Iranian Journal of Science and Technology, Transactions of Mechanical Engineering (2022) 46:335–345
https://doi.org/10.1007/s40997-021-00452-2

RESEARCH PAPER

Influence of Cutting Fluid-Based CuO-Nanofluid with Boric Acid-Nanoparticles Additives on Machining Performances of AISI 4340 Tool Steel in High-Speed Turning Operation

Mohammad Jafarian Zenjanab[1] · **Siamak Pedrammehr**[2] · **Mohammad Reza Chalak Qazani**[3] · **Mohammad Reza Shabgard**[2]

Received: 25 November 2019 / Accepted: 10 September 2021 / Published online: 8 October 2021

Abstract

This paper presents an experimental investigation on the effects of soluble cutting fluid-based CuO-nanofluid with boric acid-nanoparticles additives on machining force, surface roughness, and tool wear in high-speed turning operation of hardened AISI 4340 tool steel. In this research, a lubricant supply system has been designed for utilizing nanofluid in machining operation. Experiments are carried out with various proportions of boric acid 0.25, 0.5, and 1% by weight as nanoparticles additives in different cutting conditions. The results are also compared with the outputs of similar tests through dry cutting condition and turning under soluble cutting fluid. The results show that the use of nanoparticle suspensions improves the machining conditions in a way that the machining force, the surface roughness, and the tool wear have considerably reduced under different cutting conditions. Accordingly, the obtained results lead to decrease in machining time and tool consumption that directly influence the energy consumption in machining operation.

Keywords CuO nanofluid · Boric acid · High-speed machining · Machining force · Surface roughness · Tool wear

1 Introduction

Tool steels are of importance in modern production industry. The production of tools has various machining difficulties such as production cost, tool, and energy consumption, and surface quality problems. In order to reduce the cost of production and improve the quality of surface, lots of researchers focus on this zone which is one of the vital scopes in practical investigations. Use of nanofluids and nanoparticle additives, and high-speed cutting in machining of tool steels could solve the mentioned problems which is the gap in the reported literature in this field of study. This study focuses on different cutting fluids which are used in high-speed turning of AISI 4340 tool steel to fulfill the existing gap in this field.

High-speed turning process is one of the more practical and immense operations in modern production industry. Machining force, surface roughness, and tool wear are all crucial and appreciable factors throughout the turning operation which are mostly assessed to ascertain the turning performance (Reddy and Rao 2005). These factors depend on plenty of items such as tool material and geometry, machining input parameters such as cutting speed, feed rate, back engagement, pressure of cutting fluid, etc. As these items have been altered by creation of heat and friction from the cutting area, finding a method to reduce the temperature and friction by using coolants and lubricants is probed in recent investigations (Klocke and Kratz 2005; Chou and Song 2004). Although comprehensive investigations have been done to achieve higher productivity and better surface integrity by using different cutting fluids (Yildiz and Nalbant 2008), soluble cutting fluid-based CuO-nanofluid, with and without boric acid-nanoparticles additives, has not been exploited as cutting fluid in the reported literature. It is also of note that nano-boric acid suspensions add four different distinct specifics to fluid-based lubrication. First of

---

✉ Mohammad Jafarian Zenjanab
m.jafarian.zenjanab@gmail.com

[1] Department of Mechanical Engineering, Azad University, Sanandaj, Iran

[2] Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran

[3] Institute for Intelligent Systems Research and Innovation, Deakin University, Geelong, VIC 3216, Australia

all, it reduces flow rate of cutting fluid. Secondly, it makes CuO-Nanofluid more stable by lessening the pH of suspension (Vamsi Krishna et al. 2010). This, however, is because boric acid decreases the soluble cutting fluid pH; hence it increases difference between the pH of soluble cutting fluid and electric point pH of CuO Nanofluid. This action not only triggers the distribution of nanoparticles, but also prevents the subsidence of specks (Hwang et al. 2008). The third is the rise of lubricating properties because the added solid lubricant reduces friction and decreases wear to a minimum besides providing an easy slide between sliding interfaces. Acid boric also increases corrosion properties (Düzcükoğlu and Acaroğlu 2009).

Nanofluids are made of nano-sized solid particles dispersed into soluble cutting fluid and they are often used to increase heat transfer in industries that friction and high levels of temperature possess harmful effects on tools and workpieces (Choi et al. 1995). In recent years, many studies have been done to assess the characteristics of different nanofluids and find their practical application in various industries (Carslaw and Jaeger 1947; Acrivos 1980; Leal 1992; Whitaker 1972; Mashood Khan et al. 2020a, 2020b). Verma et al. (Verma et al. 2008) studied the effect of soluble cutting fluid-based MoS2-nanofluid. They considered three oils including paraffin oil, triglycerides (canola oil), and lecithin and tested in ball bearing as a cutting fluid-based and it caused sharp reduction in the coefficient of friction and the wear rate. Zhou and Wang (Zhou and Wang 2002) reached to the point with the study of the thermal properties of CuO-nanofluid that 0.4% volume fraction of CuO nanoparticles added to water rose the thermal conductivity of water by 17%. Hwang et al. (Hwang et al. 2007) investigated the increase of thermal conductivity in various liquids by mixing them with CuO nanoparticles. They measured the thermal conductivity increase by adding nanoparticle size 33 (nm) to water and ethylene glycol fluid. The result of their experiments showed that thermal conductivity of suspension increased by 50% and 90% respectively. Hernández Battez et al. (Hernández Battez et al. 2008) discussed the anti-wear behavior of CuO, ZnO, and ZrO2 nanoparticles suspensions in a polyalphaolefin (PAO 6) under mixed lubrication using a block-on-ring tribometer which is made of AISI 1045 and AISI D3. Their research proved cutting fluid-based CuO-nanofluid got the most decrease in the wear surface and friction by 48% and 19% in contrast with soluble cutting fluid. Avila and Abrao (Avila and Abrao 2001) compared the performance of three types of cutting fluids (an emulsion without mineral oil, one synthetic fluid, and an emulsion containing mineral oil) to dry cutting when continuous turning hardened AISI 4340 steel using mixed alumina insert. The result showed that the use of cutting fluid was responsible for reducing the scatter in the surface roughness values at high cutting speed, but the use of emulsion consisting of mineral oil had a positive influence on surface integrity. Nam et al. (Nam et al. 2011) conducted experiments for micro-drilling under nanofluid minimum quantity lubrication. They deduced that the nanofluid minimum quantity lubrication (MQL) decreases the drilling thrust forces and torques. Zgang and Li (Zhang et al. 2015), evaluated the lubricating performance of MoS2/CNT nanofluid for minimum quantity lubrication in grinding. Setti et al. (Setti et al. 2015) also investigated Ti–6Al–4 V grinding and friction coefficient of under the nanofluid influence. In their study, nanofluid is made by water and Al2O3 and CuOnano-particles additives. Hegab et al. (Hegab et al. 2018) studied the influence of nano-cutting fluids on chip morphology and tool performance. Aluminum oxide nanoparticles and Multi-walled carbon nanotubes (Al2O3) were used as nano-additives, in their research. In another study, Hegab et al. (Hegab et al. 2019), developed a model for cutting under nano-additives-based MQL. The influence of micro-textures on lubrication of cemented carbide tools under cutting fluids has been investigated by Ge et al. (Ge et al. 2019). Jamil et al. (Jamil et al. 2019) studied the influences of hybrid Al2O3–CNT nanofluids on machining of Ti–6Al–4 V. The main focus of their experiments is to compare the effect of cryogenic CO2 and hybrid nanofluid–based MQL methods for machining Ti–6Al–4 V. Sen et al. (Sen et al. 2019) investigated the effect of Al2O3 and palm oil–mixed nanofluid on cutting performance of Inconel-690 in milling. Mashood khan et al. (Mashood Khan et al. 2020c) investigated cost integrated energy-based modeling of Al-GnP hybrid nanofluid-assisted machining of AISI52100 steel. Zaman et al. (Zaman et al. 2020) employed full factorial DOE to study the effects of tool type, cooling condition, and machining parameters on AISI 4140 steel. Mia et al. (Mia et al. 2020) utilized six sigma method to optimize hard turning characteristics under dry, solid, and MQL lubrication.

In this paper, the influence of soluble cutting fluid-based CuO-nanofluid with boric acid-nanoparticles additives on machining force and surface roughness in turning in high-speed machining of hardened AISI 4340 tool steel has been explored. Primarily, materials and methods have been explained and experiments are designed and performed. The results obtained by experimental method under various conditions are illustrated and compared. The results show that 1 wt. % volume fraction of boric acid-nanoparticles added to soluble oil as cutting fluid reduces surface roughness, and tool wear considerably and decreases machining force by a quarter in comparison with dry cutting condition.

2 Experiments and Methodology

This section describes the experimental setup, machine tool, workpiece material, applied cutting conditions, and the understudy parameters in brief.

The cutting fluid-based CuO-nanofluid consists of soluble cutting fluid and CuO nanopowder. The volume percentage of nanoparticle is 1 with solid lubricant of 50 (nm) particle size. Three other different distinct suspensions have also been made by adding 0.25, 0.5, and 1 wt. % of acid boric to cutting fluid-based CuO-nanofluid which are employed during different experiments. A lubricant supply system has been designed and produced which is composed of a cylindrical tank, mixer, and fluid pump (see Fig. 1). For inhibition of sedimentation and better distribution of nanoparticles, pump has been situated underneath the tank. There is also a mixer inside the tank for this purpose. The bottom of the tank is conical, therefore, all nanoparticles are available to enter to the pump.

The exit port of pump is connected to entrance port of machine turret which has the spherical shape and base holder. A CNC Lathe machine and a fluid nozzle which is placed in the corner of the tool holder are shown in Fig. 2.

Workpiece is selected as hardened AISI 4340 with 50 (mm) diameter and 380 (mm) length. Table 1 lists the chemical composition of AISI 4340 steel.

Cermet carbide inserts of ISO designation DNMG 150,604-QM have been used for experimental tests. Further details for cutting tools and holders are listed in Table 2.

Machining experiment has been carried out on a high-speed CNC lathe (Leadwell LCP 30P Strands SMG) equipped with its own straitpoint dynamometer for force measurement. For the measurement of average surface roughness (Ra) and the assessment of surface integrity, data has been recorded by Mahr Perthometer M2 and IMM-420 SAIRAN Optical Microscope, respectively (see Fig. 3).

The experiments have been carried out to assess the effects of soluble cutting fluid-based CuO-nanofluid with boric acid-nanoparticles additives on machining force, surface roughness, and tool wear in high-speed machining and turning of hardened AISI 4340 tool steel, and the obtained results are compared with dry machining and machining under soluble cutting fluid.

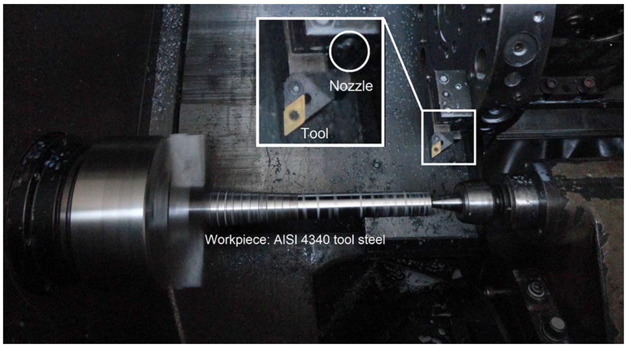

Fig. 2 High-speed CNC lathe cabin, tool, work piece, and nanofluid nozzle

The most frequently used method in experimental investigations is full factorial approach, which consists fifty-four factors in this study, due to the complex relations between machining parameters. According to Table 2, experiments have been conducted in three different cutting velocities of 100, 250 and 400 (m/min), three different feed rates of 0.1, 0.15, and 0.2 (mm/rev), and six environmental conditions including dry, cutting fluid, soluble cutting fluid-based CuO-nanofluid, 0.25 boric acid in 1% volume fraction of CuO nanoparticles suspension, 0.5 boric acid in 1% volume fraction of CuO nanoparticles suspension, and 0.1 boric acid in 1% volume fraction of CuO nanoparticles suspension. Back engagement was kept unchanged at 0.6 (mm) in all the experiments. Table 2 lists the further details for experimental tests.

Fig. 1 High-speed CNC lathe (back view), a lubricant supply system with its details

Table 1 Chemical composition of AISI 4340 steel

Material	Mo	Ni	Cu	Mn	Cr	Si	C	P
Percentage	0.25	1.6	0.1	0.6	1.61	0.28	0.35	0.01

Table 2 Experimental test condition

Work specimen	
Material	AISI 4340
Size (mm)	380 × 50 Ø
Hardness (HRC)	52 ± 3
Cutting speed (m/min)	$V = 100, 250, 400$
Feed rate (mm/rev)	$f = 0.1, 0.15, 0.2$
Depth of cut (mm)	$t = 0.6$
Length of cut (mm)	$L = 350$
Suspensions	
Suspensions type	Dry, soluble cutting fluid, cutting fluid-based CuO nanofluid, cutting fluid-based CuO-nanofluid with boric acid-nanoparticles additives (0.25, 0.5 and 1 wt. %)
Suspension flow rate (l/min)	27
Number of repetitions	3 times
Tool	
Cutting tool	DNMG 150,604-QM
Holder	PDJNL 2525 M 15
Surface roughness tester	Mahr Perthometer M2 and IMM-420 SAIRAN Optical Microscope
Dynamometer	Straitpoint on CNC lathe machine-Leadwell LCP 30P Strands SMG

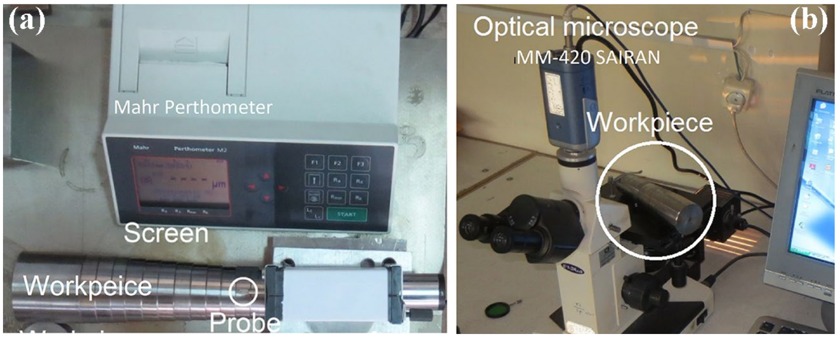

Fig. 3 **a** Average surface roughness (Ra) measurement by Mahr Perthometer M2, **b** surface integrity assessment by IMM-420 SAIRAN optical microscope

3 Results and Discussion

3.1 Machining Force under Different Cutting Conditions

Machining force is the important technical parameter relevant to the durability of tool and machined surface texture. It reflects the status of the lubricants performance and cutting operation. Through experimentation, the machining force has decreased considerably by using soluble cutting fluid-based CuO-nanofluid with boric acid-nanoparticles additives in comparison with dry cutting condition as well as machining under cutting fluid (See Fig. 4). With constant feed rate, by rising cutting speed, there is a decrease in machining force in almost all of the experiments. Considering Fig. 4d, 0.25 wt. % suspensions of boric acid-nanoparticles additives have negative influence on machining force than soluble cutting fluid-based CuO nanofluid. The least machining force can be attributed to 0.5 wt. % suspension of boric acid, Fig. 4e. However, according to Fig. 4f, 1 wt. % of boric acid suspension does not show a considerable variation in machining force.

The decrease in machining force is generally attributed to Anti-friction and anti-wear properties in CuO-nanofluid (Acrivos 1980; Leal 1992; Whitaker 1972; Mashood Khan et al. 2020a, 2020b). CuO-nanoparticles permeate into the interface between the tool and chip which can

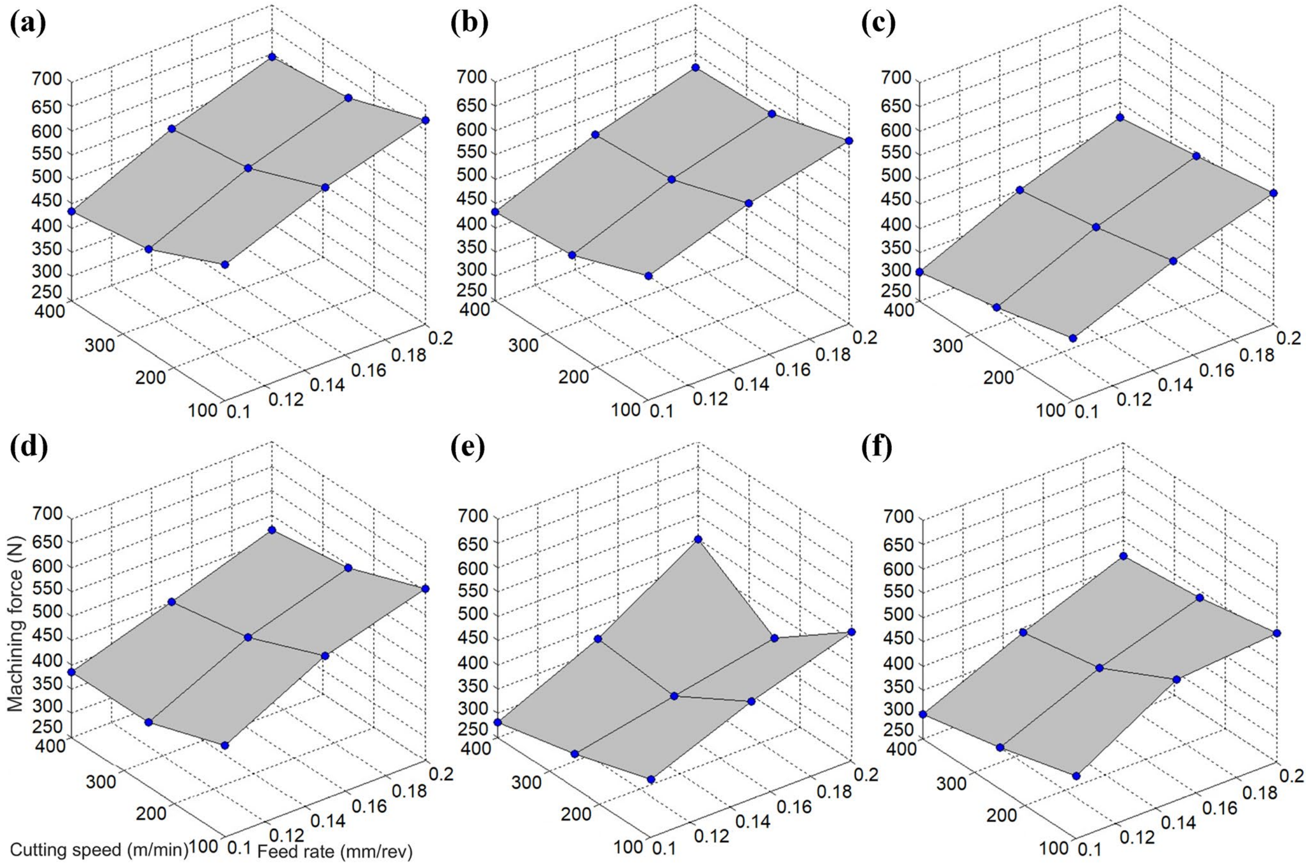

Fig. 4 Machining force under different cutting speed and feed rate: **a** dry; **b** soluble cutting fluid; **c** cutting fluid-based CuO-nanofluid; **d** cutting fluid-based CuO-nanofluid with 0.25 wt. % boric acid-nanoparticles additives; **e** cutting fluid-based CuO-nanofluid with 0.5 wt. % boric acid-nanoparticles additives; **f** cutting fluid-based CuO-nanofluid with 1 wt. % boric acid-nanoparticles additives

simultaneously reduce the distance between surfaces. Consequently, the pressure in the interface between them goes up, nanoparticles are tirbo-sintered on the surface and it makes a foam layer. This layer resists the portion of applied force and prevents the direct connections between surfaces. Therefore, coefficient of friction between contact surfaces (tool-chip and tool-workpiece) reduces and it results in the reduction of friction force. Therefore, machining force is reduced according to the following equation:

$$F_m = \sqrt{F_c^2 + F_f^2 + F_t^2} \tag{1}$$

in which F_m is the machining force. F_c, F_f, and F_t are, respectively, the cutting force, friction force, and the thrust force.

In addition, thanks to the extremely high thermal conductivity of nanofluid suspension, the temperature of cutting area decreases considerably. This, moreover, is one of the causes for reduction of tool wear rate. As a result, the high thermal conductivity of nanofluid suspension prevents the increase of cutting force due to the slow tool wear rate. On the other hand, experiments prove that soluble cutting fluid is unlikely to reduce the machining force. This indicates the low efficiency of conventional cutting fluid in cooling and specially lubrication.

According to Fig. 4d, the negative impact of 0.25 wt. % suspension of boric acid can be expressed in a way that the additive boric acid reduces fluid flow and prevents absorbing CuO-nanoparticles to the interface of tool-chip-workpiece, hence the lubrication properties of CuO-nanofluid reduces. In this case, due to the low portion of boric acid, the negative impact is much stronger than its positive effects such as lubrication and stability. Nevertheless, these influences totally change when the portion of boric acid is twice. In this situation positive impacts dominate negatives, so machining force reduces more than the machining under CuO-nanoparticles suspension. The results show that the machining force doesn't have considerable changes between 1 wt. % suspension of boric acid and CuO-nanofluid.

It is also of note that the machining force reduction ratio decreases more sharply by using nanoparticles suspension in comparison with dry machining condition and cutting under soluble fluid. This indicates that with increasing pressure and temperature in cutting area as a consequence of high-speed machining, nanoparticles suspension can cooperate in this process with its own tirbo-sintered on the cutting surfaces, while soluble cutting fluid cannot resist this situation and it evaporates immediately in these circumstances. Hence nanoparticle suspensions will be useful and valuable in high-speed machining.

With constant cutting speed and varying feed rate, it is quite apparent that the machining force reduces when nanoparticle suspensions have been used, as nanoparticles suspensions can decrease the friction between the interface of tool-workpiece and tool-chip as well as the temperature in cutting area. In all experiments, with an increase in feed rate, machining force has also increased. As the mentioned factors increase the contact area between the tool and workpiece that leads to an increase in friction force, machining force is thereby increased.

3.2 Surface Roughness under Different cutting Conditions

The average surface roughness, R_a, is the workpiece geometrical quality index. A lower value of R_a achieves better corrosion, fatigue, and more accurate cooperation.

The variation of surface roughness in different cutting speeds and feed rates under six machining conditions of dry, cutting fluid and soluble cutting fluid-based CuO-nanofluid with and without boric acid-nanoparticles additives have been measured and illustrated in Fig. 5.

The values of surface roughness for the samples using nanoparticles suspensions are much lower than cutting fluid and also dry machining. This is justified by anti-friction and anti-wear properties and high thermal conductivity of CuO-nanofluid and also by lubricant properties and stabilization of boric acid. CuO nanoparticles based in cutting fluid causes reduction of friction coefficient between tool and chip, so the built-up edge phenomenon becomes more difficult to happen (Boothroyd et al. 1999). Friction reduction between tool and chip also improves chip flow and reduces vibrations between workpiece and the tool, then roughness resulting from aforementioned factors (natural surface

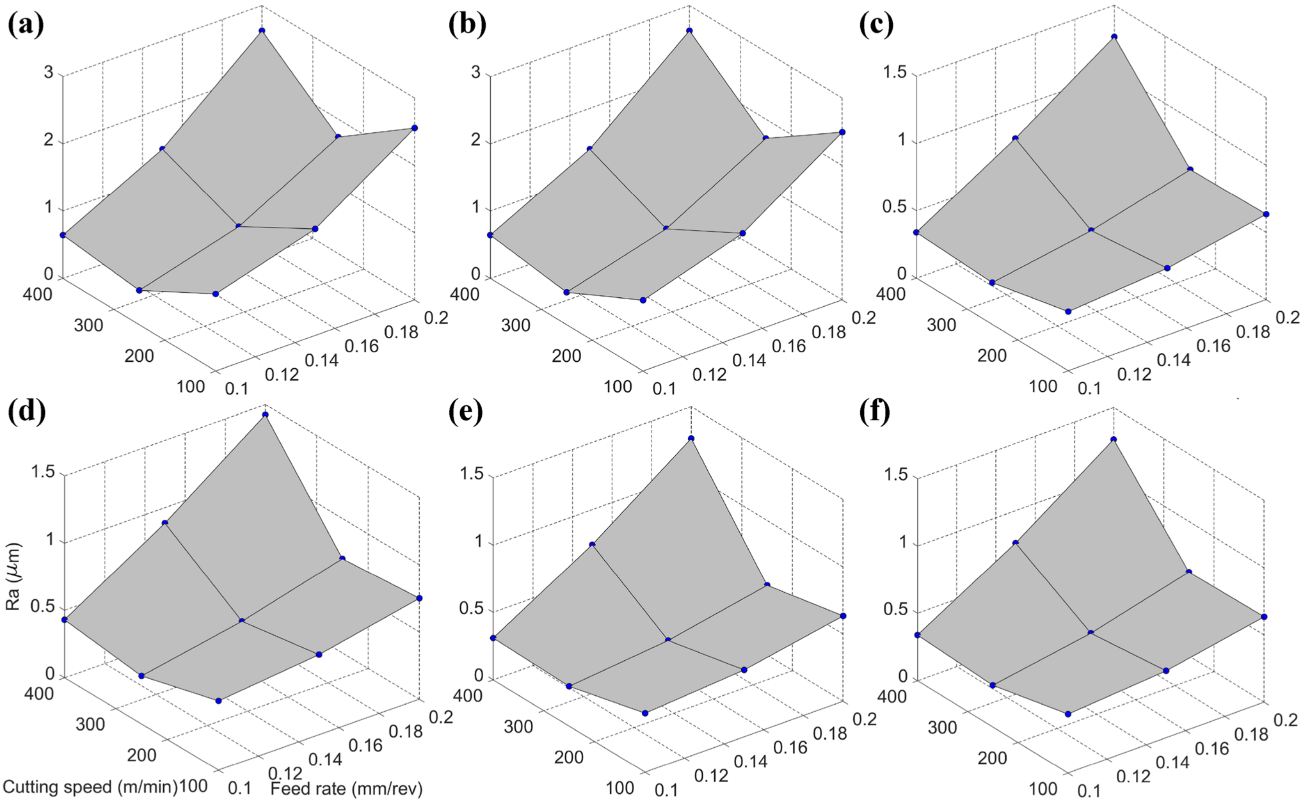

Fig. 5 Surface roughness under different cutting speed and feed rate: **a** dry; **b** soluble cutting fluid; **c** cutting fluid-based CuO-nanofluid; **d** cutting fluid-based CuO-nanofluid with 0.25 wt. % boric acid-nanoparticles additives; **e** cutting fluid-based CuO-nanofluid with 0.5 wt. % boric acid-nanoparticles additives; **f** cutting fluid-based CuO-nanofluid with 1 wt. % boric acid-nanoparticles additives

roughness) decreases (Leppert 2011). Another reason for this event is reducing the temperature of cutting area due to the high heat transfer coefficient, and the reduction of heat at noticed area can decrease the tool wear rate (Boothroyd et al. 1999).

The reduction of tool wear rate prevents change of the radius and the cutting edge geometry from increasing surface roughness (ideal surface roughness). Besides, it decreases the vibration of machine tools by reducing the machining force. In brief, nanofluid suspensions reduce not only natural surface roughness, but also ideal surface roughness by contributing in friction and heat at cutting area, and they all reduce average surface roughness, Ra.

According to Fig. 5c and d, the average surface roughness with suspension of 0.25 wt. % boric acid as nanoparticles additives increases in contrast with CuO-nanofluid. Suspension with 0.5 wt. % boric acid has the least average surface roughness.

In machining operation under CuO-nanofluid with 1 wt. % boric acid additive, the significant change in the average surface roughness is not observed as well, regarding Fig. 5f. The reasons for these changes can also be attributed to the positive and negative impacts of boric acid which were explained in Sect. 3 of the current research.

There is a slight drop in surface roughness by increasing cutting speed between 100 and 250 (m/min). This indicates that the surface roughness approaches to its ideal condition, which is related to machining parameters and tool geometry (Boothroyd et al. 1999) and can directly be attributed to the rising temperature that leads to the softening of workpiece which leads to the surface roughness reduction (Suresh et al. 2012). However, the upward behavior of the curves during machining under 250 and 400 (m/min) cutting speeds denotes the negative effects of high temperature and friction. The high temperature and friction between chip and tool cause built-up edge phenomenon, tool wear, and inappropriate chip flow (Boothroyd et al. 1999).

The change in feed rate shows the minimal impact on the surface roughness when CuO-nanofluid and its various suspensions are used. As the obtained surface roughness in machining conditions under nanofluids is much lower than in dry and soluble oil machining in high feed rates. This is due to the sharp drop in temperature and friction coefficient on the interface between tool-workpiece and tool-chip. Moreover, the average surface roughness grows when feed rate increases (Boothroyd et al. 1999), which can be explained as the following:

$$R_i = \frac{0.0321 \times f^2}{r_\varepsilon} \tag{2}$$

in which R_i is ideal surface roughness. f and r_ε are, respectively, feed rate, and the tool tip radius.

As residual stress change from compressive to tensile when feed rate is raised, when using nanoparticle suspensions at high feed rate, Eq. (2) is not useful for predicting the surface roughness value in different cutting conditions. (Özel et al. 2005). This, however, is because that the hardness of the workpiece reduces during machining operation, and makes the cutting conditions improved by reducing chip bonding tool, improving chip flow, reducing cutting force and vibration (Guo and Liu 2002). Therefore, when using CuO-nanofluids due to the high heat transfer coefficient, anti-friction, and anti-wear properties, the impact of mentioned factors increases and surface roughness reduces.

The optical camera details for machined surfaces under dry, cutting fluid, and nanoparticle suspensions have been presented in Fig. 6. At all, the surface damage that occurs during machining process and how it forms is critical information, since they are used in the crucial parts of product. Machined surfaces include cracks, cavity, and grooves. The fine-scale damage, cracks and cavities have been marked in this figure, which is related to the discontinuous chip formation and the interaction between the tool and the workpiece. The cracks in the finished surface can be induced by a combination of thermal processes, while cavity has a close relationship with built-up edge phenomenon and lubricant between workpiece and tool. Furthermore, the amount and depth of scratches in dry machining condition which are due to the built-up edge (BUE), blunted edge tool, and surge of machining force as the main reasons for vibration, are more than the machining conditions where nanofluids are applied.

3.3 Tool Wear under Different Cutting Conditions

The average tool wear is associated with the cutting tool failure as a result of the friction between the workpiece and tool. The tool wear measurement in different cutting speeds and feed rates for six machining conditions of dry, cutting fluid and soluble cutting fluid-based CuO-nanofluid with and without boric acid-nanoparticles additives have been performed and presented in Fig. 7.

According to Fig. 7, the experiment shows that the application of boric acid-nanoparticles additives is an effective way for tool wear minimization in turning operation under fluid-based CuO-nanofluid. The best cutting fluid performance in terms of the least tool wear can be considered, respectively, in the machining with cutting fluid-based CuO-nanofluid with 0.5 wt. % boric acid-nanoparticles additives. As mentioned in the previous sections of the current research paper, this effect can be attributed to the contribution of lubricating characteristics of boric acid-nanoparticles that causes friction reduction and coherency of nanoparticles distribution in boric acid. However, under cutting condition with fluid-based CuO-nanofluid with 0.25 wt. % boric acid-nanoparticles additives, tool wear has been more than the cutting condition under CuO-nanofluid.

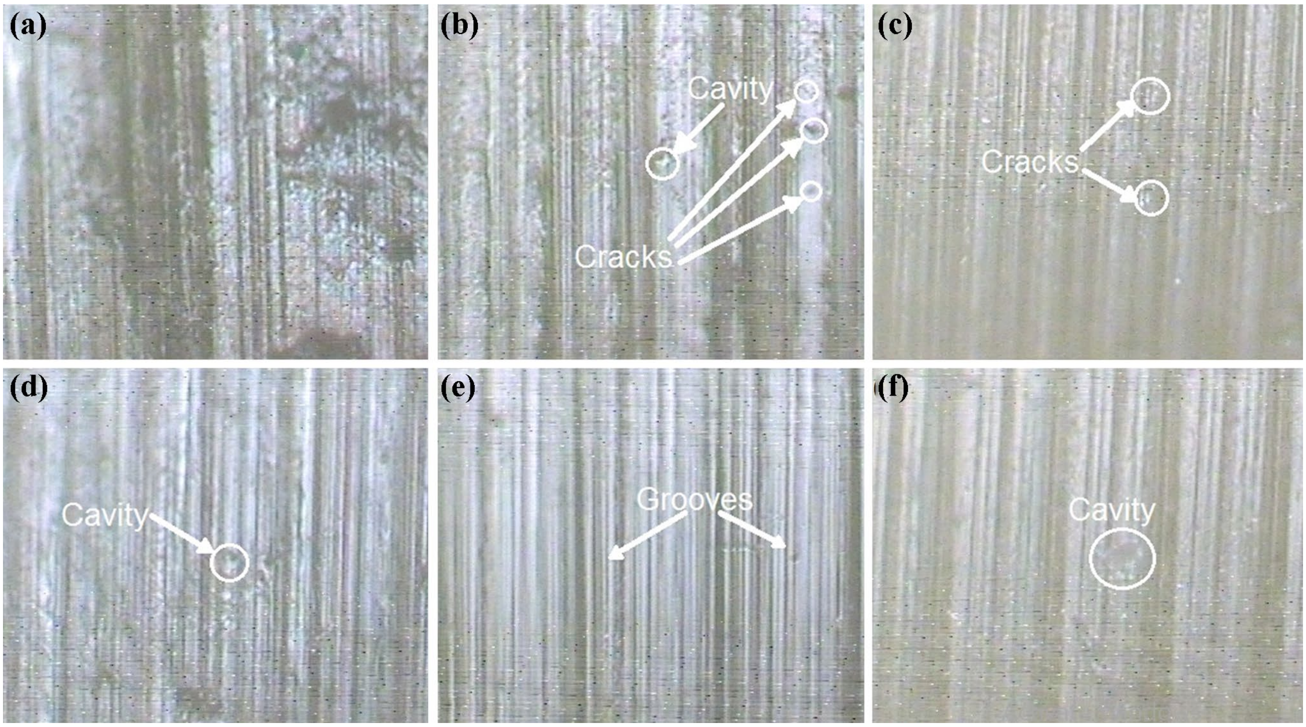

Fig. 6 The optical camera images of the machined surfaces: **a** dry; **b** soluble cutting fluid; **c** cutting fluid-based CuO-nanofluid; **d** cutting fluid-based CuO-nanofluid with 0.25 wt. % boric acid-nanoparticles additives; **e** cutting fluid-based CuO-nanofluid with 0.5 wt. % boric acid-nanoparticles additives; **f** cutting fluid-based CuO-nanofluid with 1 wt. % boric acid-nanoparticles additives

The results could be relevant to the inefficiency of CuO-nanofluid with 0.25 wt. % boric acid-nanoparticles additives in lubricating compared to the CuO-nanofluid with 0.5 and 1 wt. % boric acid-nanoparticles additives. As boric acid reduces fluidity, it prevents the cutting fluid to thoroughly flow in cutting interface and lowers the effectiveness of CuO-nanofluid. The other characteristics of borc acid-nanofluids are their chemical instability that causes more tool wear in 1 wt. % additives in comparison with 0.5 wt. % one.

Figure 8 also depicts the scanning electron microscopy (SEM) images of tool wear under different cutting fluids. The depth of tool wear in the cutting condition under different suspensions of CuO-based cutting nanofluid is considerably lower compared to the dry cutting condition and cutting under soluble cutting fluid. This can be considered as the influences of the friction reduction between the interface of tool-workpiece and tool-chip as well as the temperature reduction in cutting area in machining under nanoparticles suspensions.

4 Conclusions

The results show that the use of nanoparticle suspensions used in this study improved machining conditions. Use of Cutting fluid-based CuO-nanofluid in all the machining conditions reduced machining force around 24 and 20% compared to the dry cutting and machining with soluble oil, respectively. The decrease in machining force is generally attributed to Anti-friction and anti-wear properties in CuO-nanofluid, and coefficient of friction between contact surfaces reduces and it results in the reduction of friction and machining forces. Moreover, the high thermal conductivity of nanofluid suspension prevents the increase of cutting force due to the slow tool wear rate. The use of cutting fluid-based CuO-nanofluid in all circumstances of machining AISI 4340 steel had a significant impact on the quality of the workpiece surface with 49 and 45% reduction on average surface roughness compared to the dry and cutting fluid machining, respectively. This is justified by anti-friction and anti-wear properties and high thermal conductivity of CuO-nanofluid and also by lubricant properties and stabilization of boric acid. CuO nanoparticles based in cutting fluid causes reduction of friction coefficient between tool and chip, so the built-up edge phenomenon becomes more difficult to happen. Friction reduction improves chip flow and reduces vibrations between workpiece and the tool, so the natural surface roughness decreases. The results for the 0.5 wt. % suspensions of boric acid-nanoparticles additives indicated the best consequence for decreasing machining force with 34 and 31% reduction contrasted to dry and soluble oil machining, respectively. This suspension had also

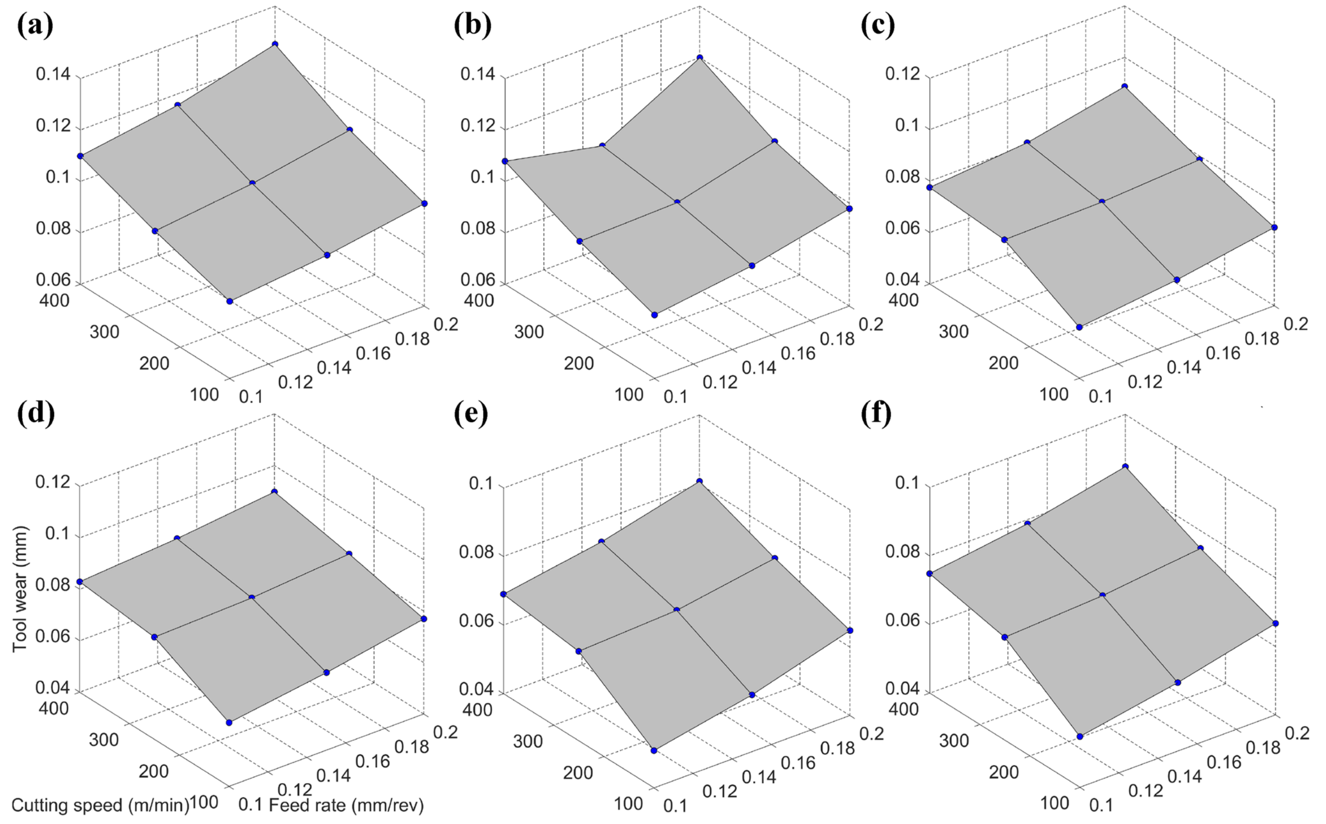

Fig. 7 Tool wear under different cutting speed and feed rate: **a** dry; **b** soluble cutting fluid; **c** cutting fluid-based CuO-nanofluid; **d** cutting fluid-based CuO-nanofluid with 0.25 wt. % boric acid-nanoparticles additives; **e** cutting fluid-based CuO-nanofluid with 0.5 wt. % boric acid-nanoparticles additives; **f** cutting fluid-based CuO-nanofluid with 1 wt. % boric acid-nanoparticles additives

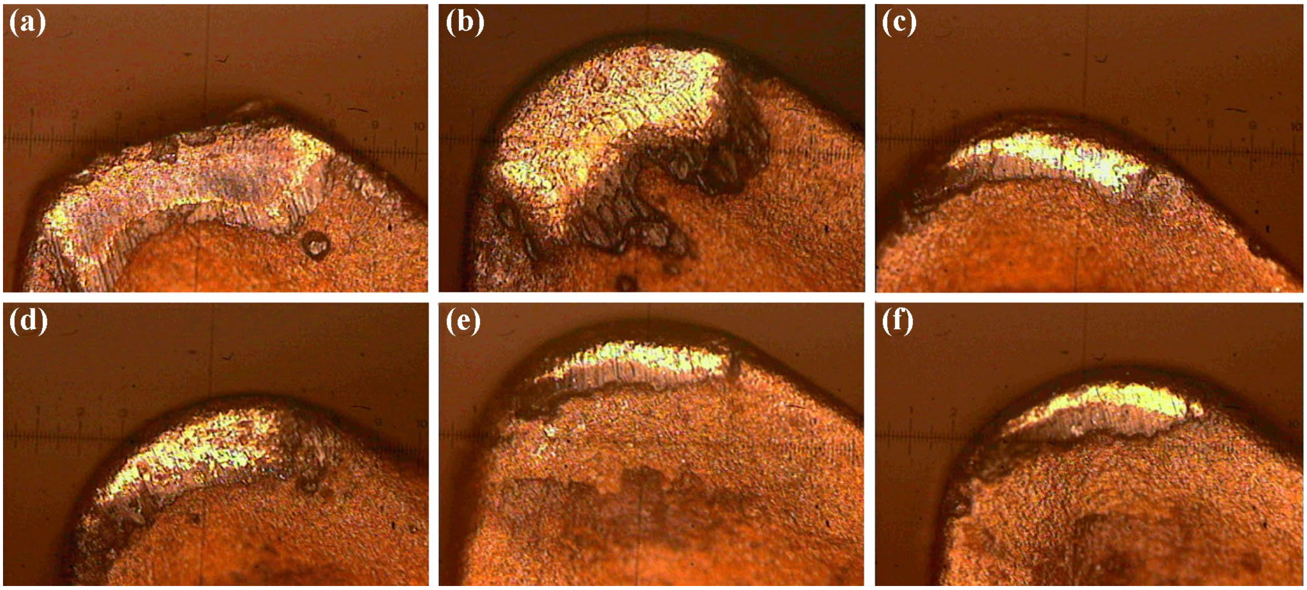

Fig. 8 The SEM images of tool wear under $f = 0.15$ (mm/rev), $V = 250$ (m/min), and 0.6 (m) depth of cut: **a** dry; **b** soluble cutting fluid; **c** cutting fluid-based CuO-nanofluid; **d** cutting fluid-based CuO-nanofluid with 0.25 wt. % boric acid-nanoparticles additives; **e** cutting fluid-based CuO-nanofluid with 0.5 wt. % boric acid-nanoparticles additives; **f** cutting fluid-based CuO-nanofluid with 1 wt. % boric acid-nanoparticles additives

the best surface integrity with the reduction ratio of 59% and 58% in comparison with dry and soluble oil machining, respectively. This effect can be attributed to the contribution of lubricating characteristics of boric acid-nanoparticles that causes friction reduction and coherency of nanoparticles distribution in boric acid. The lowest amount of tool wear was also in the machining condition under CuO-nanofluid with 0.5 wt. % boric acid-nanoparticles additives, with 0.1 of (mm/rev) and cutting speed of 400 (m/min). Nanofluid suspension has an extremely high thermal conductivity which causes considerable decrease in temperature of cutting area and consequently reduces tool wear rate. Among all the experimental tests under different cutting conditions, the least machining force occurred in feed rate 0.1 of (mm/rev) and cutting speed of 400 (m/min), and the lowest surface roughness was also obtained with the same feed rate, and cutting velocity of 250 (m/min) when 0.5 wt. % suspensions of boric acid-nanoparticles additives were used.

Declaration

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Acrivos A (1980) A note on the rate of heat or mass transfer from a small particle freely suspended in linear shear field. J Fluid Mech 98:299–304

Avila R, Abrao A (2001) The effect of cutting fluids on the machining of hardened AISI 4340 steel. J Mater Process Tech 119:21–26

Boothroyd G, Knight WA, Dekker M (1999) Fundamentals of machining and machine tools. Markaze Nashre Daneshgahi, Tehran, pp 180–174

Carslaw HS, Jaeger JC (1947) Conduction of heat in solids. Oxford University Press, Oxford

Choi SUS, Singer DA, Wang HP (1995) Development and application of non-Newtonian flows. ASME, San Francisco, pp 99–105

Chou YK, Song H (2004) Tool nose radius effects on finish hard turning. J Mater 148:259–268

Düzcükoğlu H, Acaroğlu M (2009) Lubrication properties of vegetable oils combined with boric acid and determination of their effects on wear. Energ Source Part A 32:275–285

Ge D, Deng J, Duan R, Liu Y, Li X, Yue H (2019) Effect of microtextures on cutting fluid lubrication of cemented carbide tools. Int J Adv Manuf Technol 103:3887–3899

Guo Y, Liu C (2002) Mechanical properties of hardened AISI 52100 steel in hard machining processes. J Manuf Sci E-T ASME 124:1–9

Hegab H, Umer U, Soliman M, Kishawy HA (2018) Effects of nanocutting fluids on tool performance and chip morphology during machining Inconel 718. Int J Adv Manuf Technol 96:3449–3458

Hegab H, Kishawy HA, Umer U, Mohany A (2019) A model for machining with nano-additives based minimum quantity lubrication. Int J Adv Manuf Technol 102:2013–2028

Hernández Battez A, González R, Viesca JL et al (2008) CuO, ZrO2 and ZnO nanoparticles as antiwear additive in oil lubricants. Wear 265:422–428

Hwang Y, Lee J, Lee C, Jung Y, Cheong S, Lee C, Ku B, Jang S (2007) Stability and thermal conductivity characteristics of nanofluids. Thermochim Acta 455:70–74

Hwang Y, Lee JK, Lee JK et al (2008) Production and dispersion stability of nanoparticles in nanofluids. Powder Technol 186:145–153

Jamil M, Khan AM, Hegab H, Gong L, Mia M, Gupta MK, He N (2019) Effects of hybrid Al2O3-CNT nanofluids and cryogenic cooling on machining of Ti–6Al–4V. Int J Adv Manuf Technol 102:3895–3909

Klocke F, Kratz H (2005) Advanced tool edge geometry for high precision hard turning. CIRP Ann Manuf Techn 54:47–50

Leal LG (1992) Laminar flow and convective transport processes. Butterworth-Heineman, Boston

Leppert T (2011) Effect of cooling and lubrication conditions on surface topography and turning process of C45 steel. Int J Mach Tool Manu 51:120–126

Mashood Khan AM, He N, Jamil M, Raza SM (2020a) Energy characterization and energy-saving strategies in sustainable machining processes: A state-of-the-art review. J Prod Syst Manuf Sci 2:26–49

Mashood Khan A, Jamil M, Mia M, Hea N, Zhao W, Gong L (2020b) Sustainability-based performance evaluation of hybrid nanofluid assisted machining. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.120541

Mashood Khan A, Gupta MK, Hegab H, Jamil M, Mia M, Hea N, Sang Q, Liu Z, Pruncu CL (2020c) Energy-based cost integrated modelling and sustainability assessment of Al-GnP hybrid nanofluid assisted turning of AISI52100 steel. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.120502

Mia M, Gupta MK, Pruncu CI, Sen B, Khan AM, Jamil M, Faraz S, Asef F, Shah Imran GM, Azizur Rahman M (2020) Six sigma optimization of multiple machining characteristics in hard turning under dry, flood, MQL and solid lubrication. J Prod Syst Manuf Sci 1:1–6

Nam JS, Lee PH, Lee SW (2011) Experimental characterization of micro-drilling process using nanofluid minimum quantity lubrication. Int J Mach Tool Manu 51:649–652

Özel T, Hsu TK, Zeren E (2005) Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened AISI H13 steel. Int J Adv Manuf Technol 25:262–269

Reddy NSK, Rao PV (2005) Selection of an optimal parametric combination for achieving a better surface finish in dry milling using genetic algorithms. Int J Adv Manuf Technol 28:463–473

Sen B, Mia M, Gupta MK, Rahman MA, Mandal UK, Mondal SP (2019) Influence of Al2O3 and palm oil–mixed nano-fluid on machining performances of Inconel-690: IF-THEN rules–based FIS model in eco-benign milling. Int J Adv Manuf Technol 103:3889–3403

Setti D, Sinha MK, Ghosh S, Rao PV (2015) Performance evaluation of Ti–6Al–4V grinding using chip formation and coefficient of friction under the influence of nanofluids. Int J Mach Tool Manu 88:237–248

Suresh R, Basavarajappa S, Gaitonde VN, Samuel GL (2012) Machinability investigations on hardened AISI 4340 steel using coated carbide insert. Int J Refract Met 33:75–86

Vamsi Krishna P, Srikant RR, Nageswara Rao D (2010) Experimental investigation on the performance of nanoboric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel. Int J Mach Tool Manu 50:911–916

Verma A, Jiang W, Abu Safe HH, Brown WD, Malshe AP (2008) Tribological behavior of Deagglomerated active inorganic nanoparticles for advanced lubrication. Tribol T 51:673–678

Whitaker S (1972) Forced convection heat transfer correlations for flow in pipes past flat plates, single cylinders, single spheres, and for flow in packed beds and tubes bundles. AIChE J 18:361–371

Yildiz Y, Nalbant M (2008) A review of cryogenic cooling in machining processes. Int J Mach Tool Manu 48:947–964

Zaman PB, Sultana N, Dhar NR (2020) Quantifying the effects of cooling condition, tool type and cutting parameters on machinability of turning AISI 4140 steel using full factorial DOE. J Prod Syst Manuf Sci 1:23–39

Zhang Y, Li C, Jia D, Zhang D, Zhang X (2015) Experimental evaluation of the lubrication performance of MoS2/CNT nanofluid for minimal quantity lubrication in Ni-based alloy grinding. Int J Mach Tool Manu 99:19–33

Zhou L, Wang B (2002) Experimental research on the thermophysical properties of nanoparticle suspensions using the quasi-steady state method, Annual Proceeding Chinese Engineering Thermophysics pp 889–892