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ORIGINAL ARTICLE

Performance improvement of eco-friendly MQL technique by using hybrid nanofluid and ultrasonic-assisted grinding

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Abstract MQL technique has many technological and economic advantages in grinding operation. It can improve grinding performance in terms of surface integrity, grinding forces and G-ratio. On the other hand, MQL is eco-friendly technique because of its small consumption of cutting fluid. Despite these advantages, MQL technique has a serious thermal problem in grinding operations due to a small amount of cooling. Nanofluids can increase heat transfer from workpiece/wheel interface due to its high thermal conductivity. On the other hand, ultrasonic machining can decrease heat generation due to its reciprocating mechanism and reduction of time and length of contact between grain and workpiece. So, it is anticipated that simultaneous utilization of these techniques can reduce thermal damages. In this research MWCNT, Al_2O_3 and hybrid MWCNT/Al_2O_3 nanofluid oil mists have been utilized in ultrasonic assisted grinding. MWCNT has high thermal conductivity and Al_2O_3 has good lubrication effect. Output parameters were maximum temperature, grinding forces and friction coefficient. The results revealed that combination of MQL and UAG decrease of maximum grinding temperature up to 56.3% in comparison to dry grinding (from 254 to 111 °C). Moreover, tangential and normal grinding forces and friction coefficient have been reduced up to 61.5, 47.1, and 27.3%, respectively. Moreover, shiny surface without any thermal damages and burning obtained in comparison to dark and burned surface in dry grinding.

Keywords Minimum quantity lubrication · Ultrasonic-assisted grinding · Hybrid nanofluid · Grinding temperature · Grinding forces

1 Introduction

Metal working fluids (MWFs) play an important role in cooling, lubrication and removal of chips from the grinding zone. Those are essential to achieving good surface finish and avoiding thermal damages. Generally, flood cooling is applied to most of the machining operations, where the cutting fluid is delivered to machining zone at a large flow rate. Despite a number of advantages, flood cooling is associated with environmental hazards and health problems to operators. At the same time, the quality of cutting fluid deteriorates with use and time. Some studies indicated that flood cooling may fail in dissipating the heat from the grinding zone as a result of inadequate pressure and flow rate. The debility is due to its inefficiency to penetrate the high hydrodynamic pressure prevalent at grinding region [1, 2].

Furthermore, the cost of grinding fluid, filtering and waste disposal of the metal working fluids is even higher than the tool cost and constitutes a great part of the total cost [3]. It is reported that in automotive fabrication, 15–30% of the machining cost is related to the use of grinding fluid [4].

Two lubrication methods have been developed in order to reduce cooling costs and environmental hazards: dry and minimum quantity lubrication (MQL). Although the dry condition can reduce the volume of consumed cutting fluid, it may result in insufficient cooling and lubrication in the grinding zone [5]. This leads to excessive tool wear, poor surface accuracy,

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Multi-walled carbon nanotubes

Performance improvement of eco-friendly MQL technique by using hybrid nanofluid and ultrasonic assisted grinding

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excessive processing temperatures and other shortcomings. MQL technique uses high-pressure air to atomize a very small amount of grinding fluid and sprays it through a nozzle to uniformly impinge on the position of the cutting tool, and thus achieving the effect of a cooling lubricant [6]. According to the literature, MQL technique has many technological advantages in grinding processes due to its efficient lubrication. Therefore, improvement of surface roughness, G-ratio and also decreasing of grinding forces and friction coefficient are expected. On the other hand, MQL technique is eco-friendly and reduces fluid consumption up to 0.001 rather than conventional fluid. This method has been gradually replacing traditional cooling-lubricating methods as it to provide better grinding performance. It not only reduces grinding forces but also improves wheel life and workpiece surface quality [7, 8]. Rabiei et al. [9] have investigated MQL technique for grinding of soft and hard steels. They have reported that in the case of hard steels, MQL technique results in improvement of surface roughness and quality as well as decreasing grinding forces and friction coefficient [9].

Despite to these advantages, MQL technique has serious problems such as extreme hydrodynamic pressure, clogging of chips/debris, and especially severe machining temperature [10, 11]. Serious thermal problem limits its industrial applications. During grinding operation without using sufficient cooling and lubrication, thermal damages and dimensional inaccuracy will be generated on the workpiece surface. So, the methods of minimum quantity lubrication and dry grinding have not yet been fully successful in industrial applications. Effective application of MQL technique in processes with high frictional impacts (such as grinding) needs lubricants with improved tribological characteristics to facilitate large thermo-mechanical effect on the process [3, 12, 13].

Hadad et al. [12] have investigated temperatures and energy partition in grinding with vitrified Al_2O_3 and resin bond CBN wheels using MQL technique. They have reported that MQL technique needs to be more investigated considering workpiece temperature reduction and cooling/lubrication properties of oil mist. It also has shown that maximum temperature for CBN wheel (in workpiece/wheel interface) is 110 °C by implementing MQL. However, it is 130 °C for dry grinding and 50 °C for conventional fluid [12]. Also, Hadad et al. have reported analytically and experimentally that MQL cannot meet the grinding cooling requirements in comparison with fluid grinding. Therefore, the widespread application of MQL in grinding is highly questionable. Li et al. have also confirmed thermal problem of pure MQL and have investigated nanofluid MQL grinding to overcome the poor heat transfer of MQL cooling. Nguyen and Shen have shown the effectiveness of MQL in providing lubrication, however, its efficiency in removing heat from the machining zone has been doubted [14, 15]. Also, suggestions have been given to increase the fluid consumption to a moderately adequate level to avoid the risk of thermal damages [16, 17].

To overcome this problem, Tawakolli, Sadeghi and Hadad have carried out experimental and analytical researches to improve the performance of grinding processes. It has been done by optimization of MQL and grinding parameters, implementing different water and oil-based cutting fluids, grinding wheels and etc. [3, 18–20]. Saberi et al. [21] have utilized vortex tube to surmount the lack of coolant challenge in MQL technique and verified the idea by simulation and experimental test. They have reported that CAMQL leads to significant reduction of tangential grinding force and friction coefficient in the surface grinding of CK45 soft steel, in comparison to dry and conventional fluid cooling [21].

Using nanofluids is an efficient suggestion to increase the industrial applications of MQL. It has the potential to improve the performance of MQL grinding by improvement of coolant-lubricant properties of oil mist. Nanoparticles not only increase the heat transfer coefficient of the cutting fluid but also improve its lubrication properties. Therefore, they are used to reduce cutting forces in the grinding process. The thermal conductivity of cutting fluids increases by floating nanoparticles which have high thermal conductivity and high surface/volume ratio [22–24]. The thermal conductivity of multi-walled carbon nanotube (MWCNT) is significantly higher in comparison to that of many nanoparticles [25, 26]. On the other hand, the Al_2O_3 nanoparticle has the best lubrication effect in comparison to other common nanoparticles (ZrO_2 < CNTs < ND < MoS2 < SiO_2 < Al_2O_3) [27]. So, it can reduce heat generation in grinding operation by effective lubrication. Therefore, a hybrid nanofluid produced with these two nanoparticles has a potential to dissipate heat more efficiently than conventional MWFs and many other nanofluids. By a combination of MWCNT and Al_2O_3 nanoparticle and generation of hybrid MWCTNs/Al_2O_3, effective lubrication and cooling are anticipated.

Another suggestion to do so is ultrasonic-assisted grinding [28]. The periodic cutting mechanism in UAM results in fundamental differences from the conventional cutting mechanism. These differences include increasing of length and time of contact, different cutting path and nonuniform uncut chip thickness. Molaie et al. [28] have reported an experimental investigation of the vibration-assisted grinding process combined with MQL using oil-based nanofluids with MoS2 nanoparticles. They have shown that imposed horizontal ultrasonic vibration significantly decreases the grinding normal force [28].

Several techniques of temperature measurement are commonly employed. Typical approaches include thermal imaging and thermocouple measurements. Other techniques involve use of heat-sensitive coatings, low melting-point coatings and fiber optics [29].

The embedded thermocouple method is the most widely used of these techniques. With this method, a double pole thermocouple is welded to the bottom of a blind hole drilled close to the ground surface from the underside of the workpiece. Welding the small tip of a double pole thermocouple at the bottom of the small hole requires special discharge welding equipment and skills. During grinding, the thermocouple measures the temperature below the workpiece surface during successive passes until the welded junction is broken by the grinding action. Accurately determining the position of the temperature measurement below the surface being ground is complicated by its size and also the blind hole [30].

A thermo-camera records the temperature field distribution on the side of the workpiece. The technique provides a graphic image of the whole temperature field including distances well removed from the grinding zone. Thermal imaging has the advantage that subsurface temperatures are provided in real-time. Direct readings illustrate the temperature field throughout the grinding process [29]. Thermal imaging has lower accuracy rather than embedded thermocouple method but is very user friend technique, so is very suitable for comparative studies. Preparation of set up in embedded thermocouple method is very difficult and need long time and accuracy. On the other hand, this technique is destructive method and each thermocouple can be used for one test. Due to comparative nature of this study, thermal imaging method is utilized.

With regard to mentioned literature review, reduction of thermal damages can significantly increase industrial applications of eco-friendly MQL technique. So, the main goal of this research is to improve cooling-lubricating properties of MQL technique which results in a reduction of temperature and thermal damages. In this regard, hybrid MWCTN/Al_2O_3 nanofluid MQL oil mists are combined with ultrasonic vibration. Due to their different mechanism in decreasing workpiece temperature, a considerable reduction of workpiece temperature is expected.

2 Improvememt of coolant and lubricant in grinding by minimum quantity lubrication, ultrasonic-assisted grinding and nanofluid

2.1 Mechanism of efficient lubrication of minimum quantity lubrication

MQL technique uses a minimum quantity of lubrication and is referred to as near dry grinding. In this technique, an air–oil mixture (or air–water mixture) called an aerosol is fed to the machining zone (Fig. 1a). Aerosols are oil droplets dispersed in a jet of air. Oil droplets carried by the air fly directly to grain/workpiece interaction zone. Efficient penetration of oil droplets by using lubricant sources such as wheel pores and grain fractures provides efficient lubrication (Fig. 1b). Aerosols are generated using a process called atomization, which is the conversion of bulk liquid into a spray or mist (i.e., collection of tiny droplets), often by passing the liquid through a nozzle.

The effective lubrication with MQL technique can be explained with its small and high-speed oil mist droplets originated from the high-pressure air (Fig. 1). Therefore, oil mist droplets can penetrate to cutting zone efficiently.

The main benefits of the MQL are the following:

- Environment friendly coolant delivery system, less waste disposal, reduced power consumption.
- Elimination of recirculation and filtration system.
- Avoiding unwanted thermal shock for workpiece and tool.
- Reduced storage space requirements.
- Reduced overall cost of machining/grinding.
- Cleaner and safer workplace Barczak [7].

2.2 Kinematic of ultrasonic-assisted grinding and conventional grinding

Figure 2 depicts schematic of ultrasonic-assisted machining for a single cutting edge (tool) in a cycle. In this cutting mechanism, the cutting edge is involved with the workpiece just in half of cycle (steps 1 and 2). The periodic cutting mechanism in UAM results in fundamental differences from the conventional cutting mechanism. These differences include increasing of length and time of contact, different cutting path and nonuniform uncut chip thickness (Fig. 3).

In this mechanism, thinner and shorter chips are generated due to the different cutting path and consequently nonuniform chip thickness. Hence, required average force to remove the smaller volume is reduced (Fig. 3). Also, as tool velocity exceeds the chip velocity, a reversed tool-chip friction force is generated that thereby reduces the tangential force.

In UAG, the removal process is made easier because of the high-frequency interaction between the active grits and the rapid acceleration of the workpiece. The chips are cutten away more easily. Due to the oscillating impacts between the grits and the workpiece, the microcracks in the contact zone can spread more quickly and have a positive effect on the next process of chip formation. Consequently, the grinding forces and friction effects are reduced. So, less plastic deformation occurs in the contact zone.

But in case of conventional surface grinding, there are three stages of material deformation as a grain interacts with a workpiece: rubbing, plowing and cutting. These are illustrated in Fig. 4 for an abrasive grain deforming a workpiece. In the rubbing mode of deformation, material removal is negligible although friction is apparent. In rubbing, the force on each grain is too small to cause large penetration of the workpiece. Elastic deformation and some plastic deformation take place at the peaks of asperities evidenced by polishing of the workpiece and a slow process of smoothing. Plowing occurs when the penetration of the grains is increased. In the plowing stage, scratch marks become evident and ridges are formed at the sides of the scratches. The scratch marks are evidence of significant penetration, but the rate of material removal remains negligible. As the penetration of

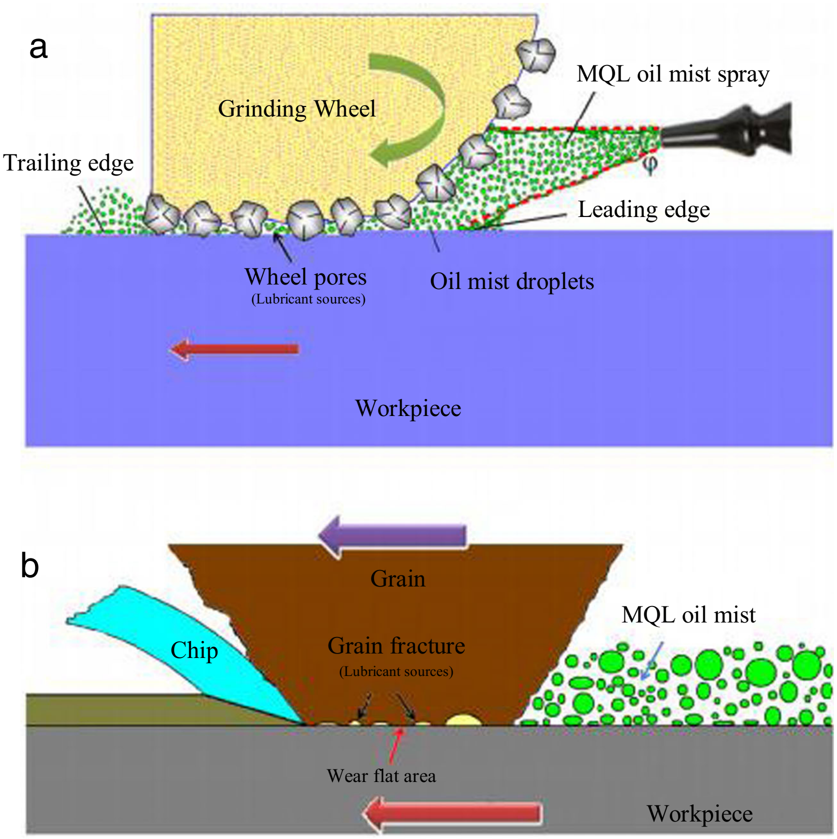

Fig. 1 **a** Schematic of oil mist spray in MQL grinding and **b** lubricant sources at the interface of grain and workpiece surface (Tawakoli, 2010)

the grains is further increased, material removal rapidly increases and chips are produced [31].

2.3 Nanofluid

Nanofluids are a new class of fluids engineered by dispersing nanometer-sized materials, called nanoparticles in a base fluid (such as oil, water or glycol) to improve thermal and tribological behaviors. In other words, nanofluids are nanoscale colloidal suspensions containing condensed materials. These are the new class of engineered fluids, exhibiting several novel properties like improved thermal conductivity, better cooling, and lubrication in comparison to those of base fluids. These advantages make them useful in many heat transfer applications such as fuel cell, vehicle

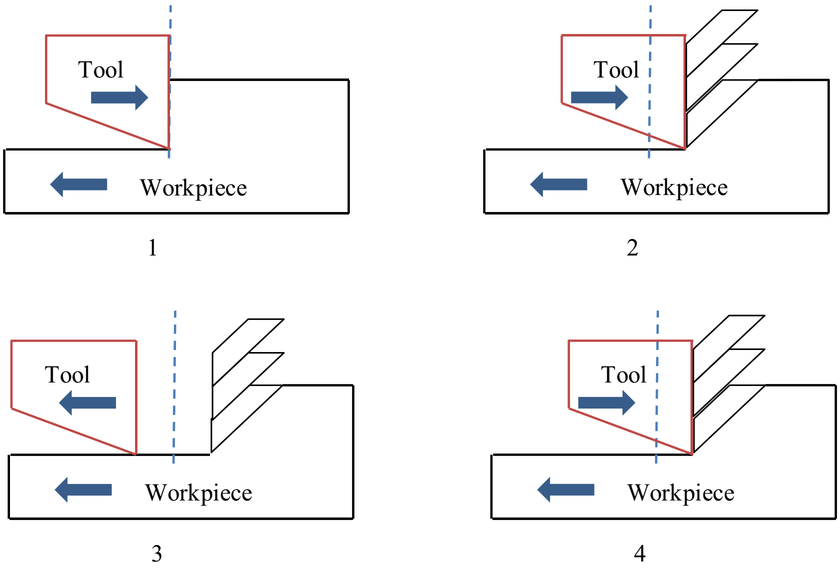

Fig. 2 Schematic of ultrasonic assisted machining: periodic tool-workpiece separation (D.E. Brehl, 2008)

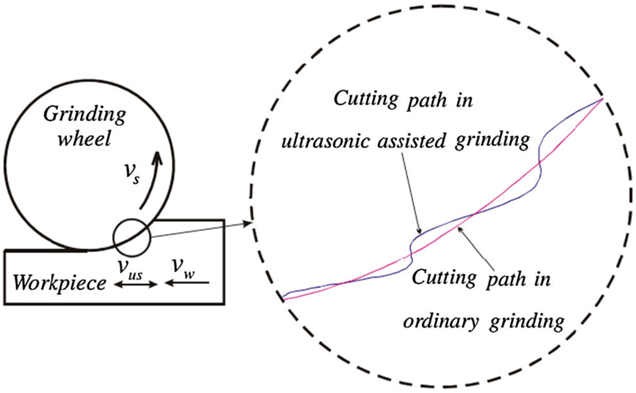

Fig. 3 Cutting path of single grain under no ultrasonic and under ultrasonic vibration (Abdullah, 2012)

cooling, micro-channel applications, and also in manufacturing processes.

The concept of nanofluid is relatively a new concept which emerged for the first time in 1995. Choi and Eastman [32] have introduced the word "nanofluids." After that, the concept has gotten ample attention in the research community and there has been a swift growth in the research articles related to nanofluids. In the last 5 years, there is almost a 32% increase of nanoparticle research articles [33].

Nanoparticles (=NPs) are the oxides, carbides, nitrides, ceramics, and few nanometer-sized metals (1–100 nm). The common NPs are aluminum oxide (Al_2O_3), silicon carbide (SiC), copper oxide (CuO), titanium oxide (TiO_2), carbon nanotube (CNT), molybdenum disulfide (MoS_2), and metal NPs such as copper and silver as well as single-walled, double-walled and multi-walled carbon nanotubes. Each kind of nanoparticle has different molecular structural characteristics and chemical characteristics. Hence, the corresponding nanofluids have different impacts on lubrication and heat transfer performances [34].

2.3.1 Multi-walled carbon nanotube thermal conductivity

MWCNTs nanoparticles can effectively increase the thermal conductivity of cutting fluid [35]. The thermal conductivity of nanofluids with cylindrical nanoparticles (for example MWCNTs) is modeled by Leong et al. [36]. Accordingly, the corresponding effective thermal conductivity of a MWCNTs-based nanofluid is calculated as the following equation:

$$K_{eff} = \frac{\left\{ \left(\boldsymbol{K_p}-\boldsymbol{K_{lr}}\right)\varnothing_{\boldsymbol{P}}\boldsymbol{K_{lr}}\left[\gamma_1{}^2-\gamma^2+1\right] + \left(\boldsymbol{K_p}+\boldsymbol{K_{lr}}\right) \times \gamma_1{}^2\left[\varnothing_{\boldsymbol{P}}\gamma^2\left(\boldsymbol{K_{lr}}-\boldsymbol{K_f}\right)+\boldsymbol{K_f}\right]\right.}{\gamma_1{}^2\left(\boldsymbol{K_p}+\boldsymbol{K_{lr}}\right)-\left(\boldsymbol{K_p}-\boldsymbol{K_{lr}}\right)\varnothing_{\boldsymbol{P}}\left[\gamma_1{}^2+\gamma^2-1\right]} \quad (1)$$

where K_p is the thermal conductivity of nanoparticle, K_{lr} is the thermal conductivity of the interfacial layer between the particle and fluid medium, K_f is the thermal conductivity of the fluid, and $\varnothing_{\boldsymbol{P}}$ is the volume fraction of nanoparticles $\gamma = 1 + h/a$ and, $\gamma_1 = 1 + h/2a$ (h is the thickness of the interfacial layer 2 nm for MWCNTs, and a is the nanoparticle radius of 15 nm for MWCNTs). In this study, the thermal conductivity of MWCNTs is 3000 W/mK, the thermal conductivity of the base cutting oil is 0.6 W/mK and the thermal conductivity of the interfacial layer is 1.25 W/mK. So, the thermal conductivity of the suspension with 2.5 wt% MWCNTs is 5.2 W/mK calculated from Eq. (1) and is about 8.66 times greater than that base oil [35, 36].

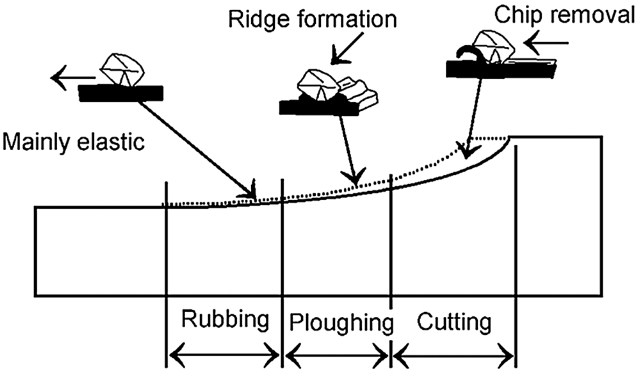

Fig. 4 Rubbing, plowing and cutting regimes of deformation in abrasive machining [34]

2.3.2 Mechanism of improvement of friction coefficient by aluminum oxide

Nanoparticles with different structures, shapes, and sizes will vary in physical and morphological features, demonstrating diverse lubrication performances. The nanoparticle surface effect is illustrated in Fig. 5. Nanoparticles exhibit small size but with the high specific area and surface binding energy, as well as numerous atoms on the surface. Furthermore, many vacant bonds will exist on the nanoparticles without adjacent atoms to the surface atoms. Hence, the nanoparticles are unsaturated, unstable, and easy to combine with other atoms. They are also easy to combine with polar atoms in mineral oil, making the nanofluid produce higher surface energy. Therefore, nanofluid is absorbed by the workpiece and

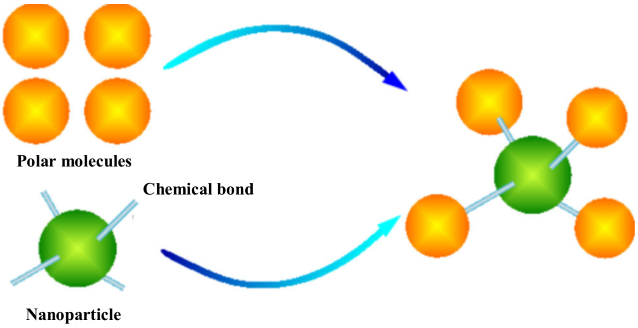

Fig. 5 Schematic of nanoparticle surface effect [27]

grinding wheel surface more tightly, which manifested a better lubrication effect [27].

The good lubrication performance of Al_2O_3 nanofluid is related to its structures and characteristics. Al_2O_3 nanoparticles are spherical with characteristics of high strength, hardness, and heat resistance. The Al_2O_3 nanoparticles are hard phase (HR = 2700–3000), showing good abrasive resistance during the friction process and can carry some support to friction surface load between the area. Therefore, this phenomenon can reduce the actual contact area of friction pair and tangential sliding friction force, thus inhibiting plowing of the micro-bulge on the abrasive surface to the workpiece surface. The Al_2O_3 nanoparticles scatter in the lubricant film, which narrows the effective contact area generating cohesion effect. The Al_2O_3 nanoparticles can change the sliding friction into the combination of sliding and rolling frictions, thus reducing the sliding friction coefficient and shear stress during the abrasive process. Furthermore, the Al_2O_3 nanoparticles demonstrate good resistance to high temperature. The melting point of oil film can reach 2200 °C, which is adequate to hinder the slippage of dislocation and the growth of crystal grains to a certain extent. As such, the lubricant film is strengthened, and its high-temperature resistance improves [27].

3 Experimental procedure

In the present work, the effect of eight different grinding environments (medium) on coolant-lubricant properties of grinding processes has been investigated. General specifications of these environments are listed in Table 1. Coolant properties of the grinding processes have been monitored by temperature measurement. The temperature has been recorded by a high speed IR temperature sensor with a laser marking thermometer (CTLF-SF50-C3 model) from micro-epsilon company. The response time of infrared camera was 9 ms and temperature resolution was 0.5 °C. Lubricant properties of grinding environments have been monitored by measurement of normal and tangential grinding forces. These forces have been recorded by using a KISTLER 3-component dynamometer in three directions. Figure 6 shows SEM analysis of MWCNTs and Al_2O_3 nanoparticles which are used in this research.

The workpiece was 100 Cr6 hardened steel (bearing steel) with 50±2HRC. Also, the dimensions were 130 mm × 20 mm × 20 mm and tests have been done through the 20 mm width for all of the tests. The tests have been conducted with a 2.5 axis CNC surface grinding machine in down cut plunge mode. The tests have been carried out with aluminum oxide grinding wheel.

The equipment which is utilized to control the minimum quantity of lubricant was RSK100 system. The MQL parameters were the flow rate of 150 ml/h and air pressure of 5 bars. Figure 7 shows the experimental setup in this study. To maintain the uniformity in the wheel topography, the wheel was dressed using a single point diamond dresser before each experiment.

The dressing parameters were a total depth of cut of 60 μm, the wheel speed of 15 m/s and a feed rate of 500 mm/min.

Figure 8 illustrates the UAG set-up. The vibration system consists of a piezoelectric transducer, a booster, a horn and a fixture. The ultrasonic power supply converts 50 Hz electrical supply to high-frequency electrical impulses. These high-frequency electrical impulses are fed to a piezoelectric transducer and transformed into mechanical vibrations of ultrasonic frequency (25 kHz), due to the piezoelectric effect. The vibration amplitude is then amplified by the booster and the horn and transmitted to the workpiece attached to the horn. The resultant vibration of the workpiece reaches 30 μm at a frequency of about 25 kHz. Vibration is applied to the workpiece in the feed direction of the grinding wheel.

The machining parameters and the experimental setup data are summarized in Table 2.

Table 1 Coolant-lubricant environments

1.Dry	
2.MWCNTs nanofluid MQL (MQL 1)	2.5 wt%
3.Al_2O_3 nanofluid MQL (MQL 2)	2.5 wt%
4.MWCNTs/Al_2O_3 hybrid nanofluid MQL (MQL 3)	2.5 wt%
5.UAG	Amplitude 30, frequency 25 KHz
6.Combined MWCNTs nanofluid MQL with UAG	
7.Combined Al_2O_3 nanofluid MQL with UAG	
8.Combined MWCNTs/Al_2O_3 hybrid nanofluid MQL with UAG	

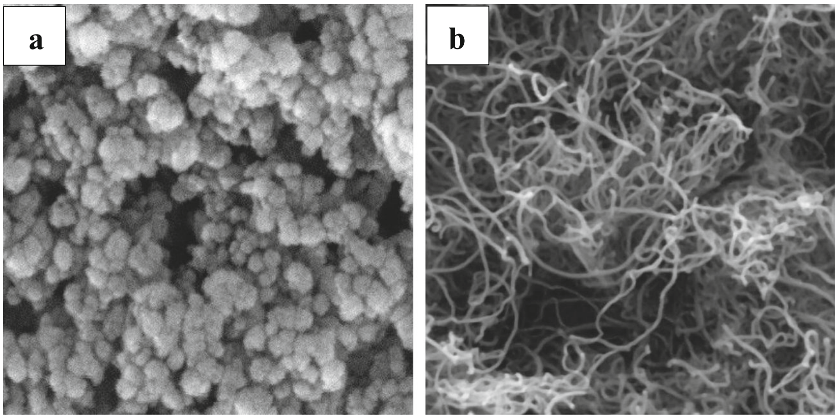

Fig. 6 SEM analysis of the nanoparticles. **a** MWCNTs and **b** Al_2O_3, (magnification: 50,000)

4 Results and discussion

4.1 Friction coefficient

Figure 9 shows force ratio (F_t/F_n) or friction coefficient results for eight different coolant-lubricant environments. This figure clearly indicates that MQL technique reduces friction coefficient in all experiments. This is the most important effect of MQL technique that confirms the efficient lubrication and precise delivery of the oil mist in the workpiece/grain interface. This efficient lubrication improves the slipping of grain between the wheel and the workpiece.

The results show that MQL technique with MWCNTs nanofluid, Al_2O_3 nanofluid, and hybrid MWCNTs/Al_2O_3 nanofluid can reduce friction coefficient up to 16.4, 18.3 and 24.6% respectively in comparison to dry grinding. Al_2O_3

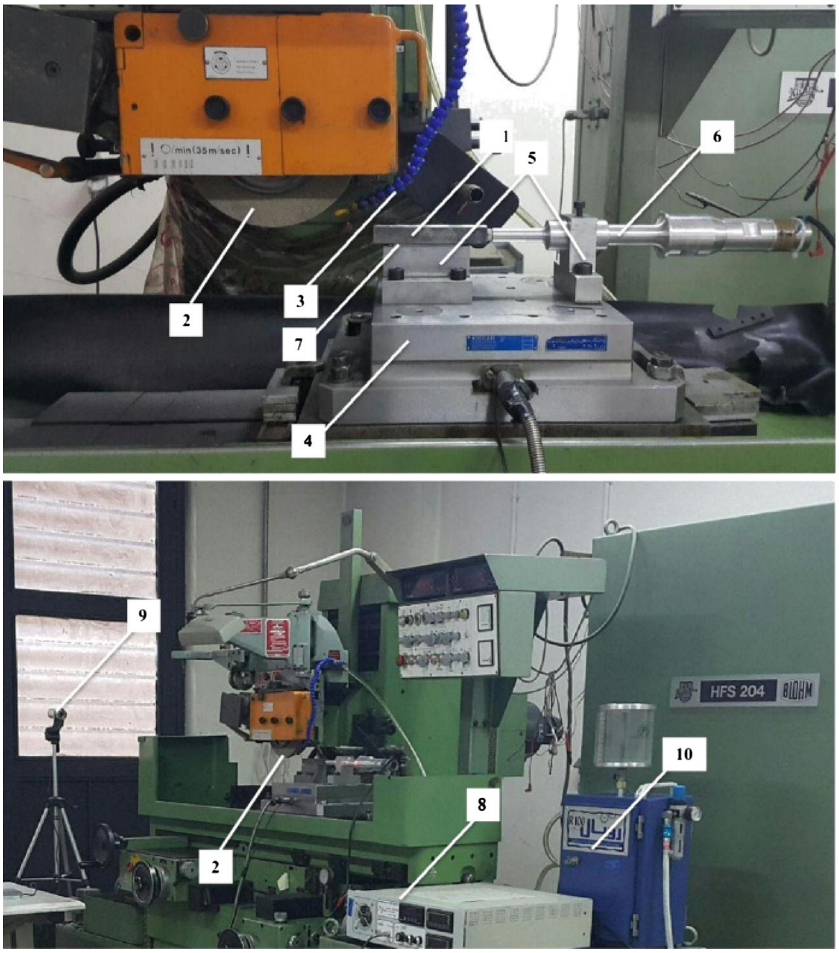

Fig. 7 Experimental setup: *1* workpiece, *2* grinding wheel, *3* MQL nozzle, *4* dynamometer, *5* fixtures, *6* transducer, *7* linear bearing, *8* ultrasonic pulse generator, *9* infrared camera, *10* MQL system

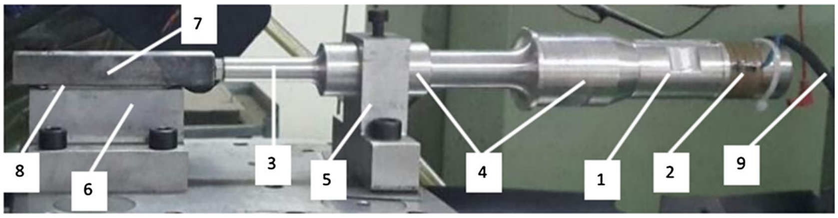

Fig. 8 Ultrasonic-assisted grinding setup: *1* transducer, *2* piezoelectric rings, *3* horn, *4* booster, *5* transducer fixture, *6* workpiece fixture, *7* workpiece, *8* linear bearing, *9* ultrasonic power supply cable

nanofluid has lower friction coefficient with respect to MWCNTs nanofluid due to its better lubrication specification. Al_2O_3 nanoparticles are spherical and they enter into the space between abrasive grains on grinding wheel and the workpiece during sliding friction, serving as "bearings." The original sliding friction is replaced by rolling friction, and nanoparticles bear most friction and loads on the grinding surface, thereby improving the lubrication effect of the grinding area.

Also, the results show that hybrid MWCNTs/Al_2O_3 improves friction coefficient in comparison to single MWCNTs and Al_2O_3 nanofluid.

In the case of ultrasonic-assisted grinding, UAG causes a reduction in friction coefficient. Since, they apply an additional stress to assist in breaking the instantaneous welds. Moreover, they reduce the time that any two asperities on opposite surfaces may remain in momentary contact and hence keep them from forming a stronger weld. Furthermore, periodic grain/workpiece separation provides a periodic gap between grain/workpiece (Figs. 2 and 3). So, better lubrication and cooling effects are achieved compared to conventional machining. Moreover, the periodic cutting mechanism modifies chip geometry and generates thinner and smaller chips. So, rubbing and plowing (Plowing) forces decrease which leads to decrease of grinding forces and friction coefficient. The results show decreasing of friction coefficient in UAG up to 11.5% in comparison to dry grinding.

As expected, according to Fig. 9, combination of MQL and UAG result in maximum decreasing of friction coefficient. The results show that combination of MWCNTs nanofluid, Al_2O_3 nanofluid, and hybrid MWCNTs/Al_2O_3 nanofluid with UAG can reduce friction coefficient up to 24.6, 21.5, and 27.3%, respectively (Fig. 9, Table 3).

Table 3 shows friction coefficient decrease percent for eight different coolant-lubricant environments in different specific removal rates.

4.2 Grinding force

4.2.1 Tangential grinding force

Tangential grinding force consistes of three components: rubbing force, plowing force and cutting force (Eq. 2):

$$F_t = F_{t\ \text{Cutting}} + F_{t\ \text{rubbing}} + F_{t\ \text{plowing}} \tag{2}$$

The results of grinding forces versus specific removal rates are shown in Figs. 10 and 11. Figure 10 and Table 4 show lower tangential grinding forces in MQL grinding in comparison to dry

Table 2 Experimental conditions in grinding experiments

Grinding machine	2.5 axis BOHLM CNC surface grinder
Dynamometer	KISTLER (type: 92,558)
MQL system	RSK100, Royal Sanat Khavaran Co (Iran)
Grinding mode	Plunge surface grinding, down cut
Grinding wheel	Aluminum oxide
Workpiece materials	100Cr6 hardened steel,50 ± 2HRC (bearing steel)
Dimensions of workpiece	130mm×20mm×20mm
Wheel speed	30 m/s
Wheel diameter	200 mm
Feed rate	3000 mm/min
Depth of cut	10, 20, 30, 40
Air pressure in MQL	5 bars
MQL oil flow rate	150 ml/h
Dresser	Single point diamond
Total depth of dressing (μm)	60
Dressing speed	500 mm/min

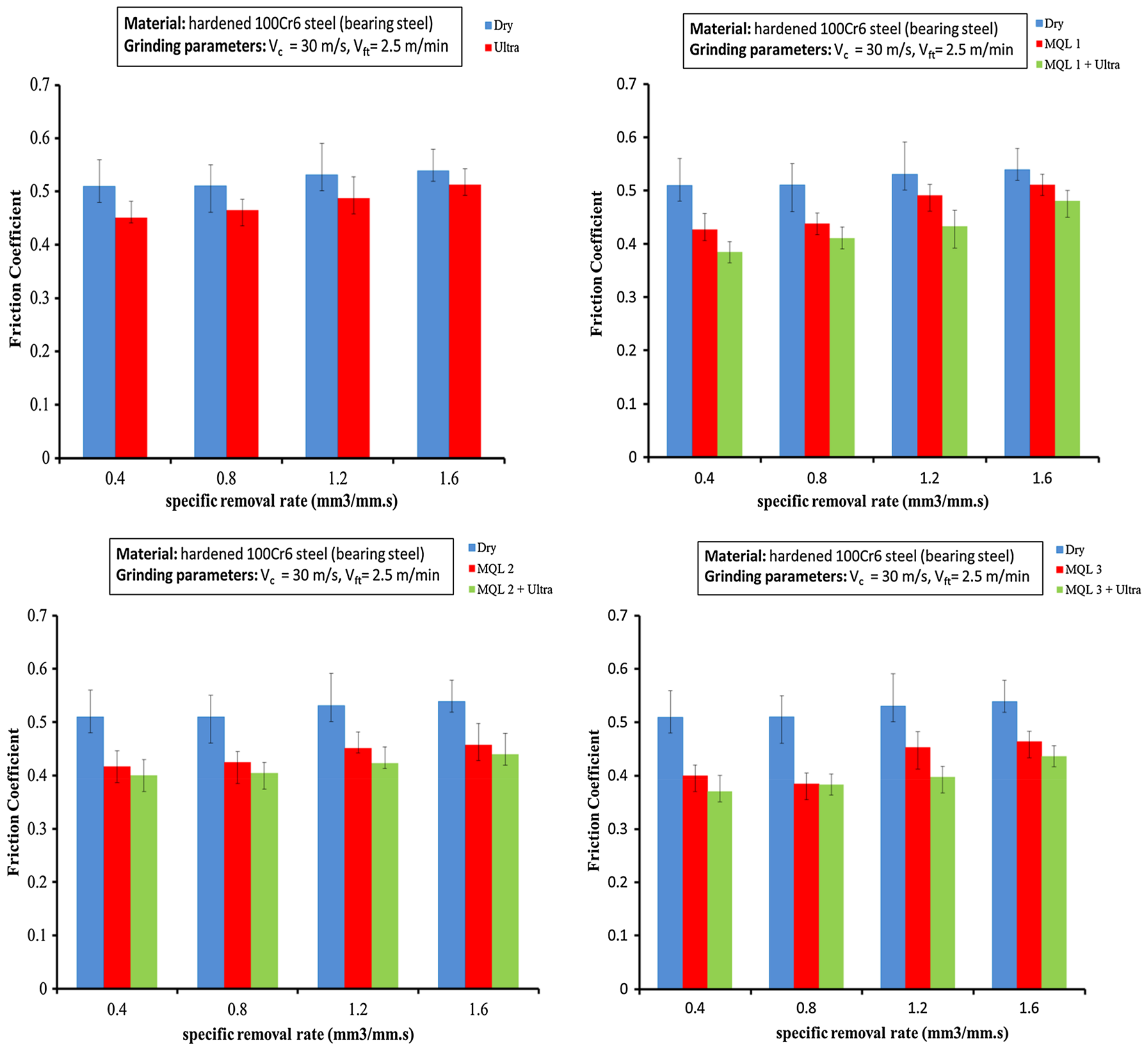

Fig. 9 Friction coefficient vs. specific removal rate for eight coolant-lubricant environment

grinding for all of the tests. This is due to effective lubrication of the abrasive grains at the grinding contact zone. Effective penetration of oil mist makes a durable lubricant tribofilm with lower shearing strength than base steel. So, it leads to decrease of cutting force by providing better sliping of the grain at the workpiece/grain interface. As durable lubricant layer has lower shearing strength, cutting force and consequently tangential force decreases. Tangential grinding force is the needed force to cut and remove chips from the workpiece. This force is the main grinding force that specifies the amount of power consumption of grinding machine (Eq. 3):

$$\mathrm{P} = F_t V_c \tag{3}$$

where P is power consumption of grinding machine, F_t is tangential grinding force and V_c is wheel speed.

The results show that MQL technique not only decreases the amount of metal cutting fluids but also decrease power consumption and tangential grinding force.

Moreover, the results show that MQL technique with MWCNTs nanofluid, Al_2O_3 nanofluid, and hybrid MWCNTs/Al_2O_3 nanofluid can reduce tangential grinding force up to 36.5, 42.3, and 46.2% in comparison to dry grinding respectively. Al_2O_3 nanofluid has better

Table 3 Friction coefficient decrease percent in comparison to dry grinding

Specific removal rates(mm^2/mm . s) Coolant-lubrication environment	0.4	0.8	1.2	1.6
UAG	11.5	8.8	8.1	4.9
MQL MWCNTs	16.4	14.25	7.5	5.3
MQL Al_2O_3	18.3	16.7	14.9	15.1
MQL MWCNTs/Al_2O_3	21.5	24.6	14.7	13.9
MQL MWCNTs + UAG	24.6	19.5	18.5	10.9
MQL Al_2O_3 + UAG	21.5	20.7	20.2	18.5
MQL MWCNTs/Al_2O_3 + UAG	27.3	24.9	25.1	19.0

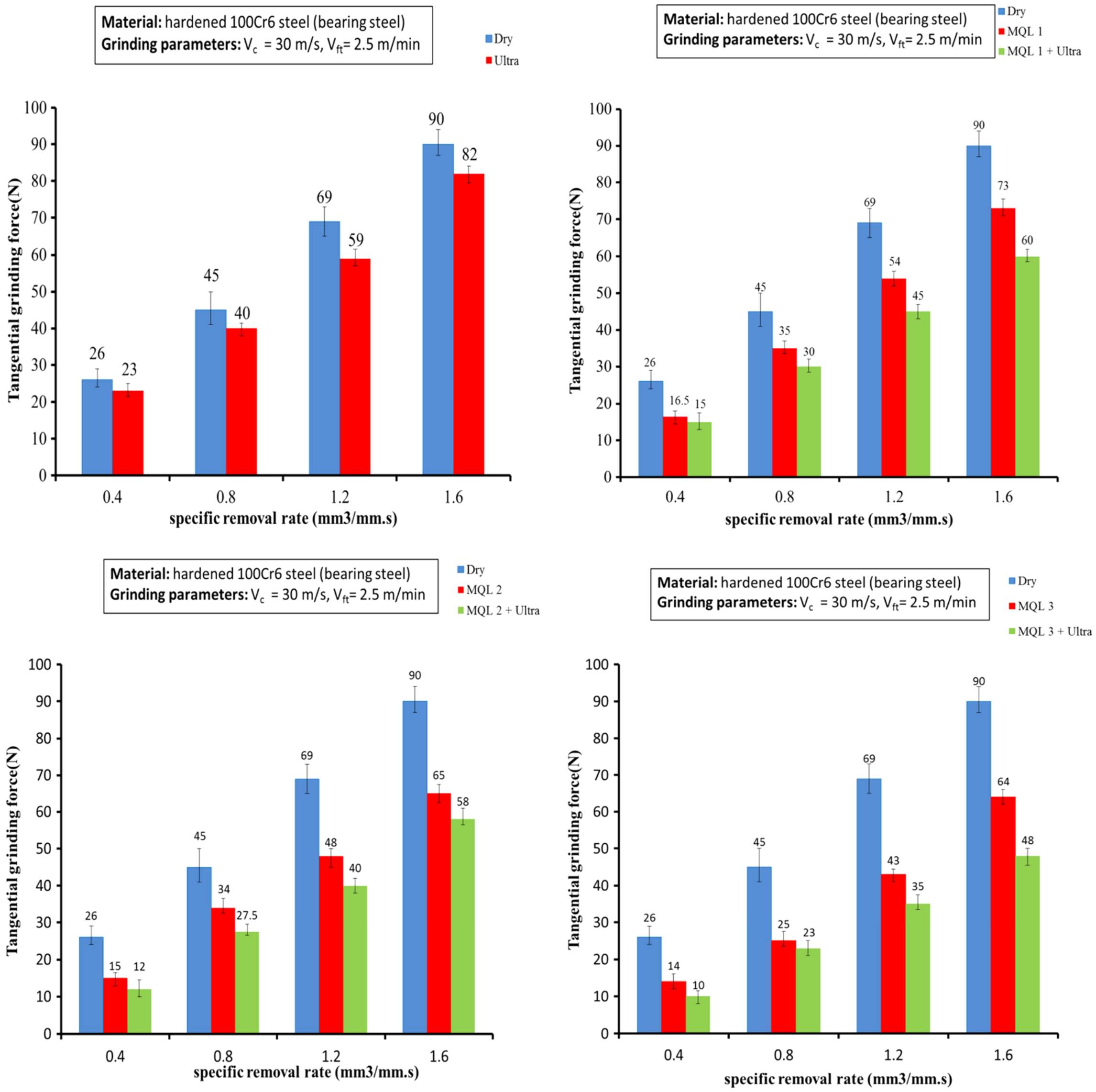

Fig. 10 Tangential grinding force vs. specific removal rate for eight coolant-lubricant environment

lubrication specification rather than MWCNTs nanofluid. So, lower tangential grinding force is achieved. It should be mentioned that MQL with nanofluid oil mist has lower tangential grinding force in comparison to UAG due to its efficient lubrication.

In UAG, periodic cutting mechanism and thinner and smaller chips decrease undesirable rubbing and plowing forces. So, total tangential grinding force decreases. Moreover, tool velocity exceeding the chip velocity produces a reversed grain/workpiece friction force thereby reducing the tangential force. These lead to decrease of 13.0, 12.5, 16.9, and 9.8% for different specific removal rates.

The combination of UAG with nanofluid MQL results in minimum tangential grinding forces. This result is up to 42.3, 53.8, and 61.5% decrease for MWCNTs nanofluid, Al_2O_3 nanofluid, and hybrid MWCNTs/Al2O3 nanofluid respectively. Different and independent coolant-lubricant mechanism of MQL technique, nanofluids, and UAG cause more effective cooling-lubrication operation that result in improvement of tangential grinding force.

4.2.2 Normal grinding force

Normal grinding force is the required force for penetration of grain to the workpiece. As shown in Fig. 11, similar results with tangential grinding force have been observed. Normal grinding force is the worst in dry grinding. The absence of heat dissipating medium has caused quick dulling of grains and cutting edges, increasing plowing and rubbing actions. It consequently has escalated the force level.

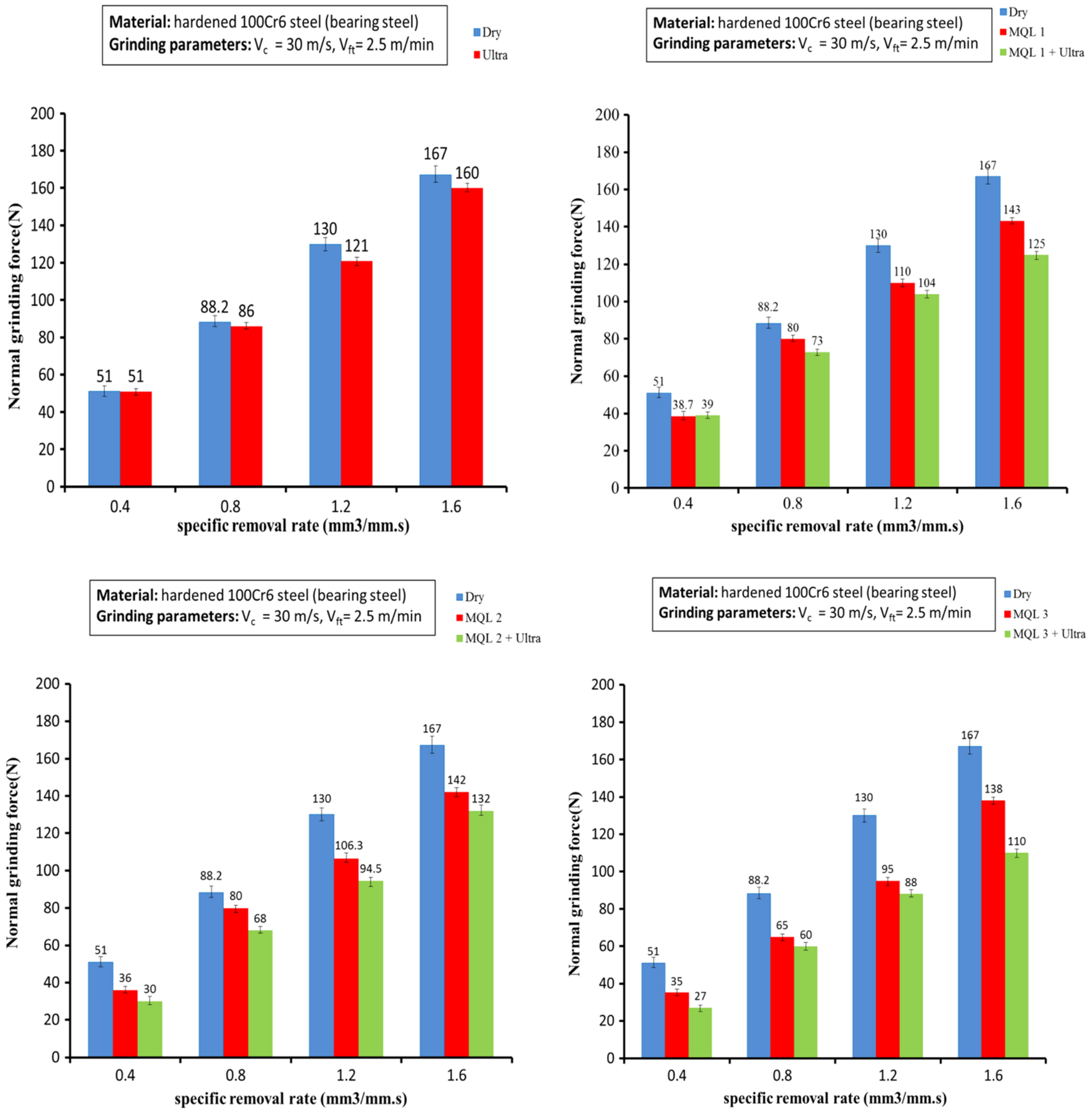

Fig. 11 Normal grinding force vs. specific removal rate for eight coolant-lubricant environments

Table 4 Tangential grinding force decrease percent in comparison to dry grinding

Specific removal rates($mm^2/mm . s$)	0.4	0.8	1.2	1.6
Coolant-lubrication environment				
UAG	13.0	12.5	16.9	9.8
MQL MWCNTs	36.5	22.2	21.7	18.9
MQL Al_2O_3	42.3	24.4	30.4	27.8
MQL MWCNTs /Al_2O_3	46.2	44.4	37.7	28.9
MQL MWCNTs + UAG	42.3	33.3	34.8	33.3
MQL Al_2O_3 + UAG	53.8	38.9	42.0	35.6
MQL MWCNTs/Al_2O_3 + UAG	61.5	48.9	49.3	46.7

Table 5 Normal grinding force decrease percent in comparison to dry grinding

Specific removal rates($mm^2/mm . s$)	0.4	0.8	1.2	1.6
Coolant-lubrication environment				
UAG	0	2.5	6.9	4.2
MQL MWCNTs	24.1	9.3	15.4	14.8
MQL Al_2O_3	43.1	16.4	18.2	23.5
MQL MWCNTs/Al_2O_3	31.4	26.3	26.9	17.4
MQL MWCNTs + UAG	23.5	17.2	20	25.1
MQL Al_2O_3 + UAG	80.7	44.9	51.4	38.9
MQL MWCNTs/Al_2O_3 + UAG	47.1	32.0	32.3	34.1

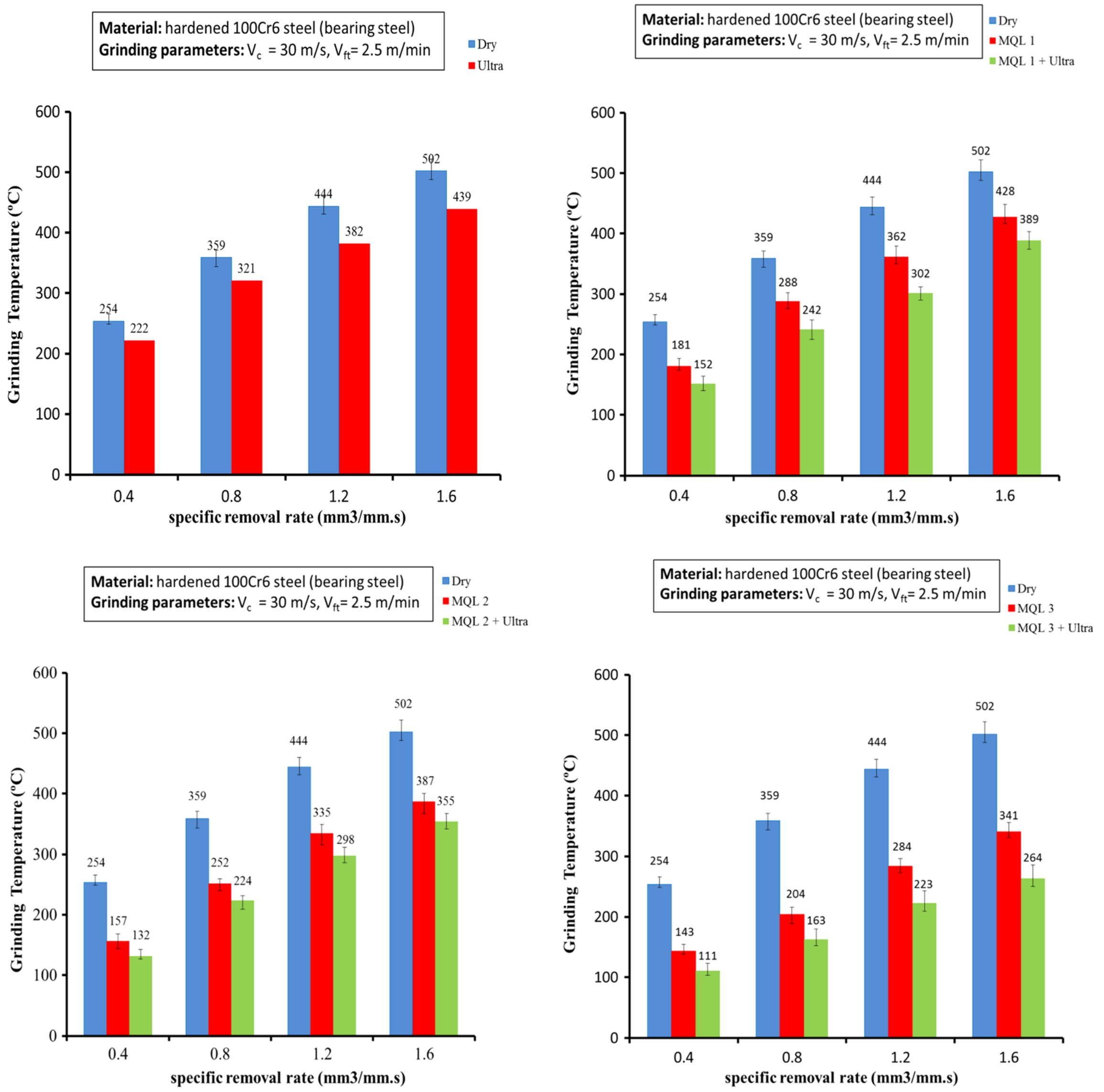

Fig. 12 Grinding temperature vs. specific removal rate for eight coolant-lubricant environments

But in the case of MQL grinding, efficient penetration of nanofluids to cutting zones results in durable lubricant tribofilm with lower shearing strength. So, penetration of grain is easier and normal grinding force is lower. Table 5 shows normal grinding force decrease percent in different specific removal rates. The results show decrease of normal grinding force in comparison to dry grinding up to 24.1, 43.1, and 43.1% in MQL grinding with, MWCNTs nanofluid, Al_2O_3 nanofluid and hybrid MWCNTs/Al_2O_3 nanofluid respectively.

Ultrasonic-assisted grinding leads to sharper cutting edges and consequently lower rubbing and plowing forces by decreasing of uncut chip thickness. In UAG grinding, normal grinding force decreases 2.5, 6.9 and 4.2% for different specific removal rates.

As expected, combination of hybrid MWCNTs/Al_2O_3 nanofluid in MQL technique with UAG has the best results (Fig. 11 and Table 5). Table 5 shows that combination of hybrid MWCNTs/Al_2O_3 nanofluid in MQL technique with UAG leads to decrease of normal grinding force up to 47.1%. Generally, decrease of normal grinding force results in improvement of surface roughness.

4.3 Temperature result

In grinding process, the average total heat flux, Q, in the contact zone can be expressed as [37]:

$$Q = \frac{F_t V_c}{b l_c} \tag{4}$$

where F_t is tangential grinding force, V_c is wheel speed, b is the width of the workpiece and l_c is the length of contact of grain with the workpiece. According to this equation, as

Table 6 Grinding temperature decrease percent in comparison to dry grinding

Specific removal rates(mm^2/mm . s)	0.16	0.32	0.48	0.60
Coolant-lubrication environment				
UAG	12.6	10.6	14.0	12.55
MQL MWCNTs	28.8	19.8	18.5	14.7
MQL Al_2O_3	38.2	29.8	24.55	22.9
MQL MWCNTs/Al_2O_3	43.7	43.2	36.0	32.1
MQL MWCNTs + UAG	40.2	32.6	32.0	22.5
MQL Al_2O_3 + UAG	48.0	37.6	32.9	29.3
MQL MWCNTs/Al_2O_3 + UAG	56.3	54.6	49.8	47.4

tangential grinding force decreases, heat flux and consequently maximum grinding temperature decreases.

In this research, the temperature was recorded by non-contact high-speed IR temperature sensor with laser marking thermometer. The response time of the infrared camera is 9 ms. So, recording of maximum temperature is possible. Figure 12 shows the maximum temperature of grinding processes in eight different coolant-lubricant environments versus specific removal rate. Maximum temperature was recorded in dry grinding in all different specific removal rates.

The results show that MQL technique with nanofluid can reduce grinding temperatures by decreasing of generated heat in cutting zone. This decrease was up to 28.8, 38.2, and 43.7% for MWCNTs, Al_2O_3 and MWCNTs/Al_2O_3 nanofluid oil mists respectively (Fig. 12, Table 6). Efficient penetration of nanofluid into cutting zone leads to the formation of a layer with lower shearing strength. So, rubbing and plowing forces and consequently tangential grinding forces decreases. Decreasing of tangential grinding force results in decrease of heat flux and grinding temperature in cutting zone (Eq. 4).

Figure 12 also shows decrease of maximum grinding temperature in UAG in all different specific removal rates. The UAG technique results in decrease of heat generated in cutting zone by decreasing of contact time between grain and workpiece.

In surface grinding operation, the cutting (contact) length (l_c) and the cutting time (t_c) of a single grit can be obtained by the following equations:

$$l_c = \sqrt{d_s \times a_e} \tag{5}$$

$$t_c = \frac{l_c}{V_c} \tag{6}$$

where d_s is the grinding wheel diameter, a_e is cutting depth. In this study, the cutting length and the cutting time are 2.83 mm and $9.4 \times 10^{-5} s$ respectively for dry grinding at $a_e = 40\ \mu m$. However, the cutting time in UAG is not equal to that in dry grinding. The period of ultrasonic vibrations is the reciprocate of the frequency and as the $f = 25 KHz$, the duration of each vibration cycle is $4 \times 10^{-5} s$. Therefore, in UAG the cutting time will be shorter than that in dry grinding and as due to Eq. (6) the cutting speed in the both cases are equal, the contact length in UADG will be reduced to 1.2 mm. As a result of reduction in the contact length in UAG, cutting temperatures and cutting forces will be reduced. On the other hand, periodic cutting edge/workpiece separation provides a gap for dissipating heat between cutting edge and workpiece. So, more efficient cooling and lubrication effects are achieved in comparison to conventional dry grinding. Furthermore, because of

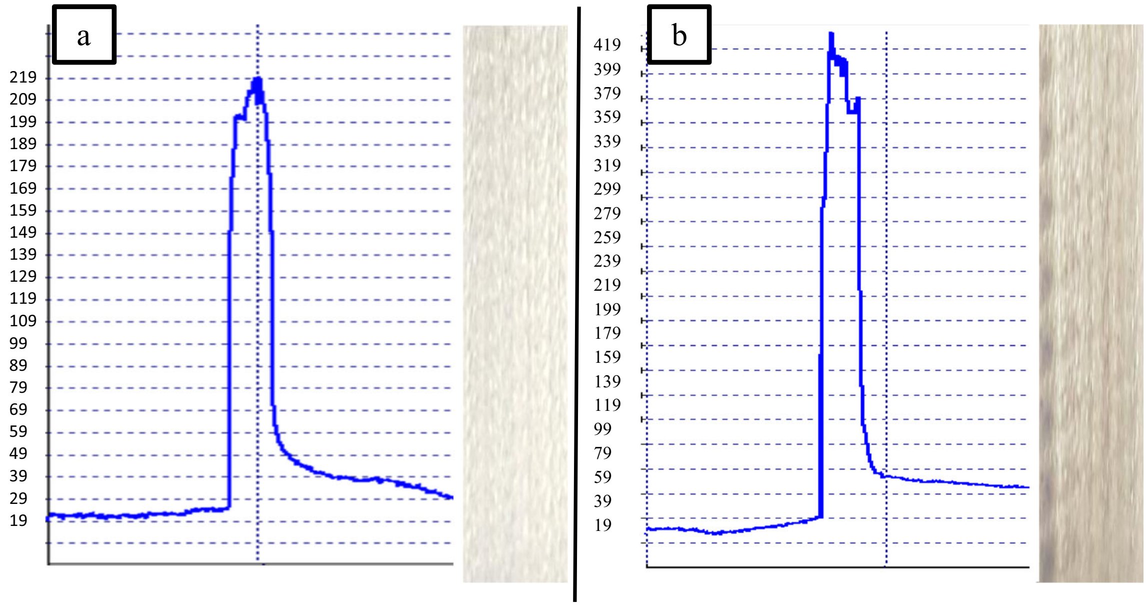

Fig. 13 Diagram of grinding temperature and corresponding grounded surface for **a** MQL 3 with UAG condition and **b** dry condition

expected lower rubbing and plowing under ultrasonic action the risk of thermal damages to the surface can be less. With regard to these effects, grinding temperature in UAG is decreased up to 14.0%.

The maximum decrease of grinding temperature was recorded in combination of nanofluid MQL with UAG. The temperature results show 40.2, 48.0, and 56.3% decreases in combinations of UAG with MWCNTs, Al_2O_3, and MWCNTs/Al_2O_3 nanofluid oil mists respectively.

Figure 13 shows the diagram of grinding temperature recorded with the infrared camera and also corresponding grounded surface. This figure clearly indicates the positive effect of hybrid MWCNTs/Al_2O_3 nanofluid MQL with UAG on grinding performance. In this research, not only utilization of hazardous cutting fluid was decreased but also by decreasing of friction coefficient, grinding forces and grinding temperature, thermal damages and burning of workpiece were decreased that can increase industrial applications of MQL technique.

5 Conclusion

MQL technique is a proper alternative to conventional coolant-lubricant environments due to its technological and economic advantages in grinding operation. It can improve general processes performance such as surface integrity, grinding forces and G-ratio. On the other hand, MQL has eco-friendly technique due to its small consumption of cutting fluid (less than 0.001 rather than conventional fluid). Despite these advantages, MQL technique has a serious thermal problem in grinding operations due to its small amount of cooling. This limitation confine of its industrial applications.

Nanofluids can increase heat transfer from workpiece/wheel interface due to its high thermal conductivity. On the other hand, ultrasonic machining can decrease heat generation due to its reciprocating mechanism and reduction of time and length of contact of grain and workpiece. So, it is anticipated that simultaneous utilization of these techniques can reduce thermal damages.

In this research MWCTNs, Al_2O_3 and hybrid MWCTNs/Al_2O_3 nanofluid oil mist are utilized in ultrasonic-assisted grinding. MWCNTs have high thermal conductivity and Al_2O_3 has good lubrication effect. The following results were observed:

Different and independent coolant-lubricant mechanism of MQL technique, nanofluids, and UAG cause more effective cooling-lubrication operation that results in improvement of friction coefficient. In this study, combination of hybrid MWCTNs/Al_2O_3 nanofluid oil mist with UAG results in maximum decreasing of friction coefficient in all the coolant-lubricant environments up to 27.3%.

The minimum amount of tangential grinding force and power consumption was recorded in combination of nano MQL and UAG. The results show 42.3, 53.8, and 61.5% decrease when using MWCTNs, Al_2O_3 and hybrid MWCTNs/Al_2O_3 nanofluid oil mist respectively.

Utilization of combination of hybrid MWCTNs/Al_2O_3 nanofluid oil mist with UAG leads to decrease of normal grinding force up to 47.1%.

The maximum decrease of grinding temperature was also observed in the combination of hybrid MWCTNs/Al_2O_3 nanofluid oil mist with UAG. The results show that grinding temperature was reduced up to 56.3% in comparison to dry grinding. The combination of hybrid MWCTNs/Al_2O_3 nanofluid oil mist with UAG decreasess grinding temperature from 254, 359, 444 and 502 °C in dry grinding to 111, 163, 223 and 264 °C, respectively.

The grounded surface in different coolant-lubricant environments clearly indicated the proper cooling and lubrication of combinations of MQL and UAG. The best quality of grounded surface was observed in the combination of hybrid Al_2O_3/MWCTNs nanofluid oil mist with UAG. There was shiny surface without any thermal damages and burning.

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