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ORIGINAL ARTICLE

Effects of nano-cutting fluids on tool performance and chip morphology during machining Inconel 718

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Abstract

Flood cooling is a typical cooling strategy used in industry to dissipate the high temperature generated during machining of Inconel 718. The use of flood coolant has risen environmental and health concerns which call for different alternatives. Minimum quaintly lubricant (MQL) has been successfully introduced as an acceptable coolant strategy; however, its potential to dissipate heat is much lower than the one achieved using flood coolant. MQL-nano-cutting fluid is one of the suggested techniques to further improve the performance of MQL particularly when machining difficult-to-cut materials. The main objective of this study is to investigate the effects of two types of nano-cutting fluids on tool performance and chip morphology during turning of Inconel 718. Multi-walled carbon nanotubes (MWCNTs) and aluminum oxide (Al_2O_3) gamma nanoparticles have been utilized as nano-additives. The novelty here lies on enhancing the MQL heat capacity using different nano-additives-based fluids in order to improve Inconel 718 machinability. In this investigation, both nano-fluids showed better results compared to the tests performed without any nano-additives. Significant changes in modes of tool wear and improvement in the intensity of wear progression have been observed when using nano-fluids. Also, the collected chips have been analyzed to understand the effects of adding nano-additives on the chip morphology. Finally, it has been found that MWCNT nano-fluid has shown better performance than Al_2O_3 nano-fluid.

Keywords Inconel 718 · Machining · Nanoparticles · Multi-walled carbon nanotubes (MCNTs) · Wear modes · Chip morphology

1 Introduction

Several studies focused on machining difficult-to-cut materials as they are associated with low productivity and high machining cost due to the excessive heat generation, difficulties in chip formation, high-temperature strength, and heat dissipation at the cutting zone in the presence of high material hardness and strength. For example, when machining of Inconel 718, the heat generated cannot be dispersed through the workpiece and chips because of its very low heat conductivity, and therefore high temperature and forces are produced during the cutting process [1–3]. In spite of the previous problems, Inconel 718 has also superior mechanical, thermal, and chemical properties (e.g., hot strength and hot hardness, high creep resistance, and chemical stability at elevated temperatures) that makes it a good choice for many applications including aerospace, automotive, oil and gas, and biomedical. Furthermore, it has unique properties such as high erosion resistivity, high thermal fatigue resistivity, high melting temperature, and resistance to thermal shock [4–7].

Flood cooling is a typical cooling strategy used in industry to reduce the high temperature generated during machining Inconel 718. The use of flood coolant raised environmental and health concerns which call for different alternatives. Thus, proposing new environmental cooling and lubricant systems is highly required especially to improve the cutting quality characteristics and achieve a sustainable machining system. Several environmentally conscious cooling and lubrication technologies during machining processes have been presented such as dry cutting, minimum quantity lubrication (MQL),

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and cryogenic technology. Eliminating the cutting fluid usage can be performed using dry cutting techniques; however, dry cutting techniques are associated with some machining difficulties such as excessive tool wear and poor surface quality [8]. Another conscious technology has been investigated in order to improve the machinability known as MQL, and the resulting mist is sprayed directly into the working zone using an optimal amount of cutting fluid with compressed air [9–12]; however, the excessive heat generation problem has not been completely solved. Also, several techniques have been discussed through the open literature to improve the machinability of difficult-to-cut materials [13]. For example, a previous work [14] used a typical rotary tool in tube-end machining to reduce the induced tool wear as only a short segment of cutting edge is engaged with the workpiece. Consequently, the proposed technique could significantly enhance the frictional behavior.

Proposing new nano-cutting fluids can contribute in facing the heat dissipation challenge during cutting processes as it offers a higher observed thermal conductivity value in comparison with the base lubricants. Additionally, it is shown that nano-cutting fluids have superior cooling properties due to their good heat extraction capabilities [15, 16]. A nano-fluid can be defined as a new fluid that results from the dispersion of metallic/non-metallic nanoparticles or nanofibers with a certain size less than 100 nm into the base cutting fluid [17]. Nano-additives can be categorized into several types which are non-metallic, mixing metallic, carbon, and ceramic nanoparticles [18].

The nano-cutting fluids have shown promising results in improving the base cutting fluid properties; however, these improvements cannot be clearly observed without applying an adequate dispersion technique. These improvements are mainly on the thermal, tribological, and rheological properties. Several studies [19–21] have focused on using nano-cutting fluids and their effects on the cutting performance characteristics, and promising results have been revealed particularly in reducing the tool wear and cutting forces. Multi-wall carbon nanotubes (MWCNTs) and Al_2O_3 nanoparticles are among the nano-additives that have superior thermal, mechanical, and tribological properties [22]; however, only a few studies have investigated their effects on different machining operations. Also, it has been found from the literature review that there is a research gap in investigating the nano-fluid effects when machining nickel-based alloys. A summary of these studies and their findings are provided in Table 1. In addition, reviewing the open literature has shown that there is no previous attempt in using MQL-MWCNT nano-fluid in enhancing the machinability of Inconel 718.

The focus of this work is mainly to investigate the effects of dispersed MWCNTs and aluminum oxide (Al_2O_3) gamma nanoparticle into vegetable oil using MQL technique during turning of Inconel 718. Investigations are carried out to study the tool wear modes and chip morphology.

Table 1 Summary for investigation of nano-cutting fluid effects on machining nickel-based alloys

Reference no.	Nano-additives type	Machining operation	Nickel alloy type	Findings
[23]	Al_2O_3 under using MQL	Turning	Inconel 600	The measured cutting force and temperature have been reduced using 6 vol.% Al_2O_3
[24]	Zinc oxide (ZnO) under using MQL	Grinding	Inconel 718	Low cutting forces, friction coefficient, and surface roughness have been observed
[25]	Hybrid nano-fluid (MoS_2 CNTs)	Grinding	GH4169	8% MoS_2 CNTs improved the surface quality and the frictional behavior
[26]	Graphene nanoplatelets under using MQL	Grinding	Inconel 718	The results show that graphene nanoplatelets lower the grinding force, temperature, and surface roughness

2 Materials and methods

In order to investigate the effects of MWCNTs and Al_2O_3 nanoparticles on the MQL performance, cutting tests were performed using different levels of feed rate, cutting speed, and weight percentages of added nano-additives. Inconel 718 (ASTM SB 637) has been utilized as the used workpiece for experimentation. Chemical composition and some other properties for Inconel 718 (ASTM SB 637) are listed in Table 2 (chemical compositions) and Table 3 (mechanical and thermal properties).

The tests were performed on a CNC lathe machine (Hass ST-10 CNC). The used depth of cut was 0.2 mm, and the information of the used cutting tool is provided in Table 4. After nine cutting passes (50 mm for each pass), the tool wear

Table 2 Inconel 718 (ASTM SB 637) chemical compositions

Inconel 718 (ASTM SB 637)
Chemical composition-wt.%: Ni 50–55%, Fe Bal, Cr 17–21%, Mo 2.8–3.3%, Ti 0.65–1.15%, Al 0.2–0.8%, Co 0.17–1%, Si 0.12–0.35%, Mn 0.07–0.35%, Cu 0.07–0.3%, C 0.03–0.08%, P 0.01–0.15%, Nb 4.75–5.5%, S 0.015%]

modes have been captured using a digital optical microscope (KEYENCE VHX-1000) at different cutting conditions. Sensitivity analysis was employed to study the significance of the cutting conditions (i.e., cutting speed and feed rate) on the process. Regarding the MQL setup, the oil-air mixture was provided by stand-alone booster system (Unist) which was installed on the machine tool. The used oil flow rate was 40 ml/h, and the applied air pressure was 0.5 MPa. In addition, ECOLUBRIC E200 was employed as a vegetable oil used for experimentation which is a cold-pressed rapeseed oil type without additives.

MWCNTs with 13–20 nm average diameter, 95% purity, 10–30 μm length, and 110 m^2/g specific surface area have been utilized to prepare the nano-cutting fluid preparations. Al_2O_3 nanoparticles properties were 20 nm size, 95% purity, and 138 m^2/g specific surface area. The desperation of MWCNTs/Al_2O_3 into the base cutting fluid was applied using an ultrasonic machine (AQUASONIC-50HT) over duration of 3 h at 60 °C followed by a stirring step using a magnetic stirrer (Hot Plate Stirrer-3073-21) for 30 min in order to ensure full dispersion of MWCNTs and Al_2O_3 nanoparticles into the base cutting fluid.

The collected chips were analyzed and the chip thickness and shape were recorded after each test. Thus, the effects of dispersed MWCNTs/Al_2O_3 nanoparticles on chip-tool interface temperature can be investigated. Also, the change in modes of tool was also recorded. Therefore, the nano-additive effects on the tool wear behavior can be easily obtained and the associated wear mechanisms can be demonstrated. The experimental setup is provided as shown in Fig. 1.

Table 3 Inconel 718 (ASTM SB 637) mechanical and thermal properties

Inconel 718 (ASTM SB 637)
Density 8193.25 kg/m^3
Young's modulus (at 23 °C) 198.57 GPa
Poisson's ratio (at 23 °C) 0.3
Tensile strength 930 MPa
Yield strength @ 0.2% offset 482 MPa
Elongation 45%
Hardness 43 Rc
Specific heat (at 23 °C) 435 J/kg °C
Thermal conductivity (at 23 °C) 11.2 W/m °C
Melting point 1350 °C

Table 4 The cutting tool information for machining Inconel 718

Inconel 718 cutting processes	
Cutting insert	Tungsten carbide CNMG 432MMH13A (ANSI)—from Sandvic Inc.
Tool holder	KENNAMETAL MCLNL-164DNC5 with clearance angle 0° and rake angle − 5°, nose radius of 0.793 mm (Honed edge)

In this investigation, three design variables were employed with three levels each (i.e., cutting speed, feed rate, and weight percentage of added nano-additives). Table 5 indicates the studied independent process parameters and their levels when machining Inconel 718. Also, L9 orthogonal array (L9OA) [27] based on the Taguchi method was implemented for the machining tests plan.

The characterization of the nano-fluid suspension stability is an important factor to ensure the nano-additive level of dispersion as well as the resulting nano-fluids thermal conductivity. Zeta potential for stability analysis was performed to characterize the nano-cutting fluids. The Zetasizer nano-device was applied to determine the zeta potential absolute values for both MWCNTs and Al_2O_3 nano-fluids. Also, sodium dodecyl sulfate (SDS) has been used as a surfactant (i.e., 0.2 g) in preparing the nano-fluids. The purpose of using surfactant is to enhance the nano-additive performance to be more hydrophilic and to increase the nano-additive surface charges which increases the nano-additive dispersion level [28, 29]. The zeta potential results for both nano-cutting fluids were in the range of moderate stability which is 30 according to the suspension stability evaluation criteria [30] (see Table 6).

The nano-fluid usage when employing flood coolant can be an environmental concern; however, when using MQL technique, an optimal amount of oil is used and it results in a very fine mist where certain procedure is followed to eliminate any concern of using the nano-additives. Also, during the experimentation phase, certain safety procedures (i.e., standard nano-additives safety data sheets) have been applied to maintain a standard health and safety level in the workshop to avoid any harmful impacts for the machine operator. Regarding the disposal method, the nano-fluids have been carefully filtered before being released to the sewer according to a standard material safety data sheet [31]. Thus, MQL nano-fluid technique offers two main advantages: (a) enhancing the machining process performance as the employed nano-additives improve the thermal and friction behavior and (b) accomplishing a sustainable process as using vegetable oils based on MQL provide effective environmental benefits.

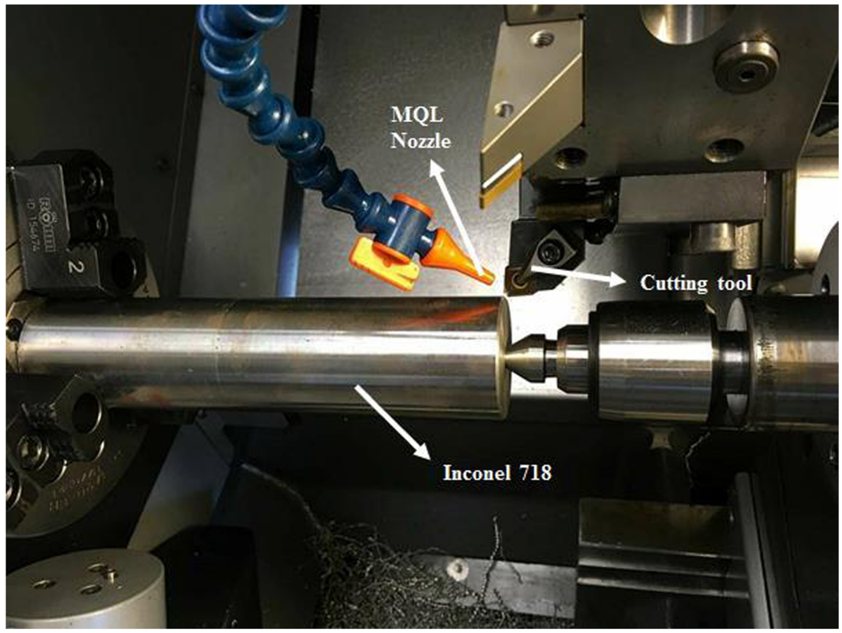

Fig. 1 Experimental setup

3 Tool wear modes investigations

The modes of tool wear and their associated wear mechanisms are presented and discussed in this section. All micrographs of worn faces were captured at the end of cutting tests. The dominant wear modes when machining under mist coolant without nano-additives were excessive flank wear, notching, built up edge (BUE), crater wear, and oxidation. Regarding the tests performed using nano-additives either using MWCNTs or Al_2O_3 nano-fluids, it was demonstrated that the dominant wear modes were flank tool wear, crater, and notching.

The employed nano-fluids (i.e., MWCNTs and Al_2O_3) showed a significant improvement in reducing the flank tool wear compared to the tests performed without nano-additives as shown in Fig. 2. Some previous studies [32, 33] confirmed that the adhesion of the material on the tool surface followed by abrasive wear mechanism (due to hard constituents in the workpiece material) is the main reason for the flank tool wear during machining Inconel 718. Thus, the observed flank wear without nano-additives (see Fig. 2b) is mainly attributed to a hybrid mechanism including both abrasive and adhesive wear. However, the employed nano-fluids improved the cooling and lubrication properties which enhance the interface bonding between the tool and workpiece surfaces and as a result, the adhesion wear severity was partially eliminated and accordingly, the flank wear has been reduced (see Fig. 2a, c).

Regarding the notching mode, it occurs at the tool nose as seen in Fig. 2b which caused by adhesion. The adhesive mechanism during machining of Inconel results due to the contact between the workpiece and cutting tool under sufficient pressure and temperature, which leads to plastic deformation in the actual contact area, and it is called cold welding phenomenon as mentioned in a previous study [34].

However, the nano-fluids offer promising performance in terms of improving the flank wear. An observed notching wear has taken place when 4 wt.% Al_2O_3 nano-fluid was employed as this cutting test was performed at a higher value of cutting speed (see Fig. 3). This result showed that MWCNT nano-fluid provides a larger improvement than Al_2O_3 nano-fluid. It could be due to the superior thermal conductivity of MWCNTs (3000 W/m K) compared to Al_2O_3 nanoparticles (35 W/m K). Also, MWCNT nano-fluid offers higher zeta potential values than Al_2O_3 nano-fluid as previously presented in Table 6 which attributes to the better improvements obtained when using MWCNTs. There is no clear physical evidence in the open literature proving that MWCNT nano-fluid offers better tribological properties than Al_2O_3. However, based on the current research results, it is claimed that MWCNT-based nano-fluid could offer better performance than Al_2O_3 as a lubricant. Also, other aspects should be considered to emphasize this point correctly. The first aspect is the nano-additive dispersion level. Also, the induced

Table 5 The levels assignment to design variable for Inconel 718 cutting processes

		Symbol	Level 1	Level 2	Level 3
Design variables	Cutting feed (mm/rev)	A	0.2	0.3	0.4
	Cutting speed (m/min)	B	40	50	60
	Nano-additives (wt.%)	C	0%	2%	4%

Table 6 Zeta potential results for both MWCNTs and Al_2O_3 nano-fluids

Nano-cutting fluid type (nano additive-wt.%)	Zeta potential absolute value
MWCNTs (2%)	31
MWCNTs (4%)	34
Al_2O_3 (2%)	29
Al_2O_3 (4%)	22

nano-additive wear [35] (tribological aspect) is an important aspect which needs to be studied and analyzed in order to justify the current results. Thus, studying and understanding the nano-cutting fluid tribological and heat transfer mechanisms is highly required.

Also, it was found that the crater wear (see Fig. 4b) was clearly noticed when pure MQL was employed (without nano-additives) at a higher value of cutting speed level (60 m/min). However, both nano-fluids showed a significant improvement in reducing the induced crater wear (see Fig. 4a. c). It is mainly because of their superior cooling and lubrication properties which face the high generated temperature. During cutting without nano-additives, the high generated temperature is intensified by cutting speed preventing the hard constituents in the workpiece material to diffuse into softer material matrix. Consequently, that leads to a chemical reactivity between the tool and workpiece. Thus, the observed crater wear when pure MQL was employed is mainly attributed to a hybrid wear mechanism including both diffusion and chemical reactivity.

The oxidation and built-up-edge wear mechanisms (see Fig. 5) have been only observed in the cutting tests performed without nano-additives. In terms of the oxidation wear mechanism which occurred at cutting speed of 50 m/min, it is mainly due to the chemical reactivity of aluminum element in the carbide tools as has been confirmed in the literature review [36]. Also, it has been investigated that oxidation wear is also attributed to a combination of high generated temperature and oxygen from the surrounding air [37]. The built-up edge phenomena has been observed at a feed rate of 0.4 mm/rev and a cutting speed of 50 m/min (without nano-additives) as shown in Fig. 5. A previous work [34] claimed that it is mainly due to the adhesive form of carbide tools which leads to the chip pressure welding on the cutting insert. Also, the range of cutting speeds used in this investigation is considered as a low cutting speed which also increased the possibility of built-up-edge formation.

It can be concluded that the employed nano-fluids offered significant improvements, it is mainly due to the promising cooling and lubrication properties which enhance the interface bonding between the tool and workpiece surfaces. In addition, the nano-fluids offer an effective heat dissipation performance which retains the cutting tool original hardness and accordingly, the continuous severe rubbing of the workpiece with the flank face was decreased as discussed in some previous studies [19, 38, 39]. Furthermore, the significant tribological properties of the resultant nano-cutting fluid reduced the coefficient of friction at the tool–chip interface as the employed nano-additives work as a spacers (see Fig. 6) to limit the induced rubbing between the cutting tool and workpiece, as discussed previously [40].

As can be seen in Fig. 6, the nano-cutting fluid is atomized into the MQL nozzle and it results in a very fine mist. Thus, the droplets of the nano-cutting fluid are formed on the workpiece and cutting tool surfaces which significantly enhances the tribological characteristics and reduces the induced friction. Also, no noticeable effect has been observed between 2 and 4 wt.% in either cases (i.e., MWCNTs and Al_2O_3) except the notching wear mode when Al_2O_3 nano-fluid was employed (using 4 wt.% only). However, both 2 and 4 wt.% have shown significant improvements in both tool wear performance and chip morphology investigations compared to test performed using classical MQL (0 wt.% of nano-additives). Thus, studying and understanding the nano-cutting fluid tribological and heat transfer mechanisms is highly required and currently under investigation to clearly investigate the nano-additive size and percentage effects on the cutting performance.

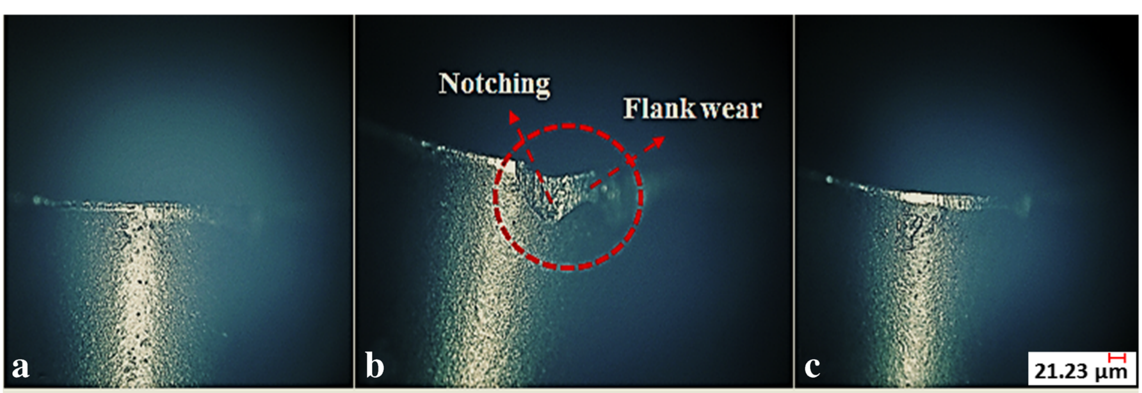

Fig. 2 The observed flank tool wear at cutting speed of 50 m/min and feed rate of 0.3 mm/rev using. **a** 4 wt.% MWCNTs nano-fluid. **b** Without nano-additives. **c** 2 wt.% Al_2O_3 nano-fluid

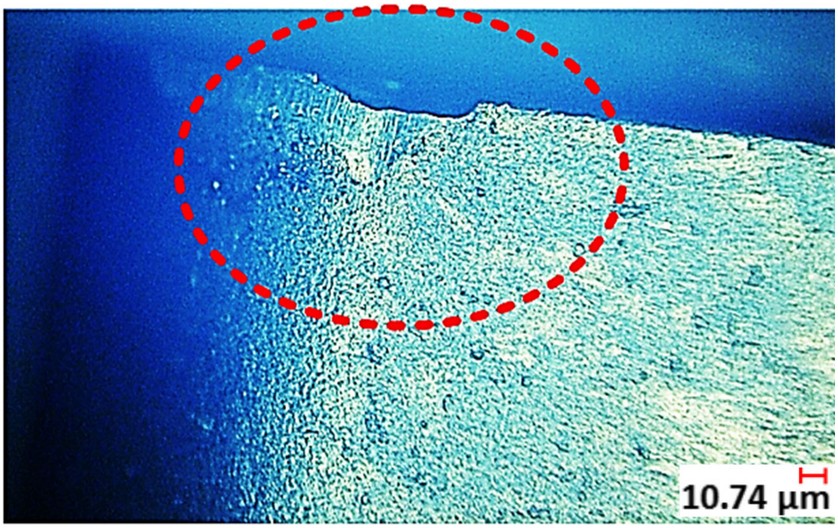

Fig. 3 The observed notching wear when using 4 wt.% Al_2O_3 nano-fluid at cutting speed of 60 m/min and feed rate of 0.3 mm/rev

4 Chip morphology examination

The chip morphology examination was carried out to provide details about the effects of dispersed MWCNTs/Al_2O_3 nanoparticles on chip–tool interface temperature. For tests performed without nano-additives, the continuous helical chips (see Fig. 7a) were generated as the material becomes much softer compared to the cutting tool material due to the high generated temperature in the cutting shear zone. Al_2O_3 nanofluid provides larger chip helix angles (θ) compared to the tests performed without nano-additives as shown in Fig. 7b. It is attributed to forming a hydrodynamic layer between the

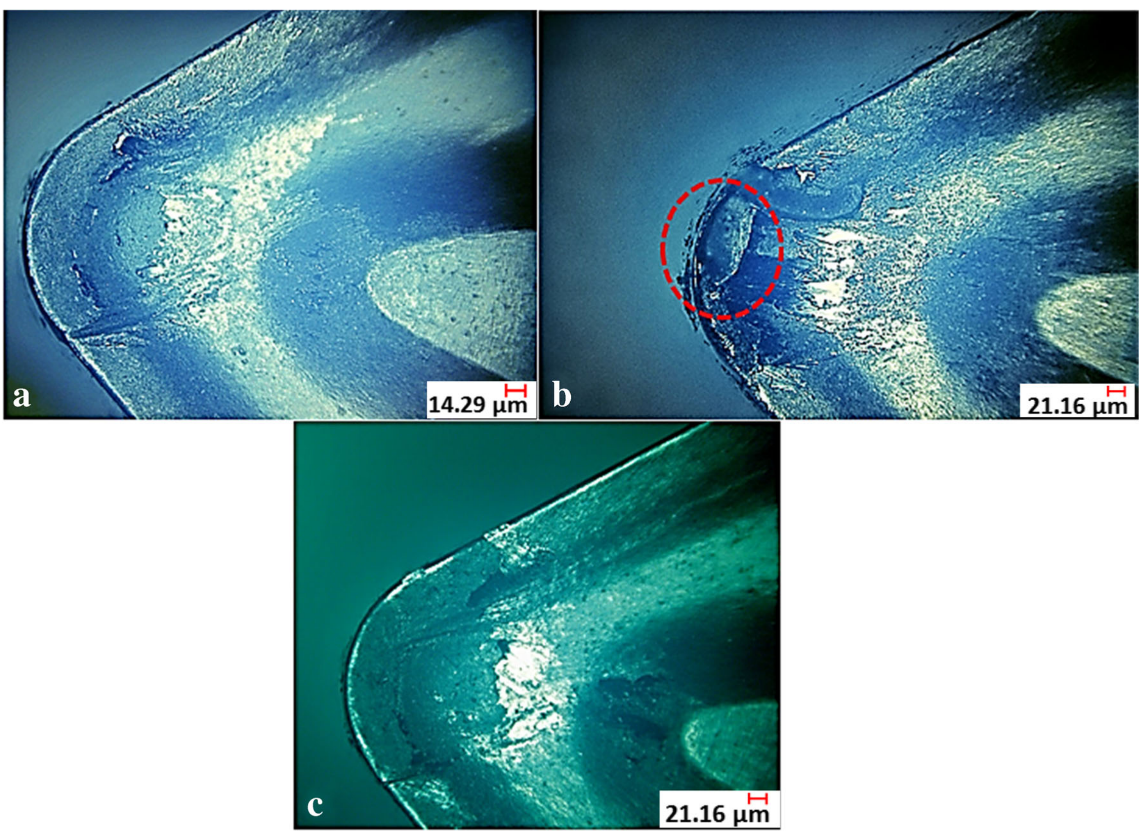

Fig. 4 The observed crater wear at cutting speed of 60 m/min and feed rate of 0.2 mm/rev. **a** 4 wt.% Al_2O_3 nano-fluid. **b** Without nano-additives. **c** 4 wt.% MWCNTs nano-fluid

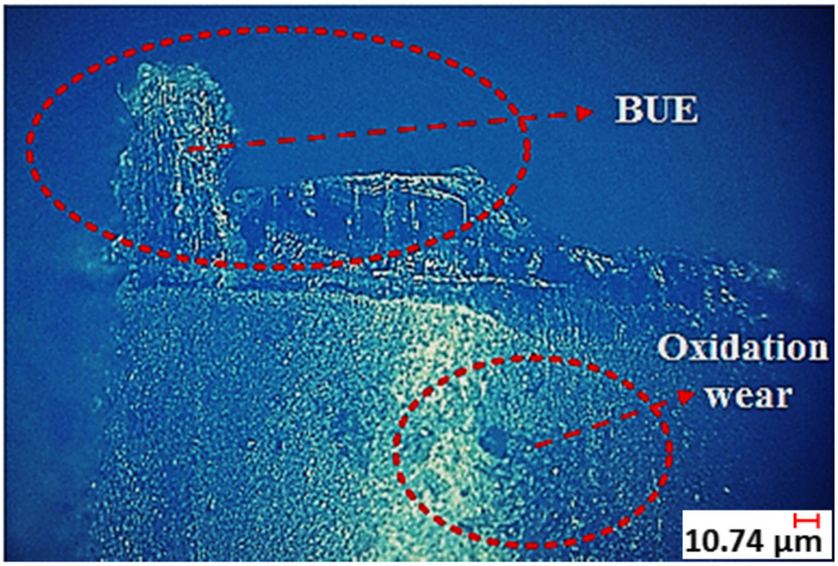

Fig. 5 The observed oxidation wear and built-up edge phenomena at cutting speed of 50 m/min without nano-additives

chip and tool rake face (see Fig. 6) [24, 38]. This hydrodynamic layer increased the chip helix angle as can be seen in Figs. 7b and 8b. The majority of tests performed using MWCNTs nano-fluid showed tiny segmented chips as shown in Fig. 7c because of the impingement of MWCNTs on the generated chips which increased the chip helix angle and forced the long chips for breaking. The schematic of the three cases is provided in Fig. 8.

The above results were confirmed with chip morphology examination revealed in a previous study [38] which applied Al_2O_3 nano-fluid during turning of AISI 4340. However, in the current study, the tiny segmented chips were observed only when MWCNTs have been employed. It is mainly due to the superior thermal properties of MWCNTs (thermal conductivity is about 3000 W/m K). Also, Inconel 718 has higher hardness and yield strength values (see Table 2) compared to AISI 4340 (i.e., yield strength of 470 MPa and hardness of 35 Rc) which accordingly prevented the occurrence of tiny segmented chips when using Al_2O_3 nano-fluid. Thus, this finding also confirms that MWCNTs have offered the best cooling and lubrication performance.

In addition, BUE-chips have been observed at a higher cutting speed (60 m/min) and feed rate of 0.3 mm/rev without nano-additives. This phenomenon takes place due to the high

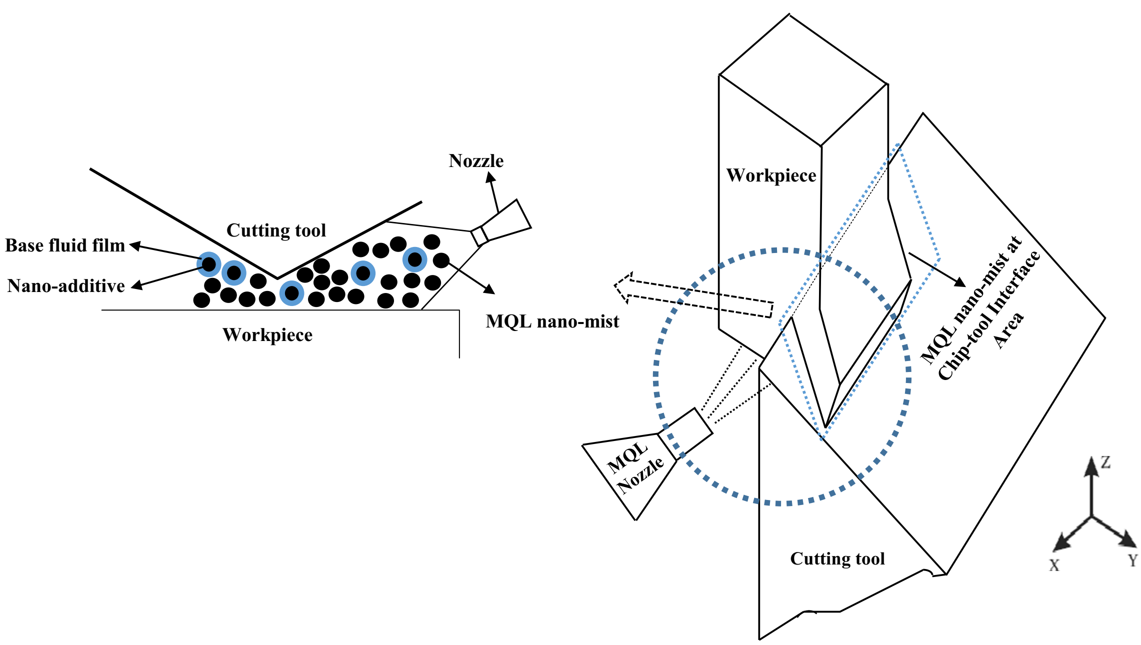

Fig. 6 MQL nano-fluid mechanism

Fig. 7 The generated chips during machining of Inconel 718 at cutting speed of 60 m/min and feed rate of 0.3 mm/rev. **a** Without nano-additives. **b** Al_2O_3 nano-fluid. **c** MWCNTs nano-fluid

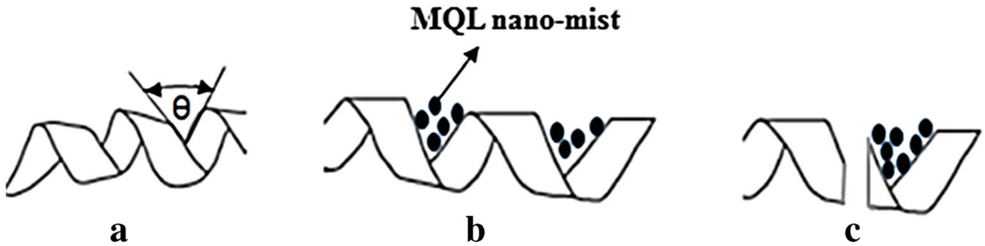

Fig. 8 Schematic of the generated chips. **a** Lower helix angle using pure MQL. **b** Larger helix angle using Al_2O_3 nano-fluid. **c** Segmented chips using MWCNTs nano-fluid

generated temperature and pressure at the tool tip (see Fig. 9a). On the other hand, no built-up edge chips were observed when either using MWCNTs or Al_2O_3 nano-fluids (see Fig. 9b) as they offer promising cooling and lubrication properties.

Also, the deformed chip thickness was measured for different cases and results were plotted at different feed rate levels as provided in Fig. 10. It can be concluded that cutting tests performed without nano-additives showed the highest chip thickness due to the chip welding tendency to the top surface layers of the tool rake face. Based on the results provided in Fig. 10, lower deformed chip thickness has been obtained using both nano-fluids. The chip thickness reduction would lead to shorter shear plane and larger shear angle [41]. Thus, lower cutting force [42] and induced friction coefficient [43] would occur as similarly discussed in previous studies. Furthermore, the chip breakability mechanism would be enhanced [44]. For MWCNTs tests, it was shown that 4 wt.% provided lower deformed chip thickness than 2 wt.%. However, 2 wt.% Al_2O_3 nano-fluid offered better performance than 4 wt.%. Thus, studying the MQL nano-fluid heat transfer and tribological mechanisms is currently under investigation to obtain the nano-additive percentage and size effects on the cutting process performance. In general, the chip morphology investigation showed nano-fluid cooling and lubrication significantly improve the Inconel 718 machinability. Finally, this work can be extended by offering a comparative performance analysis of some other nano-cutting fluids (e.g., titanium oxide (TiO_2), copper oxide (CuO), and silicon carbide (SiC) nanoparticles). This comparative analysis will be based on investigating these nano-fluid effects on the generated cutting temperature, coefficient of friction, and cutting forces during machining Inconel 718.

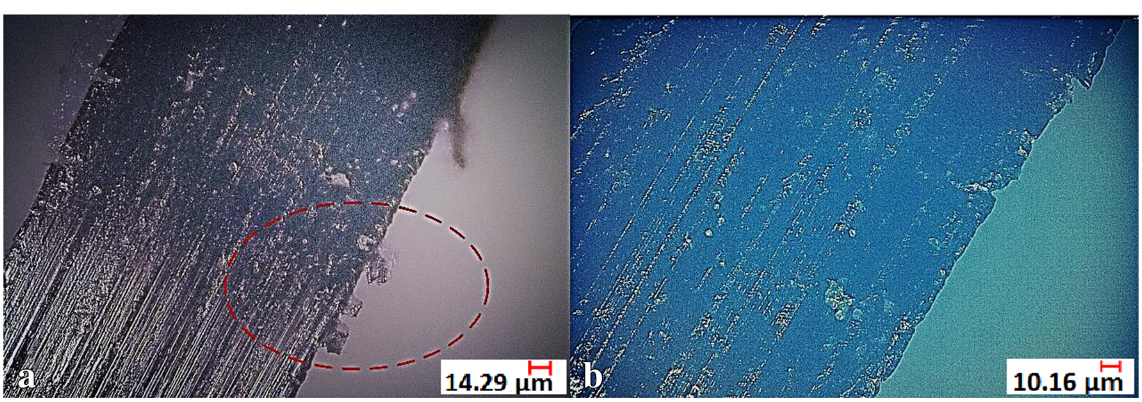

Fig. 9 Micrographs of BUE effects on the generated chips at cutting speed of 60 m/min and feed rate of 0.3 mm/rev. **a** Without nano-additives. **b** Under MWCNTs nano-fluid

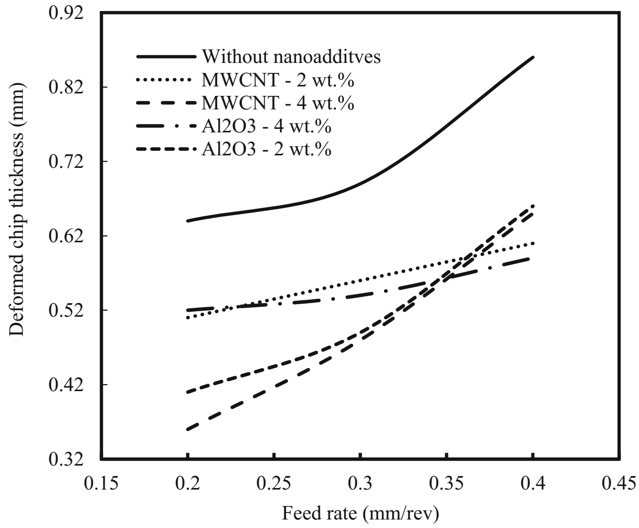

Fig. 10 Effect of feed rate on chip thickness during machining of Inconel 718 with/without nano-fluids

5 Summary

In this work, MWCNTs and Al_2O_3 nano-fluids have been used to enhance the MQL cooling and lubrication capabilities during machining of Inconel 718. The tests have been carried out to study the effects of the employed nano-fluids on the tool performance and chip morphology. The dominant wear modes noticed when cutting without nano-additives were excessive flank wear, notching, built-up edge, crater wear, and oxidation. Both MWCNTs and Al_2O_3 nano-fluids have shown promising results in enhancing the cutting tool performance. It is mainly attributed to the superior cooling and lubrication properties which enhance the interface bonding between the tool and workpiece surfaces. Lower deformed chip thickness has been observed, when nano-fluids are used, which is attributed to the increase in the shear angle. Consequently, lower cutting forces are generated due to the increase in the shear angle and effective dissipation of heat which prevents the chip welding tendency while cutting without nano-additives. The study demonstrated better cutting performance when both nano-fluids have been employed, and MWCNTs offered better results than Al_2O_3. Thus, studying and analyzing the MQL nano-fluid tribological and heat transfer mechanisms is essential to clarify the functions and effects for both nanoparticles and nanotube scenarios. Also, more investigations are still required to obtain the nano-additive size and percentage effects on the cutting process performance.

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References

1. Miller S (1995) Advanced materials mean advanced engines. Interdiscip Sci Rev 20(4):117–129
2. Davim JP (2011) Machining of hard materials. Springer Science & Business Media Verlag London
3. Gupta MK, Sood PK, Singh G, Sharma VS (2017) Experimental investigation and optimization on MQL-assisted turning of Inconel-718 super alloy. In: Advanced manufacturing technologies. Springer, Cham, pp 237–248
4. Wang ZY, Rajurkar KP, Fan J, Lei S, Shin YC, Petrescu G (2003) Hybrid machining of Inconel 718. Int J Mach Tools Manuf 43(13): 1391–1396
5. Alauddin MM, Mazid MA, El Baradi MA, Hashmi MSJ (1998) Cutting forces in the end milling of Inconel 718. J Mater Process Technol 77(1–3):153–159
6. Dudzinski D, Devillez A, Moufki A, Larrouquere D, Zerrouki V, Vigneau J (2004) A review of developments towards dry and high speed machining of Inconel 718 alloy. Int J Mach Tools Manuf 44(4):439–456
7. Kadam GS, Pawade RS (2017) Surface integrity and sustainability assessment in high-speed machining of Inconel 718—an eco-friendly green approach. J Clean Prod 147:273–283
8. Klocke F, Eisenblätter G (1997) Dry cutting. CIRP Ann Manuf Technol 46(2):519–526
9. Kamata Y, Obikawa T (2007) High speed MQL finish-turning of Inconel 718 with different coated tools. J Mater Process Technol 192:281–286
10. Cabanettes F, Faverjon P, Sova A, Dumont F, Rech J (2017) MQL machining: from mist generation to tribological behavior of different oils. Int J Adv Manuf Technol 90(1–4):1119–1130
11. Kaynak Y (2014) Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining. Int J Adv Manuf Technol 72(5–8):919–933
12. Sadeghi MH, Haddad MJ, Tawakoli T, Emami M (2009) Minimal quantity lubrication-MQL in grinding of Ti–6Al–4V titanium alloy. Int J Adv Manuf Technol 44(5–6):487–500
13. Kishawy H (2002) An experimental evaluation of cutting temperatures during high speed machining of hardened D2 tool steel
14. Kishawy H, Li L, El-Wahab A (2006) Prediction of chip flow direction during machining with self-propelled rotary tools. Int J Mach Tools Manuf 46(12):1680–1688
15. Srikant RR, Rao DN, Subrahmanyam MS, Krishna VP (2009) Applicability of cutting fluids with nanoparticle inclusion as coolants in machining. Proc Inst Mech Eng Part J J Eng Tribol 223(2): 221–225
16. Li B, Li C, Zhang Y, Wang Y, Jia D, Yang M, Zhang N, Wu Q, Han Z, Sun K (2017) Heat transfer performance of MQL grinding with different nanofluids for Ni-based alloys using vegetable oil. J Clean Prod 154:1–11
17. Ghadimi A, Saidur R, Metselaar H (2011) A review of nanofluid stability properties and characterization in stationary conditions. Int J Heat Mass Transf 54(17):4051–4068
18. Daungthongsuk W, Wongwises S (2007) A critical review of convective heat transfer of nanofluids. Renew Sust Energ Rev 11(5): 797–817
19. Sharma AK, Tiwari AK, Dixit AR (2015) Progress of nanofluid application in machining: a review. Mater Manuf Process 30(7): 813–828
20. Sharma AK, Tiwari AK, Dixit AR (2016) Effects of minimum quantity lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: a comprehensive review. J Clean Prod 127:1–18

21. Su Y, Gong L, Li B, Liu Z, Chen D (2016) Performance evaluation of nanofluid MQL with vegetable-based oil and ester oil as base fluids in turning. Int J Adv Manuf Technol 83(9–12):2083–2089
22. Nanomaterials, U.R., US Research Nanomaterials, Inc, The advanced nanomaterials provider. US Research Nanomaterials
23. Vasu V, Pradeep Kumar Reddy G (2011) Effect of minimum quantity lubrication with Al2O3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy. Proc Inst Mech Eng Part N J Nanoeng Nanosyst 225(1):3–16
24. Sinha MK, Madarkar R, Ghosh S, Rao PV (2017) Application of eco-friendly nanofluids during grinding of Inconel 718 through small quantity lubrication. J Clean Prod 141:1359–1375
25. Zhang Y, Li C, Jia D, Li B, Wang Y, Yang M, Hou Y, Zhang X (2016) Experimental study on the effect of nanoparticle concentration on the lubricating property of nanofluids for MQL grinding of Ni-based alloy. J Mater Process Technol 232:100–115
26. Pavan RB, Venu Gopal A, Amrita M, Goriparthi BK (2017) Experimental investigation of graphene nanoplatelets–based minimum quantity lubrication in grinding Inconel 718. Proc Inst Mech Eng B J Eng Manuf, 0954405417728311
27. Phadke M (1998) Quality engineering using design of experiments, quality control, robust design, and the Taguchi method. Wadsworth, Los Angeles
28. Hwang YJ, Lee JK, Lee CH, Jung YM, Cheong SI, Lee CG et al (2007) Stability and thermal conductivity characteristics of nanofluids. Thermochim Acta 455(1–2):70–74
29. Huang J, Wang X, Long Q, Wen X, Zhou Y, Li L (2009) Influence of pH on the stability characteristics of nanofluids. In Photonics and optoelectronics, 2009. SOPO 2009. Symposium on (pp. 1-4). IEEE
30. Vandsburger L (2010) Synthesis and covalent surface modification of carbon nanotubes for preparation of stabilized nanofluid suspensions. Library and Archives Canada= Bibliothèque et Archives Canada
31. Loos M (2014) Carbon nanotube reinforced composites: CNT polymer science and technology. Elsevier
32. El-Bestawi MA, El-Wardany TI, Yan D, Tan M (1993) Performance of whisker-reinforced ceramic tools in milling nickel-based superalloy. CIRP Ann-Manuf Technol 42(1):99–102
33. Bhatt A, Attia H, Vargas R, Thomson V (2010) Wear mechanisms of WC coated and uncoated tools in finish turning of Inconel 718. Tribol Int 43(5–6):1113–1121
34. Zhu D, Zhang X, Ding H (2013) Tool wear characteristics in machining of nickel-based superalloys. Int J Mach Tools Manuf 64: 60–77
35. Ghaednia H, Jackson RL (2013) The effect of nanoparticles on the real area of contact, friction, and wear. J Tribol 135(4):041603
36. Winer WO, Peterson MB (1980) Wear control handbook.: American society of mechanical engineers
37. Sayit E, Aslantas K, Çiçek A (2009) Tool wear mechanism in interrupted cutting conditions. Mater Manuf Process 24(4): 476–483
38. Khandekar S, Sankar MR, Agnihotri V, Ramkumar J (2012) Nano-cutting fluid for enhancement of metal cutting performance. Mater Manuf Process 27(9):963–967
39. Paul S, Singh AK, Ghosh A (2017) Grinding of Ti-6Al-4V under small quantity cooling lubrication environment using alumina and MWCNT nanofluids. Mater Manuf Process 32(6):608–615
40. Sayuti M, Sarhan AA, Tanaka T, Hamdi M, Saito Y (2013) Cutting force reduction and surface quality improvement in machining of aerospace duralumin AL-2017-T4 using carbon onion nanolubrication system. Int J Adv Manuf Technol 65(9–12): 1493–1500
41. Stanford M, Lister PM, Morgan C, Kibble KA (2009) Investigation into the use of gaseous and liquid nitrogen as a cutting fluid when turning BS 970-80A15 (En32b) plain carbon steel using WC–Co uncoated tooling. J Mater Process Technol 209(2):961–972
42. Suresh R, Basavarajappa S, Gaitonde VN, Samuel GL (2012) Machinability investigations on hardened AISI 4340 steel using coated carbide insert. Int J Refract Met Hard Mater 33:75–86
43. Hong SY, Ding Y, Jeong W-c (2001) Friction and cutting forces in cryogenic machining of Ti–6Al–4V. Int J Mach Tools Manuf 41(15):2271–2285
44. Jerold BD, Kumar MP (2011) Experimental investigation of turning AISI 1045 steel using cryogenic carbon dioxide as the cutting fluid. J Manuf Process 13(2):113–119