ORIGINAL ARTICLE

Influence of nanoparticle concentration in nanofluid MQL on cutting forces, tool wear, chip morphology when milling of Inconel 718

Abdelkrem Eltaggaz[1] · Shafahat Ali[1] · Kashish Badwal[1] · Ibrahim Deiab[1]

Abstract

Nanofluid minimum quantity lubrication (NFMQL) has been gaining popularity as a means of improving superalloy machinability and resolving health-related and environmental issues caused by conventional cutting fluids. In this study, Inconel 718 was machined with vegetable oil-based MQL containing varying weights of Al_2O_3 (aluminum oxide) nanoparticles. Tool wear, cutting forces, chip morphology, and average surface roughness were investigated in relation to the feed rate, the cutting speed, and the machining environment. The outcome indicates that surface roughness and cutting forces are improved by approximately 30% and 25%, respectively, when using 4 weight percentage (wt%) nanoparticles in MQL compared to the pure MQL (0 wt%). The present study also investigated various factors associated with chip morphology, such as peak, pitch, and valleys, which affect machining performance. It was found that 4 wt% NFMQL resulted in significant improvements in chip morphology. Furthermore, the chip morphology and tool wear were examined under various cutting conditions in this study, and nanoparticles at 4 wt% showed optimal results.

Keywords NFMQL · Milling · Inconel 718 super alloys · Chip morphology

1 Introduction

Inconel 718 is a high mechanical property, nickel-based superalloy used extensively in aviation, automotive, petrochemical, nuclear power generation, and biomedical industries. In an aircraft engine, nickel-based alloys account for approximately 50% of the parts, such as gas turbine rotors, heat shields, blades, heat exchangers, aerospace liners, piping, bolts, and discs [1, 2]. Its exceptional properties, such as a high strength-to-weight ratio, an ability to operate at elevated temperatures, improved corrosion resistance, high fracture toughness, and fatigue strength, have made Inconel 718 a desirable material popularly employed in various manufacturing industries [3]. However, properties like rapid strain hardening, poor thermal conductivity, and the inability to prevent adherence to the surface of the tool at higher speeds have reduced the machinability rating of these alloys. The negative characteristics causing low machinability are a product of heat generation, which is caused not only by high force of friction between the workpiece and tool but also by the conversion of energy expended on chip plastic deformation into heat.

Excessive heat input while machining can cause several issues associated with the austenite-to-martensite transition. This in turn can result in the introduction of mechanical strain and residual stresses into the work material [4]. These problems lead to high machining costs and a decrease in the overall productivity. An alternative technique for reducing cutting temperatures during machining operations is nanofluid minimum quantity lubrication (NFMQL) that improves cooling performance and increases heat transfer area.

The use of NFMQL can enhance the lubrication performance of cutting fluids and reduce the friction force, thereby decreasing the wear of the cutting tool [5, 6]. Muhammad Ahsan ul Haq et al. [7] explored the effect of nanofluid MQL during the machining of Inconel 718. The researchers investigated the effects of nanofluid MQL on energy consumption, tool wear, surface roughness, and cutting forces compared to MQL machining. Comparatively to pure MQL, using the nanofluid MQL improved the surface finish by almost 20% and reduced the cutting temperature and cut power by approximately 15% and 13%, respectively.

✉ Shafahat Ali
  Shafahat@uoguelph.ca

[1] Advanced Manufacturing Lab (AML), School of Engineering, University of Guelph, Guelph, Ontario, Canada

The nanoparticles in the NFMQL fluid can also enhance the heat dissipation capability of the nanofluid, resulting in better cooling and lubricant efficiency [8]. An investigation by Yin et al. [9] on a nanoparticle MQL showed that it improved the efficiency of the lubricant, resulting in a reduction in the cutting force required during the machining operation. Pereira et al. [10] found that ECO-350 recycled oil increased the life of the tool by up to 30% compared to canola oil when testing the rheological characteristics of these oils for MQL-based machining. Sen et al. [11] demonstrated that the effectiveness of a nanofluid MQL containing Al_2O_3 and palm oil improved the machining performance of Inconel. Further research conducted by Gunan et al. [12] confirmed the effectiveness of NFMQL as it reduced the flank wear and minimized the microhardness of Inconel X-750. Amrit et al. [13] examined the impact of nanographene mixed with vegetable oil on the drilling of AISI 321 and found that thrust forces, coefficients of friction, and surface roughness were improved. A similar study was conducted on the AISI 420 in conjunction with graphene nanofluid, and the results were similar [14].

Studies have investigated the impact of using various types of nanoparticles as well as different amounts of nanoparticle concentrations in MQL lubricants. Bai et al. [15] explored the effects of different types and concentrations of nanoparticles in the NFMQL cutting fluid. As performance parameters, these researchers considered tool wear, forces, temperature, and surface roughness. Nanoparticles of alumina were found to reduce both the force and the amount of wear. Using titanium dioxide, however, improved the surface roughness. Wang et al. [16] investigated various types of NFMQL lubricants including MoS2, Al_2O_3, and pure palm oil on several materials, such as ductile cast iron , Inconel 718, and AISI 1045 steel in the grinding process. It was shown that lubricants including Al_2O_3 performed better than Mos2 and pure palm oil in reducing the cutting forces and specific grinding energy. Similarly, Senol et al. [17] investigated the nickel alloy's performance under different conditions. They determined that the hBN-mixed nanofluid MQL performed the most efficiently based on surface roughness, cutting forces, and temperature. A similar result was obtained when hBN nanofluid MQL was used for machining nickel alloy Inconel 625 [18].

The fluids and lubricants used in the machining process serve to dissipate the generated heat at the interface between the tool and the workpiece. It is important to note, however, that some cutting fluids may cause skin and respiratory disorders in operators. There has been a reduction in or elimination of the use of harmful cutting fluids in the machining process in recent years. It is for this reason that scholars have been developing alternative solutions to fluids and lubricants. Minimum quantity lubrication coolants have an edge over flood fluids or lubricant usage. The MQL has proved to be a promising cooling approach to enhance the surface quality, reduce the cost, and have less impact on the environment. Nouzil et al. [19] conducted a comprehensive review discussing the different nanoparticles available in machining, both in vivo and vitro. In this study, the lubricating properties, heat dissipation capabilities, and potential toxicity to both humans and the environment were examined. This review concluded that NFMQL significantly enhanced performance of machining by reducing heat generation, cutting forces, and tool wear while improving surface quality. However, nanoparticles are potentially toxic, a concern that warrants further investigation. To mitigate the risks associated with nanoparticles, it is important to understand their toxicity and develop methods for handling and disposing of them properly.

Adding nanoparticles to MQL-based vegetable oil has proven to be a favorable methodology to improve thermal conductivity, surface quality and machining performance. Khanafer et al. [20] performed a numerical investigation using MQL-based nanofluids in an Inconel turning process to determine the heat transfer and flow characteristics of the nanofluid. Nanofluids exhibit high thermal conductivity. This led to better heat dissipation and lower temperatures because of the improved thermal conductivity. This was validated by evaluating the CFD results with the experimental results, which showed an error rate of less than 10.

Many studies have investigated chip morphology under cryogenic CO_2 and MQL conditions. Chip morphology has been improved using MQL when compared to dry machining [21]. An analysis was carried out to examine the wear characteristics of the tools and the chip morphology of hardened 718-Inconel in high-speed milling under cryogenic CO_2 and dry conditions. The morphology of the chips differed significantly between both conditions. Dry machining resulted in greater plastic deformation, as evidenced by the presence of long, continuous chips. Conversely, cryogenic chips have a shorter and segmented shape, which would indicate a lower degree of plastic deformation [22]. Compared to sunflower oil on its own, the thermo-physical and tribological properties of graphene-reinforced sunflower oil are improved. Consequently, friction and wear are reduced when Inconel 718 is machined. Through this enhancement, the machining processes become more efficient, tool wear is reduced, and the life of the machine components is extended [23]. This review examined the effect of machining diverse alloys using nanofluids under the conditions of MQL. There is lack of research in the literature which talks about the chip morphology of the material while machining different materials [24]. In a further study, cryogenic cooling, MQL, and CryoMQL cooling methods were evaluated for their effect on chip morphology, tool wear, surface roughness, and topography and during the machining of Inconel alloy 625.It was found that CryoMQL produced the best results for

Table 1 Chemical composition of Inconel 718

Element	Ni	Cr	Fe	Nb	Mo	Al	Si	Mn	Ti	C
% weight	53.4	18.6	18.5	5.0	3.1	0.40	0.30	0.20	0.9	0.04

parameters related to performance, such as chip morphology and tool wear [25, 26].

Based on the findings of the research, most researchers are engaged with tool wear and surface integrity during Inconel 718 machining. To reduce tool wear, improve tool durability, and enhance the surface quality of a machined surface, including lubrication and cooling, possible solutions have been proposed. Despite this, not enough work has focused on an analysis of the chip morphology. Due to the accumulation of heat and friction forces at the chip-tool interface, this type of analysis becomes especially important during the machining of Inconel 718 alloy. Therefore, the present article examines the morphology of chips during the machining of an Inconel 718 alloy. Furthermore, exploration morphology of chips is an important part of tool wear analysis because when chips slide over the tool face, they cause heat, abrasion, and build up edge (BUE). Despite this, there have been few studies that analyze chip morphology and tool wear in a comprehensive manner.

2 Methodology

2.1 Workpiece, cutting tool, and experimental setup details

In this experimental investigation, trials were executed using a HAAS VF-2 vertical milling CNC machine. A rectangular block of Inconel 718 with dimensions of L×W×H is 76 × 63.5 × 38.1 mm was used as the work material. Table 1 illustrates the chemical composition of the workpiece. Contaminants, like oil, grease, and dust, were removed from the face of the workpiece using acetone prior to machining. This was done in order to prevent oxidation and damage to the surface quality by preventing formation of scales facilitated by the entry of foreign particles on the surface. A face-end mill consisting of three rhombic-shaped carbide PVD TiAlN-coated inserts having a grade composition of TiC and TiAlN is used with 1 in diameter in the machining experiments. Figure 1 illustrates the experimental setup.

In this study, cutting speed, feed rate, and weight percentage (wt%) of addition nanoparticles in the cutting fluid were chosen as the three process parameters. The parameters selected along with their levels are presented in Table 2. Several previous experimental studies were used as a basis for selecting the cutting parameters.

The design matrix created to investigate the effect of the machining parameters on various machinability
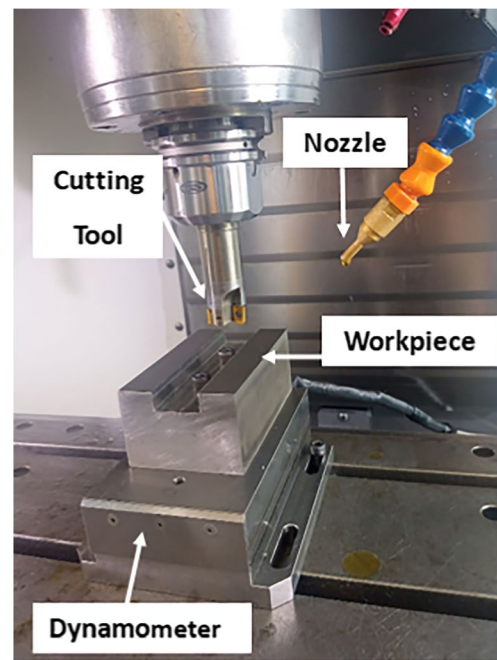
Fig. 1 Kistler's 9257A piezoelectric dynamometer

Table 2 Selected parameters with their levels.

Cutting Parameters	Level 1	Level 2	Level 3
Cutting speed	100 m/min	150 m/min	200 m/min
Feed	0.1 mm/rev	0.15 mm/rev	-
Percentage of nanoparticles	0% N MQL	2% N MQL	4% N MQL

characteristics is shown in Table 3. An array of L18 has been used for the design of the experiment in this study. The depth of cut was constant for the experimentation at 0.5 mm.

2.2 Preparation of nanofluid

The mist mixture was generated from a stand-alone booster system (Eco-Lubric), which provided fluid flow rates of 60 ml/h and air pressures of 0.5 MPa. The cutting fluid was also formulated with the vegetable oil ECOLUBRIC E200. Used rapeseed oil is environmentally safe, suitable for industrial applications, and biodegradable within 28 days with a 90% rate of degradation. Alumina oxide (Al_2O_3) nanoparticles with a diameter of 18 nm, 93% purity, and 138 m2/g specific surface were used to prepare the NMQL fluid. The Al_2O_3 nanoparticles were added to the lubricating fluid with

Table 3 Design of the experiment

Run no.	Machining condition	Cutting speed (m/min)	Feed (mm/rev)
1	0% N MQL	100	0.1
2	0% N MQL	100	0.15
3	0% N MQL	150	0.1
4	0% N MQL	150	0.15
5	0% N MQL	200	0.1
6	0% N MQL	200	0.15
7	2% N MQL	100	0.1
8	2% N MQL	100	0.15
9	2% N MQL	150	0.1
10	2% N MQL	150	0.15
11	2% N MQL	200	0.1
12	2% N MQL	200	0.15
13	4% N MQL	100	0.1
14	4% N MQL	100	0.15
15	4% N MQL	150	0.1
16	4% N MQL	150	0.15
17	4% N MQL	200	0.1
18	4% N MQL	200	0.15

filler weight fractions of 0 wt%, 2 wt%, and 4 wt% for the investigation of its effect on the machining performance of a NMQL fluid. The weight fractions were selected from a previous work [8]. To ensure complete distribution of used nano-additives into the base cutting fluid, an ultrasonic soni-cator was equipped to disperse nanoparticles into the base oil for 3 h at 60 °C. A magnetic stirrer was then utilized for the stirring stage for 30 min. The nanofluid was also surfactant-treated with 0.2 mg of sodium dodecyl sulfate to ensure adequate dispersion of nano-additives. By doing so, the nanofluid is improved in terms of viscosity and thermal conductivity, as well as its stability. To ensure a standard level of health and safety in the workshop during the experi-mentation phase (i.e., standard safety data sheets for nano-additives), certain safety procedures (i.e., standard safety data sheets) were applied. According to a standard material safety data sheet, the nanofluids are filtered before disposal in the sewer (Fig. 2).

2.3 Cutting force measurement

To ensure free machining of the workpiece and to simplify the process of mounting the workpiece on the dynamometer for a force analysis, profile milling of the workpiece was conducted to generate a U-shaped cross section as illustrated in Fig. 3 A repeatability test was conducted three times for each experiment. Kistler's piezoelectric dynamometer 9257A was used to measure cutting forces.
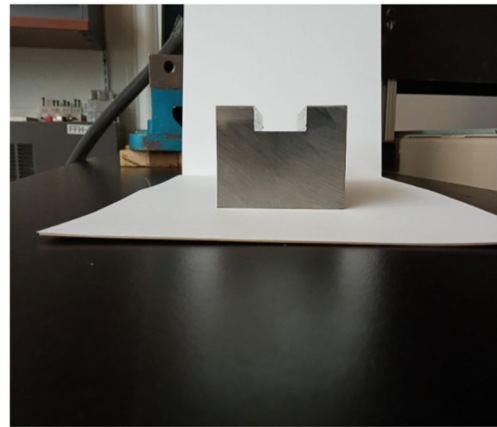
Fig. 2 U-shaped cross section of Inconel 718

2.4 Flank wear measurement

There were several measurements of tool wear (VB_{max}) conducted before the tool wear criterion was reached. The flank wear was measured using an optical microscope at an interval of three passes. For surface integrity to be main-tained, the VB_{max} should not exceed 0.3 mm, which is a failure of the tool wear criterion based on **ISO 8688** [27]. All measurements were then reported in Table 4.

2.5 Surface topography and surface roughness measurement

A surface roughness tester, Mitutoyo SJ210, was used to measure the average roughness of the surface. In order to ensure that the tip of the probe was perpendicular to the surface of the workpiece, the probe was positioned parallel to the surface. Table 4 presents the results of the surface roughness measurement after each of the three passes. In addition, a KEYENCE digital microscope was used to observe the topography of the workpiece's surface.

Fig. 3 Front side of the chip produced at a cutting speed of 150 m/min and a feed rate of 0.15 mm/rev

Table 4 Magnitude of cutting forces and surface roughness

Run order	Coolant condition	Cutting speed (m/min)	Feed (mm/rev)	Resulant cutting force (N)	Surface roughness (μm)
1	0% N MQL	100	0.1	73.49	0.615
2	0% N MQL	100	0.15	45.54	1.359
3	0% N MQL	150	0.1	46.26	0.714
4	0% N MQL	150	0.15	52.51	1.721
5	0% N MQL	200	0.1	43.33	1.653
6	0% N MQL	200	0.15	57.85	2.966
7	2% N MQL	100	0.1	60.26	0.769
8	2% N MQL	100	0.15	39.86	1.166
9	2% N MQL	150	0.1	40.26	0.961
10	2% N MQL	150	0.15	46.63	0.854
11	2% N MQL	200	0.1	41.29	0.902
12	2% N MQL	200	0.15	48.45	1.364
13	4% N MQL	100	0.1	40.85	0.424
14	4% N MQL	100	0.15	35.14	0.511
15	4% N MQL	150	0.1	34.89	0.661
16	4% N MQL	150	0.15	39.94	0.755
17	4% N MQL	200	0.1	35.93	0.791
18	4% N MQL	200	0.15	37.83	0.919

Fig. 4 Back side of the chip produced at a cutting speed of 150 m/min and a feed rate of 0.15 mm/rev

2.6 Chip morphology

The chips produced throughout the machining process that corresponded to various combinations of the input parameters were collected in separate bags. The chip samples were polished using waterproof SiC papers with a grit ranging from 320 to 1000 and immersed into Kalling's No. 2 etchant for subsequent polishing for etching the chips. Lastly, these chips were observed under a digital microscope to capture clear images of the front and back surfaces of each chip, as shown in Figs. 3 and 4.

2.7 Minimum quantity lubrication system

For setting up the nanofluid MQL coolant environment, a separate independent assembly of the MQL system was attached with the CNC setup; the nozzle of the coolant system was introduced into the CNC system through a circular opening and was positioned in such a manner that a vertical and horizontal distance of approximately 2 in from the tip of the milling tool was maintained. The weight percentage of nanoparticles mixed with the cutting fluid was about 2 wt% and 4 wt%.

3 Results

3.1 Surface integrity and cutting forces

3.1.1 Surface roughness and surface topography

It is important to note that smooth surfaces are extremely rough at the atomic level. There are several forming operations involved in this case, which are responsible for the surface roughness. These surfaces slide over one another when tangential forces are applied. It is not uncommon for strong junctions to fail in shear or break at a short distance from each other. The real contact area between two manufacturing surfaces is typically smaller than the apparent contact area between them because their asperities make contact with each other. Due to elastic deformation of the irregularities, the contact area increases with normal pressure maintaining a friction coefficient equal to the ratio of frictional and normal forces (stresses). The magnitude of the surface roughness can help determine the extent of the irregularities on any surface [28]. These irregularities may become a site for the initiation of cracks or a ground for corrosion.
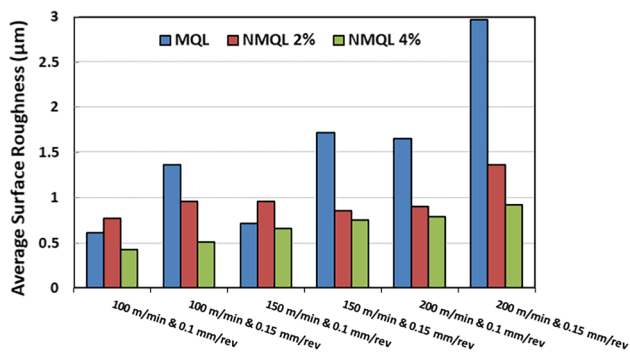
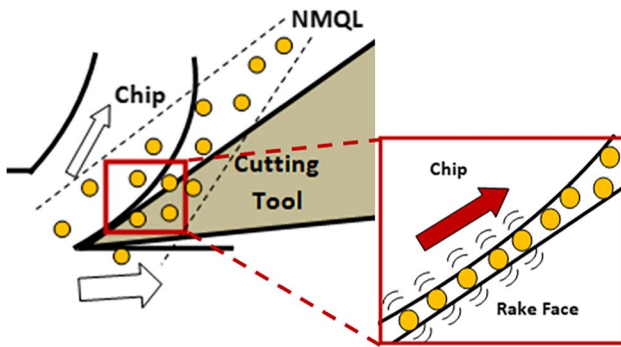**Fig. 5** Plot for various cutting conditions vs surface roughness

Fig. 6 Rolling effect of nanoparticles during the machining process

Furthermore, these cracks can also lead to catastrophic failure of a mechanical component subjected to mechanical forces when in use. Table 4 displays the magnitude of the cutting forces and surface roughness measured for each experimental run.

A comparison of the impact of the feed rate and cutting speed and on the surface roughness has been presented in Fig. 5 for both pure MQL lubrication conditions and NFMQL lubrication conditions, respectively.

It is evident from a comparison of the data that variations in speed and feed have similar impacts on work roughness. A deviation in the feed rate will have a greater effect on the quality of the work surface than a change in its speed [21]. In addition, surface roughness decreases with a raise in speed up to a certain point. After that point, the surface roughness increases with increasing speed. Due to the increase in the feed rate, the roughness also increases. As a result of the 4 wt% NFMQL lubrication environment, surface roughness was reduced to the lowest level. A rolling effect was created between the tool and the workpiece by including nanoparticles to the fluid, which enhanced the thermal conductivity (see Fig. 6). As a result, tool flanks are less likely to wear during milling, which results in better quality work [29]. Nanoparticles roll along the machining path, causing a mist to form due to their ball bearing effect [30].

Figure 7a, b, and c indicate the surface roughness topography at 100 m/min and 0.15 mm/rev under pure MQL, 2
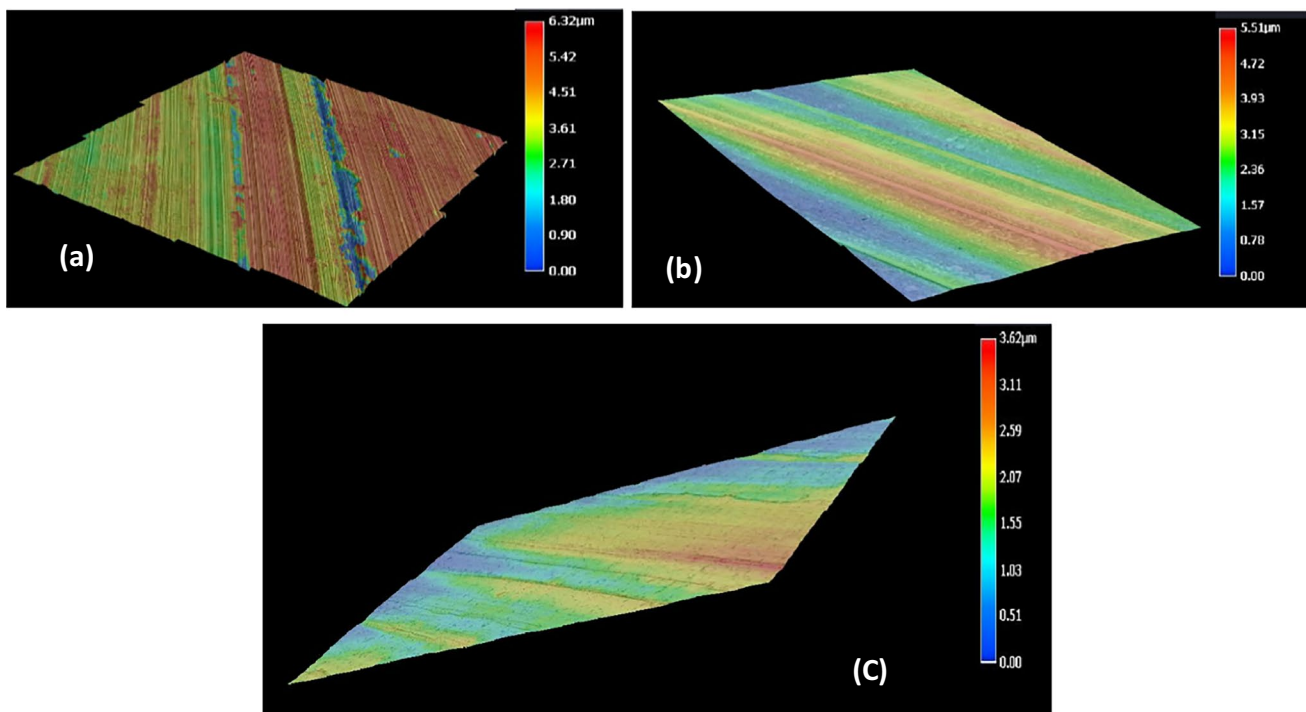
Fig. 7 Surface topography at 100 m/min and 0.15 mm/rev with **a** MQL, **b** NMQL 2 wt%, and **c** NMQL 4 wt%

wt% and 4 wt% NFMQL, respectively. It can be noticed that the surface quality has been enhanced significantly using the 4 wt% concentration. Generally, the results demonstrate that for each percentage of nanoparticles used in the MQL fluid as a coolant, an increased value of surface roughness is obtained. An explanation for this could be that at higher speeds and feeds, there is not enough time available for the heat to be transmitted/supplied from the tool to the chips and allow cooling of the cutting tool inserts. This leads in a greater amount of heat being accumulated at the tool/chip interface. During processing, this heat is unable to be dissipated from the cutting inserts to the chips in the area of cutting because of the poor thermal conductivity of the work material. The presence of high heat results in the formation of BUE and the initiation of thermal cracks on the cutting tool insert, which causes wear. These thermally cracked and worn-out inserts begin to produce burrs and transmit scratches onto the surface of the work material. This results in the generation of rough surfaces with an inappropriate surface quality.

The best surface quality is achieved when the wt% of Al_2O_3 nanoparticles is at a maximum (4%). This could be explained by closely looking at the tribological properties of Al_2O_3, which allow them to dissipate heat effectively and enhance thermal conductivity. On mixing the Al_2O_3 nanoparticles in the MQL oil, a transition in the surface morphology of the powdered Al_2O_3 nanoparticles takes place. The surface morphology changes from having a hexagonal close packed structure into that of a nearly spherical-shaped crystal structure. This change in the crystal structure results in an increase in the surface to volume ratio and a decrease in the nanoparticle clogging. Since the surface area rises with an increase in the high surface to volume ratio, more heat is transmitted/transferred from the tool to the chip at the cutting zone, thus improving the heat dissipation. As a result of adequate and improved heat dissipation, thermal cracking at the surface of the cutting tool insert is reduced. Burrs on the surface of the work material are also prevented, which results in a further improvement in the surface quality.

3.1.2 Cutting forces

During the milling process, the force plays a significant role; it determines both the cutting parameters and the cutting temperature. Thus, the milling force has a significant impact on the wear of the tool, the accuracy of the machining process, the surface quality of the finished product, as well as the performance of the nanoparticles. The reduction in the cutting force that occurs as a result of an improved lubrication performance results in an improved cutting performance [31]. Since the cutting force is a vital indicator of the amount of power and energy needed for turning, it is important to determine the optimal conditions in which the cutting forces

are at a minimum. When turning nickel-based superalloys at higher cutting speeds, Thakur et al. [32] discovered that the shear plane angle increased, which decreased the area of the chip-tool contact. Cutting force, as well as other components of force, can be reduced by reducing the chip-tool contact area, increasing the angle of the shear plane, and accelerating the shearing and chipping velocity [33].

Figure 8 illustrates the changes in the cutting force with changes in the cutting parameters for addition of 0 wt%, 2 wt%, and 4 wt% nanoparticles in the lubricating oil. The graph illustrates that with a rise in the cutting speed and feed, the magnitude of the cutting forces decreases. The reason for a decrease in the magnitude of the cutting forces can be explained by understanding morphology of the chips produced at various speeds. Due to the lack of proper heat dissipation at minimum speeds and feeds, a greater amount of heat accumulates at the cutting zone. This results in the formation of chips, which are highly bent in the direction opposite to the insert, as illustrated in Fig. 9. This phenomenon of chips bending in the opposite direction tends to increase the gap between the tool and the chip and reduces the contact between them. It is therefore easier to remove material from the workpiece using a smaller magnitude of forces. It has also been observed that the environmental conditions when cutting have a substantial effect on the generated cutting forces. The cutting forces are reduced by approximately 20% and 45% when using NFMQL 2 wt% and 4 wt%, respectively, compared to that of a MQL at a lower machining speed and feed rate. This becomes less apparent at higher speeds at which the cutting forces are reduced by 15% and 35% when implementing NMQL 2 wt% and NFMQL 4 wt%, respectively, compared to MQL at higher speeds of 200 m/min and 0.15 mm/rev feed.

The properties of Al_2O_3 nanoparticles, such as heat resistance, excellent hardness, spherical-shaped structure, and wear resistance, allow the same effect to be seen for an increase in the wt% nanoparticles of the MQL fluid. These spherical shaped particles enter the sliding contact between the tool chip interface and get inserted into worn-out areas
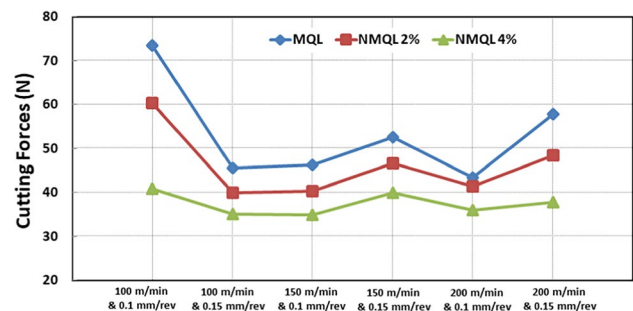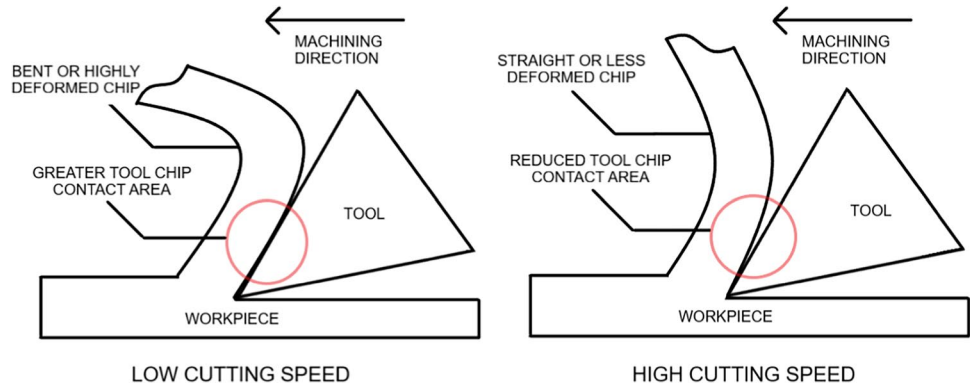

Fig. 8 Variations in the magnitude of resultant cutting forces under different milling conditions

**Fig. 9** Bending of the chips at low and high cutting speeds

to form a self-laminating film. This film acts as a pseudo-surface possessing superior properties and helps to repair dents in worn-out areas. The film also decreases the friction due to its improved thermal conductivity properties and dispersion stability. Additionally, due to the flash temperature developed by friction, hydroxyl and tribo-sinters on the wear surface chemically adsorb nanoparticles onto the friction surface of the metal. This diminishes the metal-to-metal contact and serves as a loading-bearing region [34]. Due to the spherical shape of most Al_2O_3 nanoparticles, they can function as ball bearings to prevent direct contact between friction pairs. By doing so, sliding friction is converted to rolling friction and performance is improved under severe pressure. In this way, the anti-friction and anti-wear

characteristics of Al_2O_3 reduce the cutting forces with an increase in speeds and feeds.

3.2 Tool wear and tool life

The curve for flank wear for 0 wt%, 2 wt%, and 4 wt% NFMQL at various machining lengths is shown in Fig. 10. The graph demonstrates that flank wear rises smoothly and uniformly with the cutting length for all nanoparticle concentrations up to a specific point (until tool wear criterion), at which the slope of the curve abruptly increases. This illustrates the increase in wear rate with an increase in speeds and feeds. In previous studies, an oil film was reported to cover the tool-chip interface to reduce friction and prevent

Fig. 10 Flank wear vs machining length
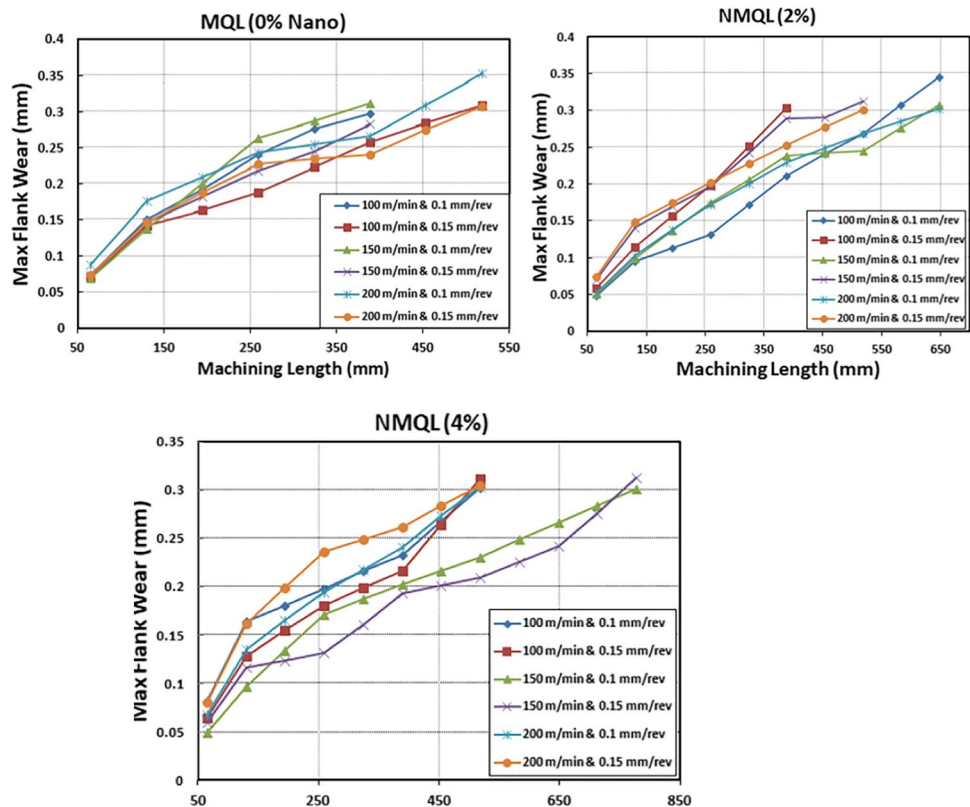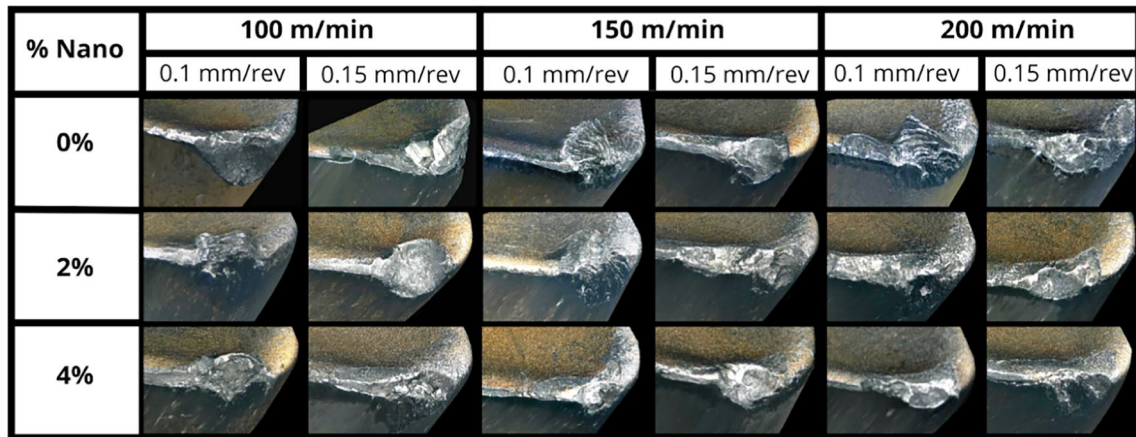
Fig. 11 Image of the nose of the inserts at different concentrations of nanoparticles

heat buildup [27]. The lubricant in an MQL allows a large amount of heat to be processed by permitting heat to move away from the cutting tool. The chip prevents tool wear, prolongs tool life, provides lubrication and removes heat from the tool. This can be explained by the loss of the hard, wear-resistant cutting layer of the tool, which tends to soften the inserts and reduce their wear resistance compared to before the coating was applied. Another factor might be a rise in the wear rate brought on by an increased accumulation in

heat at the cutting edge. It can be inferred from the plots that Experimental Run 15 has a minimum magnitude of flank wear at the highest machining length. This makes a 150 m/min cutting speed and 0.1 mm/rev feed the optimal parameters for machining. Using the 4 wt% NFMQL increased the machining length by approximately 50% compared to a 0 wt% MQL and about 15% compared with a 2 wt% NFMQL.

Figure 11 shows the images of inserts under various machining conditions. In machining settings with a 4 wt%
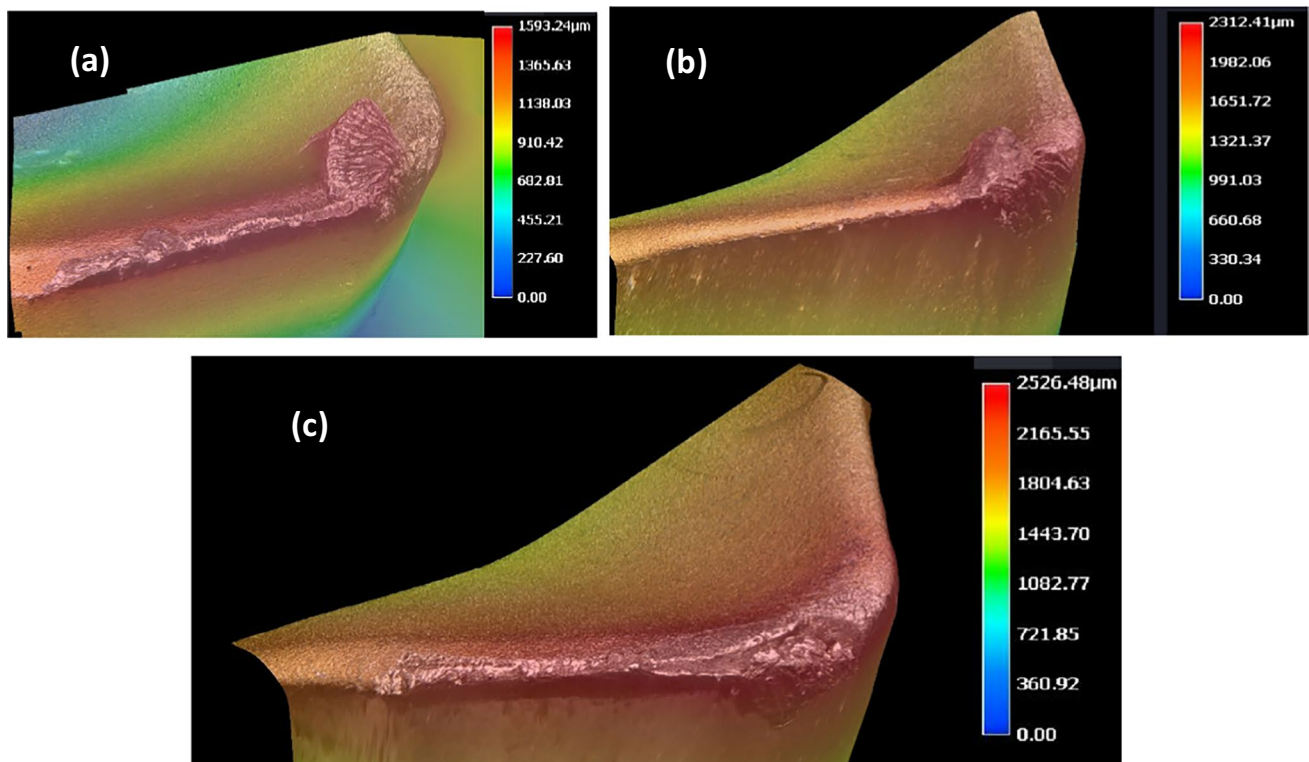
Fig. 12 Wear of the cutting tool at 150 m/min and 0.1 mm/rev under different environments: **a** MQL; **b** NMQL 2%; and **c** NMQL 4%

Table 5 Chip morphology parameters

Run order	Coolant condition	Cutting speed (m/min)	Feed (mm/rev)	Chip morphology		
				Peak (μm)	Valley (μm)	Pitch (μm)
1	0% N MQL	100	0.1	642.83	524.5	299.4
2	0% N MQL	100	0.15	476	364.4	246.4
3	0% N MQL	150	0.1	394.8	287.3	177.4
4	0% N MQL	150	0.15	359.5	234.2	458.5
5	0% N MQL	200	0.1	522.5	349.2	248.3
6	0% N MQL	200	0.15	300.2	153.3	136.2
7	2% N MQL	100	0.1	528.8	369.6	346.7
8	2% N MQL	100	0.15	306	206.3	136.7
9	2% N MQL	150	0.1	491.5	386.5	242.5
10	2% N MQL	150	0.15	215.1	158.7	92.4
11	2% N MQL	200	0.1	282.5	256.6	79.4
12	2% N MQL	200	0.15	387.0	300.5	239.3
13	4% N MQL	100	0.1	372	350.6	167.6
14	4% N MQL	100	0.15	400	308.8	154.4
15	4% N MQL	150	0.1	255.5	205.7	108.6
16	4% N MQL	150	0.15	212.23	181.7	165.7
17	4% N MQL	200	0.1	139.9	83.46	94
18	4% N MQL	200	0.15	517.6	381.1	348.9

nanoparticle addition, tool wear is seen to be at a minimum; however, for experimental runs with a 0 wt% nanoparticle addition, maximum tool wear mechanisms are seen. Due to the superior anti-wear and anti-friction capabilities of Al_2O_3, tool wear mechanisms are at their lowest for the addition of 4 wt% nanoparticles. The hexagonal, close-packed crystal structure of Al_2O_3 assists in increasing the hardness of the lubricating oil while also making Al_2O_3 extremely resistant to heat and wear. As a result, the wear on cutting tools decreases and the anti-wear qualities of the lubricating oils improve as the number of nanoparticles in them increases. The smaller size of Al_2O_3 nanoparticles also enables them

to form a sliding contact in the hydrodynamic region. This makes it easier for them to travel into worn-out areas to fill in any scars and grooves in the friction surface under the compressive stress of the lubricating oil. Al_2O_3 nanoparticles thus improve heat and wear resistance and serve as a self-laminating protective film against friction. Figure 12 denotes the tool wear in 3D images and shows the greatest concentration of stresses at different locations. Figure 12 represents the tool worn at a cutting speed of 150 m/min and a feed rate of 0.1 mm/rev and the change in the cooling conditions when 0 to 4 wt% nanoparticles are added. Additionally, the hydroxyl and tribo-sinters on the wear surface enable the chemical adsorption of the nanoparticles on the metal friction surface. This minimizes the metal-to-metal contact and serves as a loading-bearing region. As a result of their spherical morphology, Al_2O_3 nanoparticles prevent direct contact between friction pairs through the ball bearing effect. The sliding friction is transformed into rolling friction between the pairs, improving the performance under severe pressure and the carrying capacity of the lubricant.

3.3 Chip morphology

During the machining process, the chips and particles that are generated have different morphologies depending on their physical characteristics. An indication of the quality of the surface of a workpiece, the life of the tool, and the accuracy of the dimensions of the workpiece is found in the type of chip formed during machining. An important machinability element that affects the surface finish of a machined part
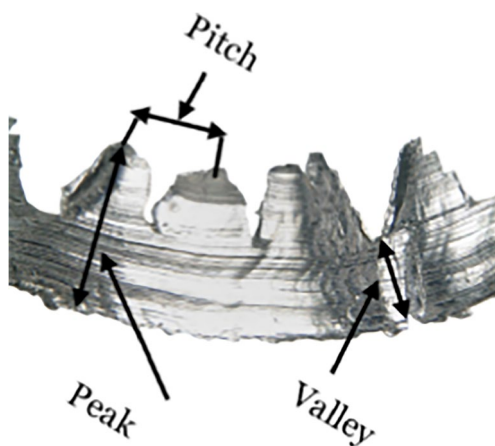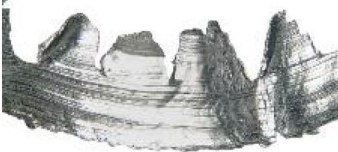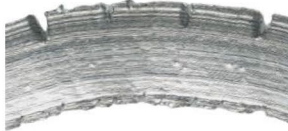

Fig. 13 Chip morphology parameters

Table 6 Chip morphologies for the free and back surface under different cutting conditions

Run No.	Smooth/Back surface	Free Surface
1		
5		
8		
10		
12		
14		
17		

is the morphology of a chip. To achieve smooth machining operations, it is preferable to work with chips that have been broken and segmented.

During machining, Inconel alloys produce chips that are segmented or serrated due to their high strength and hardening properties. There are several reasons why these types of chips may form, including increased cutting forces, increased tool wear, and poor surface finish. The low thermal conductivity of Inconel alloys results in high temperatures at the interface between the cutting tool and the workpiece, which can result in chipping or breakage of the cutting tool. As a result of this phenomenon, the tool life is reduced, and the surface finish is affected. Inconel machining results in different chip morphologies based on parameters in machining, such as the feed rate, cooling condition, depth of cut and cutting speed, as well as the tool geometry, such as the clearance angle, rake angle, and cutting-edge radius. Higher feed rates and lower speeds can produce discontinuous chips, while lesser feed rates and higher speeds can produce continuous chips. To minimize tool wear and improve surface finish, these parameters must be optimized.

During Inconel machining, the selection of the cutting tool material and coatings has a meaningful impact on the chip morphology and tool life. There are several materials commonly used for tool making, including polycrystalline cubic boron nitride (PCBN), cemented carbide, and coated carbide. The use of coatings such as TiAlN, TiN, and AlCrN can improve chip formation and tool life by reducing adhesion and wear. PVD TiAlN cutting inserts were used for machining in this study.

Chip morphology is associated with several parameters that determine the machining performance. An analysis of the morphology of chips can provide a detailed suggestion of its machinability, since this provides an insight into the shearing force, cutting energy, and surface finish. Several factors related to chip morphology have been listed in Table 5, including the peak factor, valleys, and pitch. These are the factors that help to determine machining characteristics and identify machining performance. Surface roughness and other factors in machining, such as the cutting forces and energy, increase as the serration segment values increase. Below is a table illustrating the effect of different cutting parameters on the values of chip serrations. Using NMQL improved the performance by reducing the values of the serration components, such as the peak. Compared to MQL, the 4 wt% NFMQL reduces the serration factor significantly at a 200 m/min cutting speed and a 0.1 m/min feed rate. Through these values, the different performance criteria are evaluated, and machining characteristics are improved.

Examples of chip morphology, including the pitch position, valleys, and peaks, are depicted below in Fig. 13. An average was obtained by measuring the values at three different locations in order to determine a more accurate estimate of the results. Chips that were produced under different cutting conditions are shown in Table 6.

4 Conclusions

In this study, the effect of combining nanoparticles with the MQL was evaluated under a variety of cutting conditions. Based on the findings of this study, the following conclusions can be drawn:

- Cutting tools, tool wear properties, surface roughness, cutting forces, and chip morphology were studied to gain a better understanding of their operation. This could help to improve their machinability at sustained temperatures in the future.
- The NFMQL helps to achieve optimal cutting performance by providing an effective cooling solution with superior performance. As a result of utilizing a NFMQL, the roughness, tool wear, and friction are reduced in the cutting zone, thus reducing other factors that are involved in the machining process.
- A meaningful improvement in the tool life was observed by using the NFMQL technique compared to MQL machining in this experiment. The tool life was optimized when cutting at 150 m/min with a feed of 0.1 mm/rev when a 4 wt% NFMQL was used during machining.
- The experiments also measured the morphology and tool life of the chips, which were both enhanced by using the NFMQL. Surface quality and cutting forces were measured to determine the effectiveness of the cutting operation. Additional optimized parameters have been found to be similar to those mentioned above.
- Based on a chip morphology analysis, primary and secondary cutting performance parameters can be measured to determine the performance of the machining.

Data availability Data can be requested from the corresponding author.

Declarations

Consent for publication All authors have read and agreed to the published version of the manuscript.

Conflict of interest The authors declare no competing interests.

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