interface, the test conditions such as speed, load, and oil temperature were controlled and recorded during the tests. The ball configuration of the four-ball tester is shown in Fig. 1. The lubrication properties of Boelube and nanoparticle-modified Boelube were studied in extreme pressure (EP) testing conditions according to ASTM D 2783-03 standard. A series of 10-s-duration tests were conducted at increasing loads until welding of the upper ball to one of the lower balls occurred. Each test was repeated three times. Since each test includes three lower balls, the scar diameter and transfer film data was averaged over 9 data points. The rotating speed according to the EP test standard was 1760 rpm. It corresponds to 0.762 m/s sliding speed at the contact points. The lubrication in the EP testing was in the flooded state.