J MATER RES TECHNOL. 2020;9(5):10386–10400

Available online at www.sciencedirect.com
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Journal of Materials Research and Technology
https://www.journals.elsevier.com/journal-of-materials-research-and-technology

Original Article

Performance evaluation of MQL with AL_2O_3 mixed nanofluids prepared at different concentrations in milling of Hastelloy C276 alloy

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ARTICLE INFO

Article history:
Received 29 May 2020
Accepted 7 July 2020
Available online 31 July 2020

Keywords:
Hastelloy C276
Al_2O_3 based nano-cutting fluid
Tool wear
Wear mechanisms
Surface roughness

ABSTRACT

Since some deficiencies in mist lubri-cooling techniques i.e., minimum quantity lubrication (MQL) in heavy cutting conditions have been noticed, recently nano-cutting fluids which have enrich thermal conductivity than base fluid, are begun to be used in MQL system. One of the critical issues arising in this process is the addition of the appropriate nanoparticle ratio to the base liquid. Therefore, this study aimed to find the optimum distribution rate of Al_2O_3 nanoparticles having excellent properties and machining parameters. For this purpose, by adding Al_2O_3 nanoparticles to vegetable-based cutting fluid, nano-cutting fluids were prepared in different volumetric concentrations (0.5, 1.0 and 1.5 vol%). These prepared nanofluids were used in the MQL system when milling of Hastelloy C276. Three cutting speeds (60, 75 and 90 m/min) and three different feed rates (0.10, 0.15 and 0.20 mm/rev) were added to the experimental design to study the performance of nanofluids under several cutting parameters. Apart from this experimental design, to clearly see the effect of concentration rates on tool wear and tool life, three experiments were carried out at each concentration ratio by keeping the machining parameters. Eventually, 1 vol% Al_2O_3 concentration clearly provided an improvement by up to 23% and 10% in tool life, compared to 0.5 vol% and 1.5 vol% concentration, respectively. In addition, while chipping/fracture, attrition wear and peeling of coating were observed under all cutting conditions, there was no evidence for workpiece material adhesion at 1 vol% and 1.5 vol% Al_2O_3 based nanofluid-MQL.

1. Introduction

Nickel-based super alloys have mostly been included in the production of aircraft components as they are equipped with superior qualities. However, the difficulties faced by high heat production in the cutting zone during the machining of these alloys have created various problems and showed the necessity of highly effective cooling/lubrication methods [1,2]. For this, nano-sized solid lubricants incorporated into cutting fluid can increase the cooling effect of system by means of their tribological features providing not only low friction but also high wear resistance and heat transfer properties

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https://doi.org/10.1016/j.jmrt.2020.07.018

and consequently increased the machining productivity [3]. Besides its cooling and lubrication ability, the cutting fluid, which also has effects such as removing chips from the cutting area, directly or indirectly rises the efficiency of cutting process [4]. However, the use of abundant cutting fluids leads to some techno-environmental problems [5,6]. While dermatological and respiratory diseases are observed in operators contacting with the cutting fluid that chemically decomposes at high cutting temperatures, water and soil pollution and environmental damages may also occur during the disposal of waste cutting liquids [7,8]. In addition, production costs are negatively affected due to reasons such as purchasing, storage, abundant use and disposal. As a result, the employment of high amounts of cutting fluid adversely affects employee health, environment and production costs [9]. Researchers who wanted to minimize these adversities have made various researches to reduce cutting fluid amount [10]. One of the alternative methods identified as a result of the studies is the method of MQL [11,12]. MQL, in its most general definition, is an environmentally friendly cooling/lubrication process that works by transferring a little amount (10−100 ml/h) of cutting oil through compressed air and nozzle [13]. In the MQL system, as the volume of fluid used for cutting is very limited, it evaporates almost completely, resulting in a dry workpiece and chips. By preventing inhalation and contact with the skin, this significantly reduces the health problems induced by emulsions which lead to air pollution and dermatological diseases. Moreover, since it eliminates processes such as maintenance, inspection, preparation and disposal of coolant, it also provides a positive contribution to reducing production costs [14]. Although the MQL method offers the improvements mentioned above, the cooling feature remains poor compared to conventional coolants, especially under heavy machining conditions. The nano-size solid lubricants that can be incorporated into the cutting fluid can significantly improve the machining efficiency of the system by providing better lubrication thanks to the tribological and thermal transfer properties [15]. In other words, through nano-additives, many rounding elements are located on tool-chip interface, thereby reducing friction and wear and increasing machining efficiency [16]. This is usually done by homogeneous dispersion of metallic or non-metallic additives of the base cutting fluid is less than 100 nm [17]. Depending on the properties of the nano-material, nanoparticles can make the base liquid much stronger in terms of thermal conductivity [18]. For example; the thermal conductance of the base liquid can be enhanced by 40% with the copper nanoparticles (average diameter of 10 nm), which are added to the ethylene glycol by 0.3 vol% [19]. Nanoparticles have also advantages such as long-term stability, non-blocking flow channels and less pressure drop compared to millimeter and micrometer-sized particles [18]. Some studies that demonstrate the effectiveness of nanoparticle-based cutting fluids are summarized. For example; Sen et al. who presented a comprehensive review article in 2019, stated that solid nanolubricants dispersed in MQL base fluid are a beneficial way to reduce friction during cutting operations. Moreover, it was emphasized that Al_2O_3-based nanofluid is a good option as a lubricant in cutting processes [20]. Rapeti et al. machined AISI 1040 steel by adding different rates of MoS2 into coconut oil, sesame oil and canola oil, and investigated the effect of nano-lubrication on machining performance. Researchers claimed that coconut oil with 0.5% MoS_2 nanoparticle provides better machining performance [21]. Eltaggaz et al. [22] compared 4 wt.% Al_2O_3 nanoparticle added into vegetable oil and pure-MQL (0 wt.% additive) when machining austempered ductile iron and reported that the MQL method with nano additive provides a better machining productivity. Hegab et al. [23] prepared the nanofluids reinforced by aluminum oxide (Al_2O_3) and multi-walled carbon nanotubes (MWCNTs) additives with 2 wt.% and 4 wt.% and examined the effects of nanoparticles based cutting liquids on machining efficiency of Inconel 718. They reported that Al_2O_3 and MCWNT enriched nano-cutting fluids exhibited better performance compared to the base cutting fluid (0 wt.% nano-additives). Vasu and Redy [24] machined the Inconel 600 by incorporating Al_2O_3 nanopowders into vegetable-based fluid and studied the effect of several cooling/lubrication methods (dry, MQL and Al_2O_3 reinforced MQL) on tool wear and cutting force. Under nanofluid based MQL, they find a decrease in cutting force and wear of the instruments. Anburaj and Elansezhian [25] studied the effect of various nano-fluids such as Al_20_3, ZnO and SiO nanoparticles dispersed into SAE20W40 cutting oil in different weight ratios, and stated that the cutting fluid containing 1 wt.% presented better results than other liquids. Khalil et al. [26] investigated the effect of machining environment (namely, dry, MQL + Al_20_3 and MQL + Sodium Dodecylbenzene Sulphonate (SDBS) in turning of AIS 1050 steel and claimed that Al203 nanoparticle had a positive impact to reduce the tool wear. A similar result was reported by Minh et al. [27] that Al_2O_3 based nanofluid provided an increase in tool life by up to 230% and a reduction in surface roughness and cutting force by up to 60% when milling of 60Si2Mn steel. Khandekar et al. [28] added 1 wt.% Al_2O_3 nanoparticle to the semi-synthetic cutting fluid and compared this nanofluid with dry and conventional cooling in machining of AISI 4340 steel. The researchers found that the nano-cutting fluid exhibited superior results than other methods from the point of roughness of surface, force of cutting, wear of tool, and thickness of chip.

Considering the literature summary mentioned above, it has been observed that Al_2O_3-based nano-cutting fluids presented better results in many applications compared to dry, conventional cooling, base fluid-MQL and some nanoparticle-based nano-cutting fluids. However, it was determined that the studies investigating the nanoparticle concentration ratio, which directly affects the effectiveness of nanofluid, is limited. In addition, no studies investigating the machinability of Hastelloy C276 superalloys used in critical applications under nanofluid have been found. Hence, this study focused on the machinability performance of nano-cutting oil prepared by dispersing Al_2O_3 nanoparticles with different concentration ratios (0.5, 1.0 and 1.5 vol%) into vegetable-based cutting oil when milling of Hastelloy C276 alloy with CVD TiCN/Al_2O_3/TiCN coated carbide insert. These prepared nanofluids were used in MQL system with machining parameters such as cutting speeds (60, 75 and 90 m/min) and feed rates (0.10, 0.15 and 0.20 mm/rev) to investigate the impact of nanofluids under different cutting parameters on tool life and surface roughness. Moreover, to clearly demonstrate the impression of concentration rates on tool wear and tool life, three experiments were carried out at each concentration

Table 1 – The chemical composition (wt. %) of Hastelloy C276.

Co	Cr	Mo	Fe	W	Mn	V	Si	C	Cu	Ni
0.134	14.13	15.84	5.74	3.62	0.43	0.14	0.03	0.025	0.02	Balance

Table 2 – The physical, mechanical and thermal properties of Hastelloy C276 alloy.

Properties	T (°C)	Unit	Value
Density	RT	g/cm^3	8.89
Elastic modulus	RT	GPa	205
Possion's ratio	RT	–	0.31
Tensile strength (ultimate)	RT	MPa	785
Yield strength (0.2% offset)	RT	MPa	365
Elongation	RT	%	59
Hardness	RT	HRB	87
Specific heat	RT	J/kg °C	427
Thermal conductivity	50	W/m °C	10.5
Melting range	–	°C	1323−1371

RT: room temperature.

ratio (0.5, 0.1 and 0.15 vol%) by keeping the cutting parameters constant. Finally, experimental findings were collected with a series of statistical tests. More information on this study's methodology and findings is given in the following sections.

2. Experimental procedure

2.1. *Hastelloy C276 alloy, machine and cutting tool*

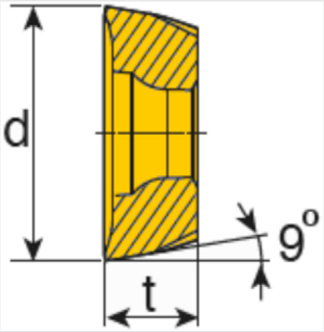
In the current study, a series of experiments were executed under Al_2O_3 doped nanofluid-MQL at various feed rates, cutting speeds and Al_2O_3 nanoparticle concentrations to investigate their effects on surface roughness, tool life and tool wear. A nickel based superalloy Hastelloy C276 with dimensions 150 × 100 × 15 mm was handled as workmaterial in the experiments. Tables 1 and 2 indicate the chemical composition of the Hastelloy C276, and its physical, thermal and mechanical properties. The milling tests were conducted on Delta Seiki CNC-1050 vertical milling machine with a maximum of 10,000 rpm and 11 kW spindle power. During the milling experiments, CVD TiCN-Al_2O_3-TiCN multilayer coated carbide inserts manufactured by TaeguTec with a specification of RYMX 1205-ML (ISO S25-S40) were used. These cutting tools were connected to the 32 mm diameter tool holder (shrink type) manufactured by TaeguTec with a designation of BT40 ODP 16 × 66 (Table 3).

2.2. *MQL and nano-cutting fluid*

In this study, the Vario model MQL system manufactured by SKF has been adopted to deliver the nanofluid together with pressured air to the machining zone in a pulverized way. Before the main experiments, preliminary tests have been performed to determine the main variables and then use them in the main experiments and thus the optimum operating parameters were reached as follows: The oil rate of flow of 100 ml/h, spray angle of 45° and spray pressure of 8 bar. Cutting oil on vegetables that has a kinematic viscosity of 10 cSt at 40 °C, a refractive index of 1.46 N^{20}D and a flash point of 170 °C was utilized in the experiments.

During the preparation of the nanofluid, 0.5%, 1% and 1.5% by volume of Al_2O_3 nanoparticles (aluminum Oxide (Al_2O_3) nanopowder/nanoparticles, gamma, purity: 99.5+%, size: 18 nm, hydrophilic) were added to the vegetable-based cutting oil. Al_2O_3 enriched nanofluids were carried out in two steps to obtain a homogeneous mixture. Firstly, the mixture was mixed for 30 min at a speed of 700 rev/min with the Daihan brand HS-100D model mechanical mixer. After that, a fresh mixture was obtained by mixing with UW-3200 ultrasonic homogenizer of Bandelin Sonopuls for a further 30 min. At the last stage, the nanofluid has been re-mixed for 60 min at 1500 rpm by aid of N11150 M magnetic stirrer (THERMAL) to ensure a homogeneous distribution of Al_2O_3 nanoparticles into the base liquids. By using this way, the obtained nanofluid reinforced by Al_2O_3 nanoparticles is provided in Fig. 1. In preparation of nano-cutting fluids, the agglomeration or precipitation of the nanoparticles in the base oil is one of the serious problems. To prevent this phenomenon, surfactants have been added to the base oil to reduce surface

Table 3 – The properties of cutting insert.

Insert	Designation	Manufacturer grade	Coating method	Coating material	d (mm)	t (mm)
	RYMX 1205-ML	TT9540	CVD	TiCN–Al_2O_3–TiCN	12	4.8

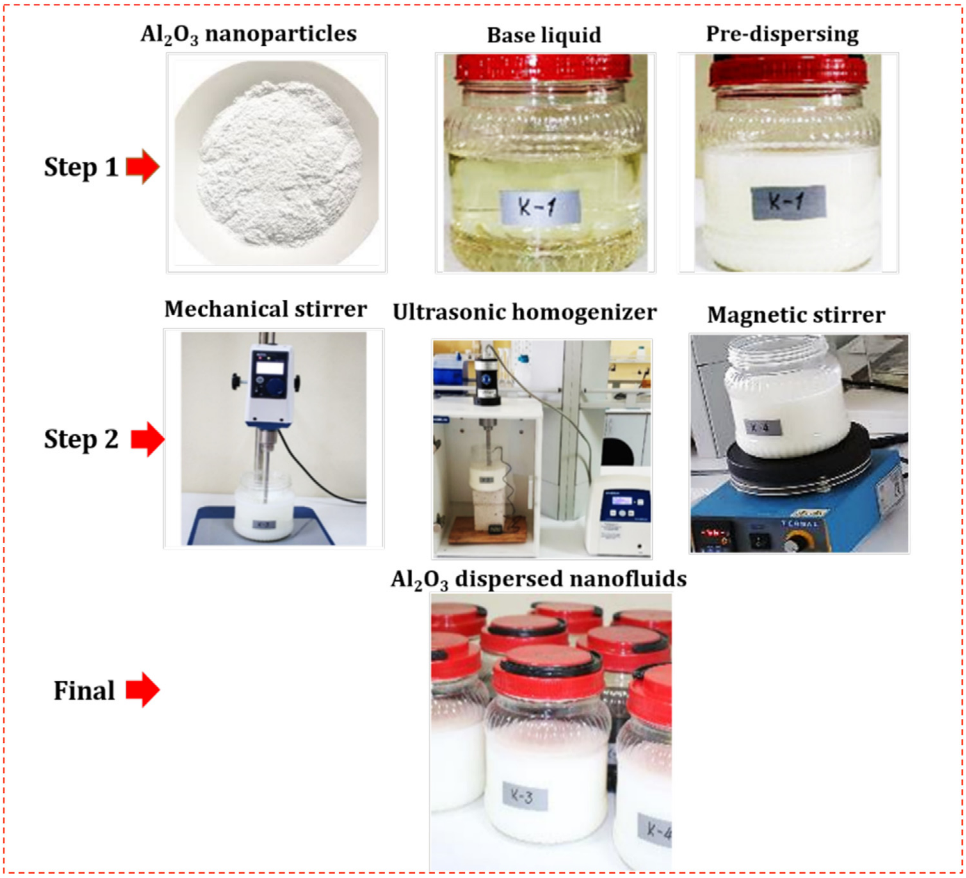


Fig. 1 – Two-step technique for Al_2O_3 based nanofluid preparation.

Table 4 – Control factors and their levels.

Factors	Symbol	Levels (coded)			Levels (uncoded)		
Cutting speed, m/min	Vc	1	2	3	60	75	90
Feed rate, mm/rev	f	1	2	3	0.10	0.15	0.20
Nanoparticle concentration (%)	NC	1	2	3	0.5	1.0	1.5

tension. However, these surfactants negatively affect the properties of the oil (such as thermal conductivity) [29]. Therefore, in the present work, no surfactant was used for preparation of nanofluid.

2.3. *Experimental design and measurement tools*

Feed rate, cutting speed and concentration ratio of nanoparticles (vol%) were chosen as process parameters in milling experiments for Hastelloy C276. The levels of mentioned parameters are illustrated in Table 4. This experimental study consists of three factors and their three levels. Therefore, Taguchi's L27 experimental design was employed to make performance comparisons between control factors and their interactions. The responses of the experimental design were surface roughness and tool life. Apart from this experimental design, to obviously see the impact of concentration rates on tool wear, three runs were carried out at each concentration ratio (0.5, 0.1 and 0.15 vol%) by preserving the cutting parameters (feed rate of 0.12 mm/rev and cutting speed of 90 m/min) and machining time (9 min for each operation) and finally the flank wear was measured. Moreover, these experiments were continued until the tool wear value reached the same value for each cutting tool and then the tool life was determined.

In current investigation, based on ISO 8688-1 standard, the tool life was determined by considering the time when flank wear is arrived to 0.3 mm. Each experiment was conducted with a fresh insert during the experiment. The wear value of cutting insert was measured using polarized optical microscope, AM 4113ZT (Dino-Lite). To determine the surface quality, average surface roughness (Ra) was considered and Ra measurements were performed by Taylor Hobson Surtronic S-25 portable stylus surface roughness tester. In these measurements, sampling length and evaluation length ware set as 0.8 mm and 4 mm, respectively. The measurements were made from four different points parallel to the machining surface and their average was considered for evaluation. The experimental system appears in Fig. 2.

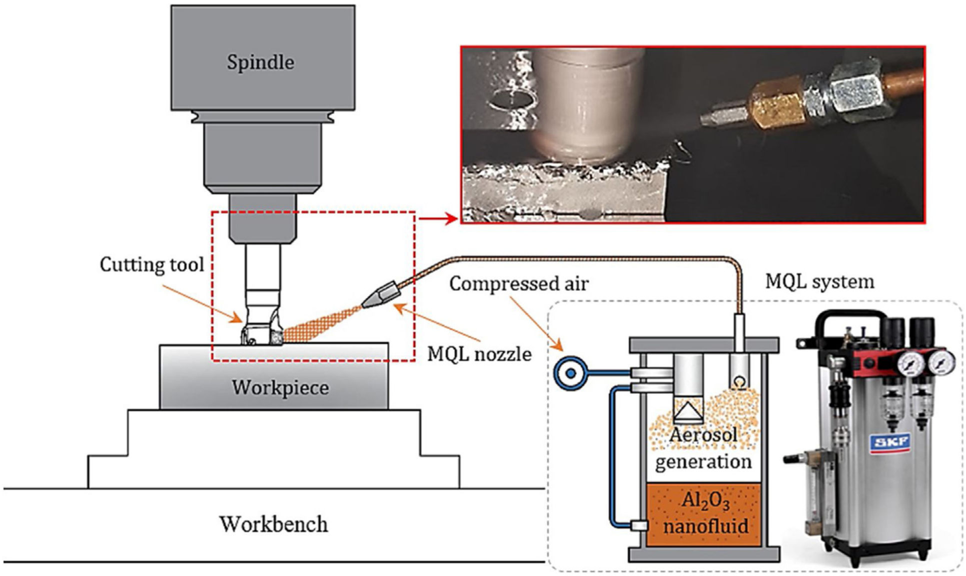


Fig. 2 – Experimental setup.

3. Results and discussion

3.1. Signal to noise (S/N) analysis

In the Taguchi's S/N analysis, one of the conditions such as nominal the better, larger the better and smaller the better is considered with regard to the desired conditions of the quality characteristic. In this work, since the maximum value in the tool life is requested, the larger the better option (refer Eq. (1)) was chosen. For the surface roughness, the smaller the better option (refer Eq. (2)) was preferred because the maximum surface quality is desired in the machined workpiece material.

$$S/N\,T_l = -10 * \log\left[1/n * \left(\frac{1}{y_1^2} + \frac{1}{y_2}^2 + \ldots + \frac{1}{y_n}^2\right)\right] \quad (1)$$

$$S/N\,R_a = -10 * \log\left[1/n * \left(y_1^2 + y_2^2 + \ldots + y_n^2\right)\right] \quad (2)$$

In this formula, $y_1, y_2, \ldots y_n$ represent the results taken separately for each experiment repeated n times for tool life and surface roughness [30]. S/N ratios calculated using Eqs. (1) and (2) for tool life and surface roughness are given in Table 5. The average tool life values obtained based on the test results was 30.75 min, while the average of S/N ratios was 27.3 dB. The average surface roughness values was 0.37 μm while the average S/N ratio of surface roughness values was 8.73 dB. Table 6 illustrates the response table for tool life and surface roughness. The graphs of S/N averages showing the effectiveness of factors and their levels on tool life and surface roughness are shown in Figs. 3 and 4, respectively. The optimum level of a factor can be defined as the level with the largest S/N ratio for that factor. Therefore, it was determined from Fig. 3 and Table 6 that the optimum parameter group for tool life: level 1, (60 m/min, S/N = 33.69) for cutting speed, level 1, (0.10 mm/rev, S/N = 32.49) for feed rate, and level 2, (Al_2O_3/1 vol%, S/N = 27.90) for nanoparticle concentration. The optimum level for average surface roughness was level 3 (90 m/min, S/N = 9.37) for cutting speed, level 1 (0.10 mm / rev, S/N = 9.76) for feed rate, and level 2 (Al_2O_3/1 vol%, S/N = 8.99) for nanoparticle concentration. In other words, the best value for tool life was achieved by the combination of $Vc_1f_1NC_2$, while the best value for average surface roughness was obtained by the combination of $Vc_3f_1NC_2$.

3.2. Tool life

Hard abrasive carbides such as M6C and M23C6 within the nickel-based superalloys cause abrasive wear that reduces tool life [31]. Therefore, it is really important to determine the optimum operating parameters to have a high tool life during the machining of such materials viz., Hastelloy C276. For this analysis, 3D surface plots are given in Fig. 5, showing tool life values change depending on process parameters. Consequently, Fig. 5(a) indicates that the tool life decreased noticeably when the cutting speed increased. The reduction in the tool life with increasing cutting speed up to 90 m/min was determined as 76.98%. This reduction was due to an increase in the heat generated within the tool-chip interface with the increasing cutting speed which triggered rapid wear. In other words, the temperature at milling area rises when the cutting speed increased. Thus, the thermal and mechanical loads to cutting tool increases and the deformation in cutting tool accelerate. These results are parallel with the previous findings [32]. In addition, Bhushan [33] stated that a large increment in cutting speed triggers more tool wear which cannot be controlled. Eventually, the cutting tool has completed its life long before the expected period. In another study, Gu et al. [34] explored the impact of cutting parameters on tool life/wear in the milling process and claimed that high cutting speed triggered the wear mechanism earlier.

Fig. 5(a) provides the variation in tool life by changing of feed rate. It was observed from Fig. 5(a) that the tool life

Table 5 – Results from the experiments and their S/N ratios.

Exp. no.	Control factors			Experimental results		SN ratios for responses	
	Vc (m/min)	f (mm/rev)	NC (%)	TL (min)	Ra (μm)	TL-S/N ratio (dB)	Ra-S/N ratio (dB)
1	60	0.10	0.5	85.4	0.38	38.63	8.40
2	60	0.10	1.0	95.5	0.35	39.60	9.12
3	60	0.10	1.5	93.0	0.37	39.37	8.64
4	60	0.15	0.5	36.9	0.38	31.33	8.40
5	60	0.15	1.0	40.2	0.36	32.08	8.87
6	60	0.15	1.5	43.6	0.4	32.78	7.96
7	60	0.20	0.5	28.9	0.4	29.22	7.96
8	60	0.20	1.0	31.4	0.38	29.94	8.40
9	60	0.20	1.5	32.7	0.49	30.28	6.20
10	75	0.10	0.5	40.2	0.28	32.09	11.06
11	75	0.10	1.0	44.2	0.35	32.92	9.12
12	75	0.10	1.5	46.2	0.37	33.30	8.64
13	75	0.15	0.5	17.4	0.39	24.82	8.18
14	75	0.15	1.0	21.4	0.37	26.63	8.64
15	75	0.15	1.5	22.8	0.38	27.15	8.40
16	75	0.20	0.5	11.1	0.41	20.87	7.74
17	75	0.20	1.0	14.1	0.4	22.97	7.96
18	75	0.20	1.5	13.1	0.42	22.33	7.54
19	90	0.10	0.5	16.7	0.29	24.48	10.75
20	90	0.10	1.0	21.8	0.28	26.75	11.06
21	90	0.10	1.5	18.4	0.28	25.30	11.06
22	90	0.15	0.5	10.0	0.32	20.04	9.90
23	90	0.15	1.0	12.3	0.31	21.78	10.17
24	90	0.15	1.5	11.2	0.34	20.95	9.37
25	90	0.20	0.5	6.7	0.44	16.52	7.13
26	90	0.20	1.0	8.4	0.42	18.46	7.54
27	90	0.20	1.5	6.7	0.43	16.52	7.33

T_{TL} (the complete mean value of the tool life) = 30.75 min.
$T_{TL\text{-}S/N}$ (total mean value of the tool life S/N) = 27.3 dB.
T_{Ra} (total mean surface roughness) = 0.37 μm.
$T_{Ra\text{-}S/N}$ (total mean value of surface roughness S/N) = 8.73 dB.

Table 6 – Response table S/N ratios and means.

Control factors	Tool life (TL)				Surface Roughness (Ra)			
	Level 1	Level 2	Level 3	Delta	Level 1	Level 2	Level 3	Delta
	Response for S/N ratios							
V	**33.69**	27.01	21.20	12.49	8.22	8.59	**9.37**	1.15
f	**32.49**	26.40	23.01	9.48	**9.76**	8.88	7.53	2.23
NC	26.44	**27.90**	27.55	1.46	8.84	**8.99**	8.35	0.64
	Response for means							
V	**54.17**	25.62	12.46	41.70	0.39	0.37	**0.35**	0.04
f	**51.28**	23.97	16.99	34.29	**0.33**	0.36	0.42	0.09
NC	28.15	**32.14**	31.95	3.99	0.37	**0.36**	0.39	0.03

Note that bold values indicate the optimal level of control factors.

decreases when feed rate increased. When feed rate increased from 0.1 mm/rev to 0.15 mm/rev and 0.2 mm/rev, the tool life decreased by 53.19% and 66.8%, respectively. In the milling operations, since there is a rise in cutting force and chip removal volume with increasing feed rate [35], this exposes more load to cutting tool and consequently provokes wear. As shown at Fig. 5(a) in combination with the lowest feed rate and the lowest cutting speed, the highest tool life has emerged. Fig. 5(b) shows that the variation in tool life depending on nanoparticle concentration ratio. It is noticed that the tool life increased owing to increasing the nanoparticle ratio from 0.5 vol% to 1 vol%. This can be attributed to that there is an increase in thermal conductivity of cutting fluid when Al_2O_3 nanoparticle concentration ratio into the base cutting fluid increased. In this way, a faster release of heat occurs in the cutting zone. Due to the additives with high thermal conductivity in base cutting fluid, nano-cutting fluids provide better heat transfer and wettability than its pure form [28]. This therefore plays an important role in reducing wear on tools. Because of the better cooling and lubricating features of the nanofluid, the cutting tool retains its original hardness for a longer time. A similar phenomenon has been reported in

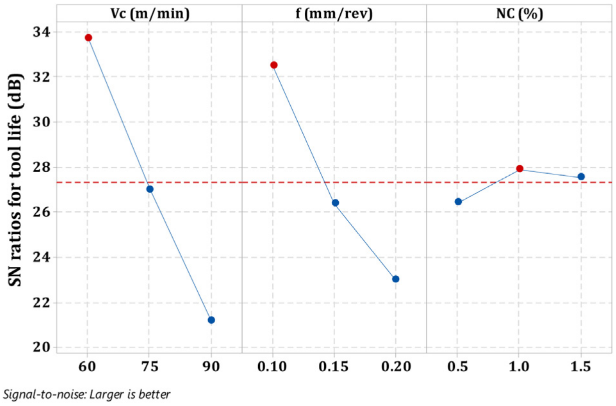


Fig. 3 – Mean of S/N ratios for tool life.

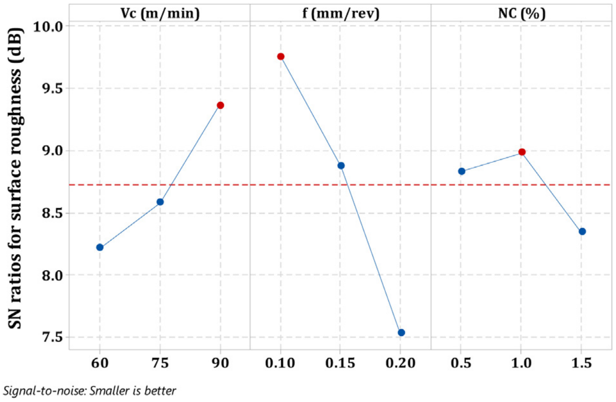
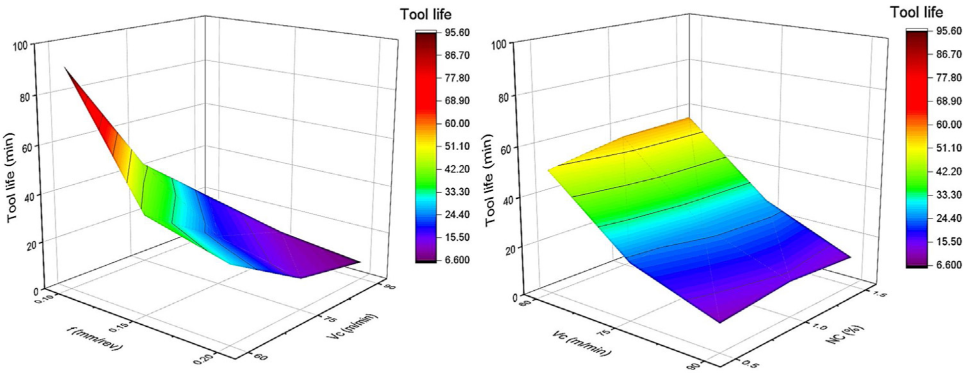


Fig. 4 – Mean of S/N ratios for surface roughness.

previous studies that nanofluids showed higher thermal conductivity than pure MQL and evacuated heat from the cutting zone faster [36]. However, there was a slight decrease in tool life when the concentration ratio continued to increase until 1.5 vol%. This can be explained by precipitation and excessive viscosity with increasing Al_2O_3 nanoparticles, and therefore reduced influence of the fluid that nano-cuts to the cutting zone [32,37].

3.3. *Tool wear and its mechanisms*

In order to clearly see the effect of nanoparticle concentration rates on tool life/wear, by keeping the cutting parameters (feed rate of 0.12 mm/rev and cutting speed of 90 m/min) and material removing time (9 min for each operation), the experiments were carried out at each concentration ratio (0.5, 0.1 and 0.15 vol%) and the worn insert obtained at the end of the experiments are shown in Fig. 6. Accordingly, flank wear was measured as 0.32 mm at 0.5 vol% concentration, while it was measured as 0.22 mm and 0.26 mm at concentrations of 1 vol% and 1.5 vol%, respectively. Further, in the tests carried out with the same cutting parameters until the wear of the tool reached 0.3 mm, the tool life values recorded at 0.5, 1 and 1.5 vol% concentrations were 10 min, 12.3 min and 11.2 min, respectively. Therefore, 1 vol% Al_2O_3 concentration ratio clearly provided an improvement in tool life by up to 23% and 10%, compared to 0.5 vol% and 1.5 vol% concentration, respectively. It is thought that this situation is caused by the decrease of penetration to tool/chip interface because of increase in viscosity of nano-cutting fluid. As shown in Figs. 8–12, SEM and EDAX analyses were carried to determine the tool wear types and their mechanisms of worn insert under 0.5, 1 and 1.5 vol% Al_2O_3 dispersed nanofluid-MQL when milling of Hastelloy C276 alloy. When an evaluation is made on these figures, it was concluded that main wear type was chipping/fracture under all cutting conditions. Because of interrupted machining process in milling, excessive mechanical loads acting on cutting insert and vibration are important factor for chipping-type damages [38]. Diniz et al. [39] stated that when hard workpiece materials and mechanical loads are excessive during the milling, to avoid the chipping/fracture the high toughness cutting tool material (such as cemented carbide tool with high Co content) that has negative axial and radial angles can be used. As illustrated in Fig. 7, micro-adhesion was determined on cutting insert. This also was proved by EDAX analysis of the worn cutting insert at 0.5 vol% Al_2O_3 concentration as shown in Fig. 8. It can be concluded that the applied cooling/lubrication method plays a preventive role for adhesion, since the size of adhesion is at a micro-level. Moreover, in Figs. 7, 9 and 11 the rough view of the worn regions shows that the attrition wear mechanism is effective [40]. With the workpiece material adhesion and



(a) (b)

Fig. 5 – 3D surface plot showing tool life depending on (a) feed rate-cutting speed (b) nanoparticle concentration ratio-cutting speed.

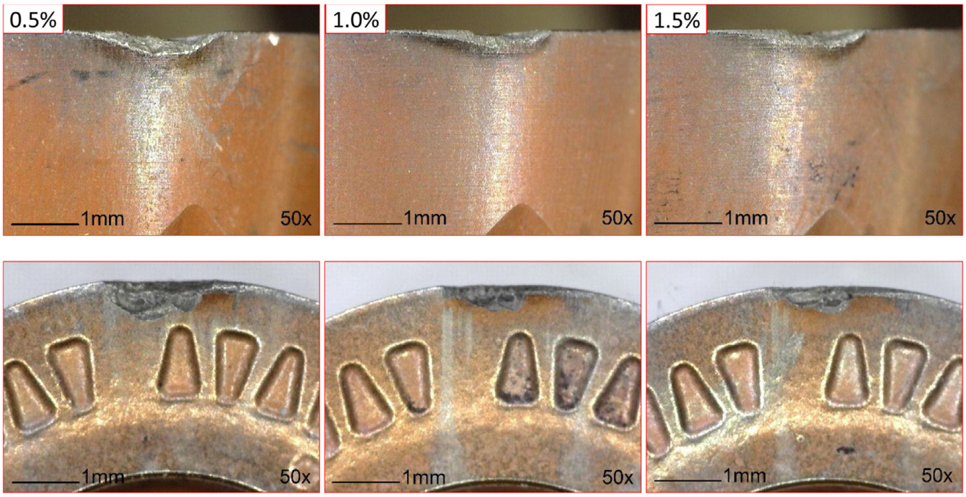


Fig. 6 – The view of flank wear under Al_2O_3 based nano-cutting fluid at different nanoparticle concentrations and fixed cutting parameters (cutting speed of 90 m/min and feed rate of 0.15 mm/rev) after 9 min machining time.

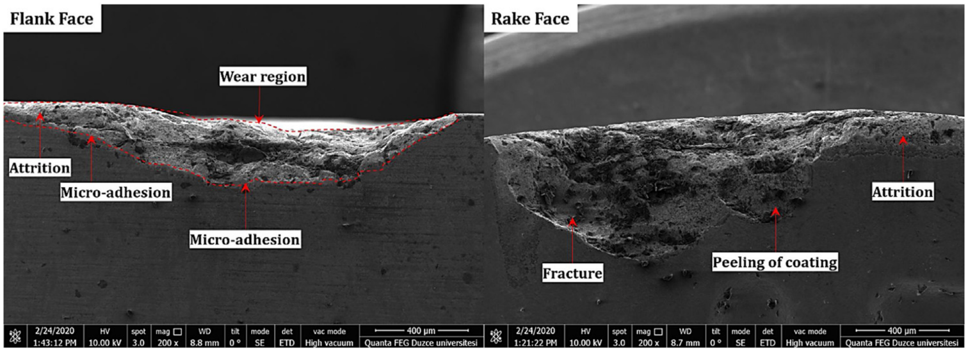


Fig. 7 – SEM analysis for worn cutting insert under 0.5 vol% Al_2O_3 concentration ratio.

sliding onto the cutting tool in a cycle, tool particles emerge and are carried conjunction with the flow of material. The movement between the cutting tool and chip, snacked cutting process, unsteady depth of cut, and vibration produce the unsteady material flow to provoke the attrition [39]. As seen in the rake face of cutting insert (Figs. 7, 9 and 11), it is believed that excessive mechanical loads also lead to the peeling of the coating material. It was evident from Figs. 10 and 12 that no adhered workpiece material was visible on the cutting tool zones, indicating that the applied cooling/lubrication methods namely 1 vol% and 1.5 vol% Al_2O_3 nanoparticles added nanofluid-MQL were suitable for the milling of Hastelloy C276 alloy with CVD $TiCN/Al_2O_3/TiCN$ coated carbide insert.

3.4. *Surface roughness*

Surface texture is among the most important parameters for chip removal operations. It directly affects the performance and production costs of mechanical parts. Therefore, it is essential for indicating optimal milling conditions to obtain high surface quality [41]. The influence of milling parameters, namely feed rate, cutting, speed and Al_2O_3 vol% concentration ratio on average surface roughness is shown as 3D surface plots in Fig. 13. According to Fig. 13(a), cutting speed and surface roughness are inversely proportional relationship; that is, the cutting speed increased when roughness of the surface decreased. It is known to increase the temperature as cutting speed increases [42]. Increasing the temperature allows the workpiece material to soften, thus reducing the cutting force and vibration [43]. It can be assumed that both of these have positively contributed to that surface roughness. In addition to this, there is a linear relationship between feed rate and surface roughness; that is, the surface quality deteriorated as the feed rate increased as illustrated in Fig. 13 (a, b). The feed rate is a function of surface roughness, which means that changes in the feed rate value have a significant effect on the surface roughness [44]. Therefore, a decline in surface quality is expected when there is a rise in feed rate. In fact, the surface quality is the best when there is a combination with high cutting speed and low feed rate. Previous studies have shown that the Al_2O_3 additive incorporated into the cutting fluid improves surface quality in comparison with dry, wet, and base fluid MQL cutting conditions [22,23]. However, it is important to use the optimum nanoparticle ratio to further improve the machining productivity. Fig. 13(b) shows a change in surface roughness according to the concentration ratio of the nanoparticles. It was determined from Fig. 13(b) that the surface condition improved as the concentration ratio increased from 0.5 to 1 vol%. As stated in previous studies, Al_2O_3 nanoparticles with the physical, chemical and

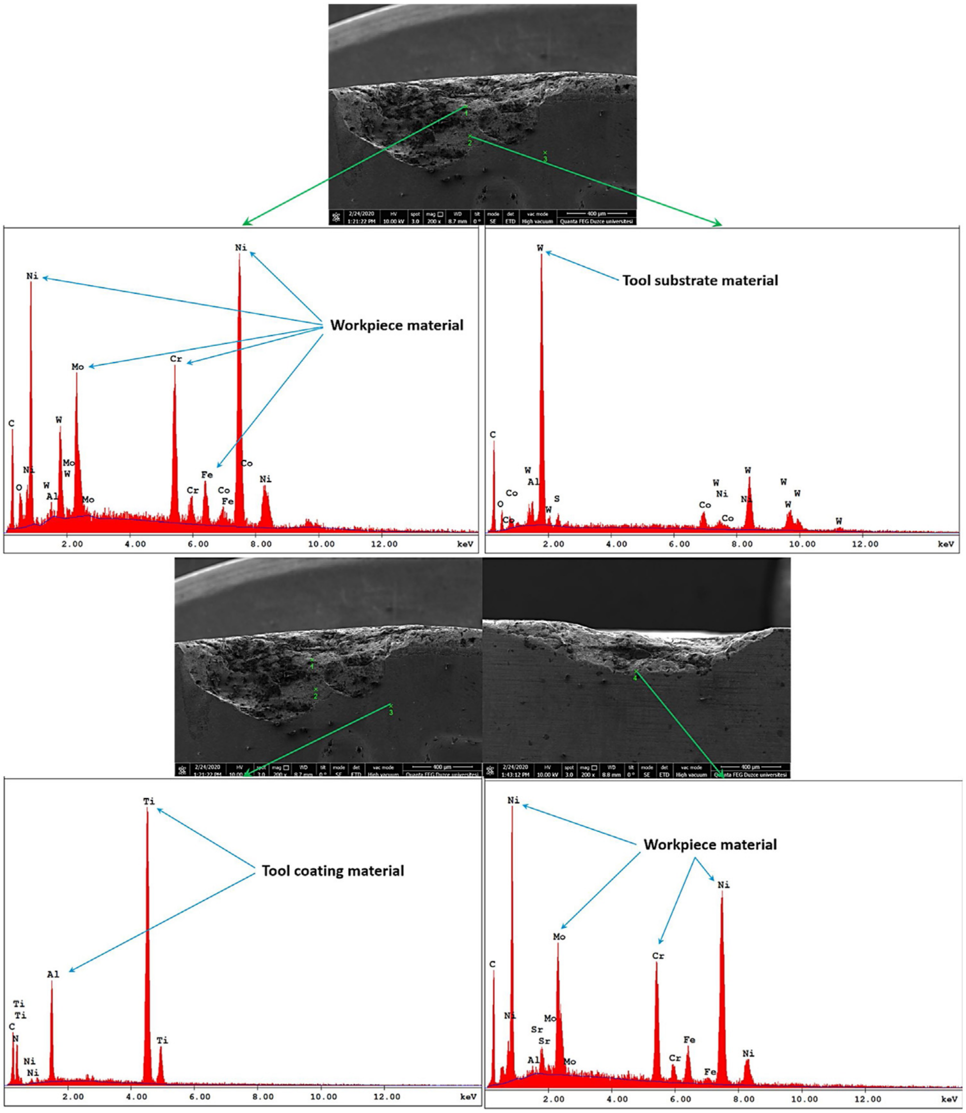


Fig. 8 – EDX analysis for worn cutting insert under 0.5 vol% Al_2O_3 concentration ratio.

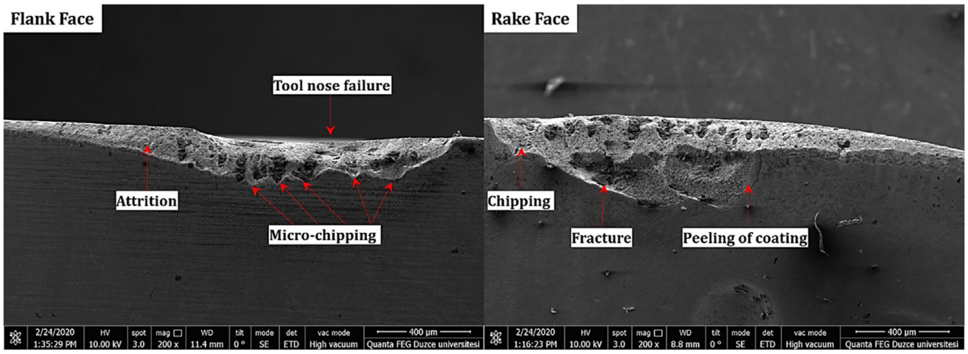


Fig. 9 – SEM analysis for worn cutting insert under 1 vol% Al_2O_3 concentration ratio.

mechanical properties embedded in the cutting oil ensure major developments in wear and friction due to the existence of specific tribological enrichment mechanisms such as defensive film effect, mending effect, rolling effect, third-body effect and tool-chip interface polishing effect, resulting in improved surface roughness [45]. In addition, as the increase in the nanoparticle ratio increases the wettability of the nano-cutting fluid, the cutting fluid spreads over a larger area on the tool-chip surface [46]. Therefore, this provides a better interaction between the machined surface and cutting

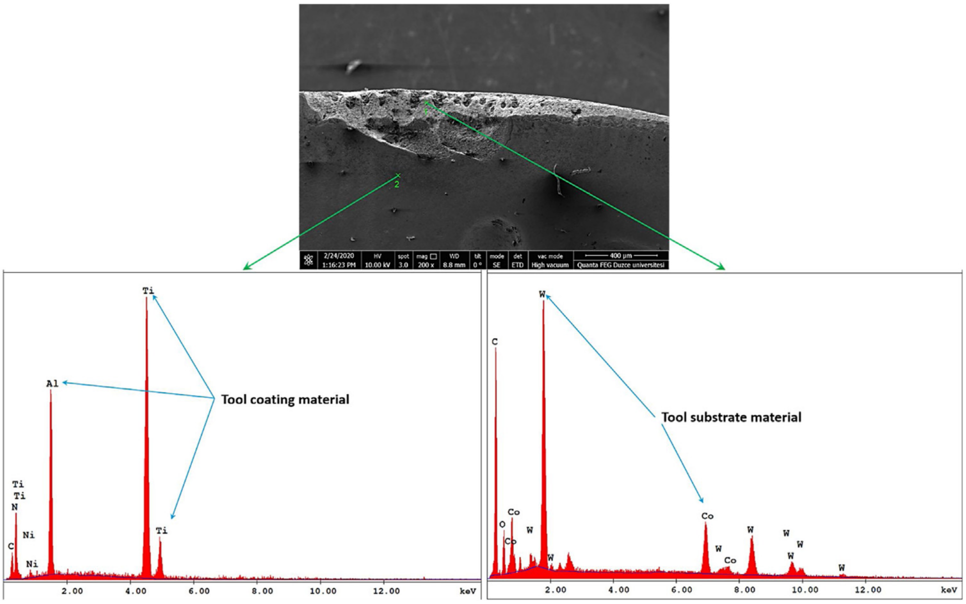


Fig. 10 – EDX analysis for worn cutting insert under 1 vol% Al_2O_3 concentration ratio.

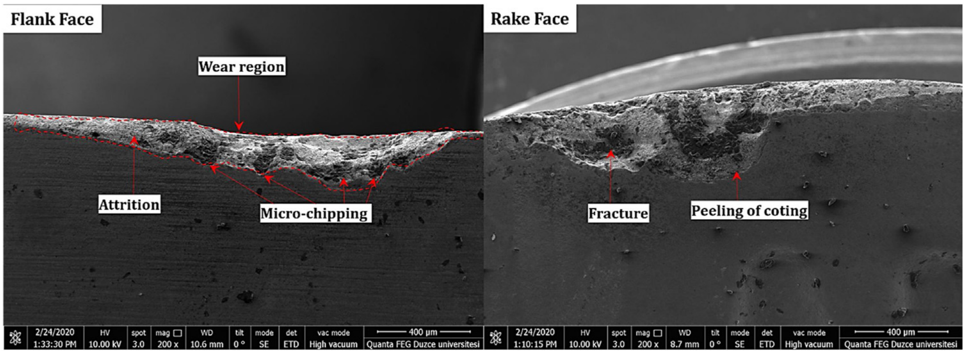


Fig. 11 – SEM analysis for worn cutting insert under 1.5 vol% Al_2O_3 concentration ratio.

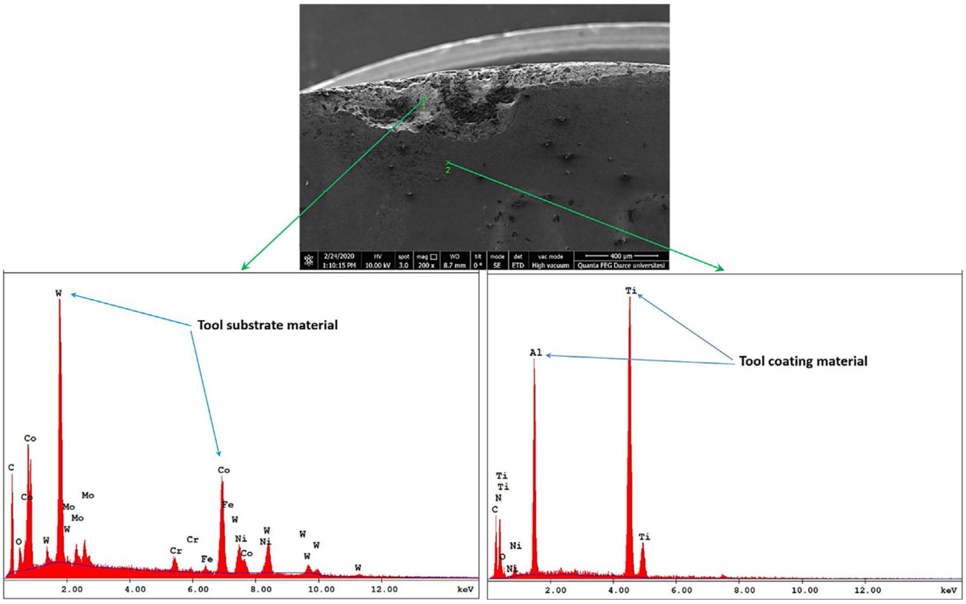
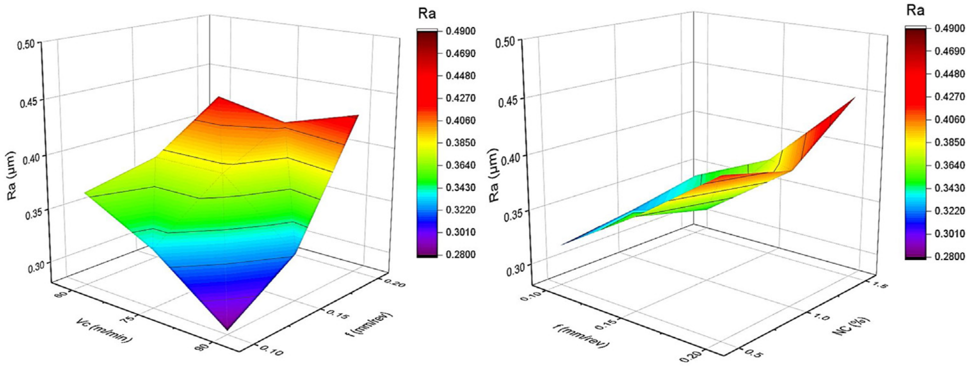


Fig. 12 – EDX analysis for worn cutting insert under 1.5 vol% Al_2O_3 concentration ratio.



(a) (b)

Fig. 13 – 3D surface plot showing surface roughness depending on (a) feed rate-cutting speed (b) nanoparticle concentration ratio-feed rate.

tool. Eventually, the improvement of surface quality with increasing the concentration ratio is attributed to developing properties of cutting fluid. But, when the concentration ratio increased from 1 vol% to 1.5 vol%, an important rise in surface roughness value is noticed (Fig. 13 (b)). The surface roughness value increased by an average of 8.3% between 1 vol% concentration ratio that provided the best surface roughness value and the 1.5 vol% concentration ratio. In other words, while the increase of the concentration ratio up to a certain point improved surface quality, a significant decrease in surface quality was observed after a certain point in both cases at the same cutting parameters. This can be referred to as the precipitation of nanoparticles after a certain point, prevention of cutting fluid to arrive milling area because of an extensive increase of viscosity, and consequently the insufficient cooling/lubrication function of nano-cutting fluid [32].

3.5. *Mathematical models*

The results of this study were used to obtain mathematical models. For this, multiple regression analysis was preferred and Minitab 17 software was used to produce the models. By only considering the effect of main factors (i.e., cutting speed Vc, feed rate f and nanoparticle concentration ratio NC), the linear tool life model was provided in Eq. (3), while the linear surface roughness model was presented in Eq. (4).

$$TL = 182.6 - 1.390V - 342.9f + 3.80\mathrm{NC} \qquad (3)$$

$$Ra = 0.32 - 0.001481V + 0.933f + 0.0211\mathrm{NC} \qquad (4)$$

$R^2_{TL} = 80.32\%$

$R^2_{Ra} = 69.96\%$

When the obtained linear equations are analyzed, it is seen that the coefficient of determination value (R^2) is not sufficient especially for surface roughness. This means that there will be more difference between the estimation values and the real values. Therefore, a quadratic equation with the interactions of the factors should be formed. The reference equation used to generate the quadric equation is expressed in Eq. (5).

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_1^2 + \beta_5 X_2^2 + \beta_6 X_3^2 + \beta_7 X_1 X_2 + \beta_8 X_1 X_3 + \beta_9 X_2 X_3 \qquad (5)$$

In the above equation, y is the response (i.e., tool life and surface roughness). X_1, X_2, X_3 are the values of the independent parameters. The term β is the estimated regression coefficient. Based on Eq. (5), the quadratic equations are generated by including machining parameters and their interaction for tool life and surface roughness. Eqs. (6) and (7) represent the quadric equations showing the relationship between responses and machining parameters.

$$T = \beta_0 + \beta_1 Vc + \beta_2 f + \beta_3 NC + \beta_4 Vc^2 + \beta_5 f^2 + \beta_6 NC^2 + \beta_7 Vcf + \beta_8 VcNC + \beta_9 fNC \qquad (6)$$

$$Ra = \beta_0 + \beta_1 Vc + \beta_2 f + \beta_3 NC + \beta_4 Vc^2 + \beta_5 f^2 + \beta_6 NC^2 + \beta_7 Vcf + \beta_8 VcNC + \beta_9 fNC \qquad (7)$$

Accordingly, Eqs. (8) and (9) obtained from this study represent the quadratic tool life model and quadratic surface roughness model, respectively.

$$T = 612.5 + 8.78Vc - 2746f + 38NC + 0.03421Vc^2 + 4066f^2 - 8.36NC^2 + 16.2Vcf - 0.169VcNC - 31.7fNC \qquad (8)$$

$R^2_{TL} = 97.38\%$

$$R_a = 0.594 - 0.00043Vc - 2.98f - 0.052NC - 0.00003Vc^2 + 5.33f^2 + 0.0733NC^2 + 0.03000Vcf - 0.001111VcNC + 0.067fNC \qquad (9)$$

$R^2_{Ra} = 84.34\%$

These mathematical models can be used to estimate the responses at different levels of process parameters. The coef-

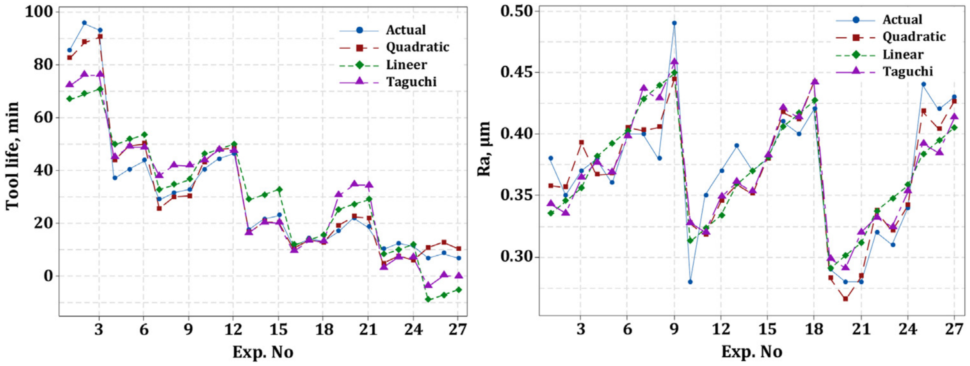


Fig. 14 – A comparison with time series plot of (a) tool life (b) surface roughness.

Table 7 – The comparison of actual results and predicted results.

Point	Linear Model			Quadratic Model			Taguchi		
	Exp.	Calculat.	Error (%)	Exp.	Calculat.	Error (%)	Exp.	Predict.	Error (%)
Tool life									
Optimum $V_1f_1NC_2$	95.5	68.71	28.05	95.5	88.45	7.38	95.5	76.10	20.31
Random $V_1f_3NC_2$	31.4	34.42	9.62	31.4	29.86	4.90	31.4	41.80	33.12
Random $V_2f_2NC_3$	22.8	32.62	43.07	22.8	20.31	10.9	22.8	20.05	12.06
Surface roughness									
Optimum $V_3f_1NC_2$	0.28	0.30	7.14	0.28	0.27	3.57	0.28	0.291	3.93
Random $V_1f_2NC_2$	0.36	0.39	8.3	0.36	0.37	2.8	0.36	0.37	2.8
Random $V_2f_3NC_1$	0.41	0.40	2.44	0.41	0.41	0	0.41	0.42	2.44

ficient of determination value was found to be as 97.38% and 84.34% for tool life and surface roughness, respectively. It can be clearly said that the coefficients of determination value have improved considerably compared to the coefficient of determination that occurred in the linear model. Moreover, Fig. 14 shows the comparison of predicted values obtained with linear, quadric equations, and Taguchi analysis and experiments. It can be seen from Fig. 14 that the model that best fits experimental results is the quadratic model.

Verification experiments are an important mission to analyze the relationship between responses achieved by mathematical models and experimental results. Hence, the verification experiments were performed and compared to the responses obtained from Taguchi analysis and mathematical models by considering the optimum levels of the parameters and randomly selected levels. Accordingly, Table 7 indicates the comparisons of actual experiments, predictions reached by the mathematical models and the Taguchi method. Therefore, it can be clearly seen the prediction values obtained by the quadratic equation covering factors and interactions were close to the real values.

4. Conclusion

During the milling of Hastelloy C276 nickel-based superalloy with CVD TiCN/Al_2O_3/TiCN coated carbide insert, the present work focused on the impacts of Al_2O_3 nanoparticle concentrations and machining parameters on tool life, surface roughness and tool wear. Experimental results were evaluated by S/N ratio analysis, 3D surface plots, and statistical analysis. In addition, multi regression equations (linear model and quadratic model) and the Taguchi method was used to obtain predicted models. Finally, validation tests were carried out. The findings of the study are summarized as follows:

- Parameter groups to provide maximum tool life and minimum surface roughness are determined by using S/N ratios. It was found that optimum parameter design for tool life was cutting speed, level 1 (60 m/min), the feed rate, level 1 (0.10 mm/rev), and Al_2O_3 nanoparticle concentration ration, level 2 (1 vol%). The optimum levels for average surface roughness were level 3 (90 m/min) for cutting speed, level 1 (0.10 mm) for feed rate and level 2 (Al_2O_3/1 vol%) for nanoparticle concentration.
- The tool life decreased significantly as cutting speed increased. The reduction in the tool life with increasing cutting speed up to 90 m/min was determined as 76.98%. When the feed rate increased from 0.1 mm/rev to 0.15 mm/rev and 0.2 mm/rev, the tool life decreased by 53.19% and 66.8%, respectively. In addition, tool life was increased by increasing the nanoparticle ratio from 0.5 vol% to 1 vol%. This is attributed to a rise in thermal conductivity and wettability

ability of the cutting fluid when the Al_2O_3 nanoparticle concentration ratio in the base cutting fluid increased. However, there was a slight decrease in tool life when the concentration ratio continued to increase until 1.5 vol%. This is explained by precipitation and excessive viscosity with increasing Al_2O_3 nanoparticle, and therefore reduced penetration of nano-cutting fluid to cutting zone.

- The surface roughness and cutting speed are inversely proportional, while the feed rate and surface roughness are linearly related. In addition, the surface roughness increased by increasing the concentration ratio from 0.5 vol to 1 vol per cent. The increase of the Al_2O_3 nanoparticles combined in the cutting oil provides notable improvements in the nano-cutting fluid's friction, wear and wettability. However, when the concentration ratio increased from 1 vol% to 1.5 vol%, a significant increase in the surface roughness value is observed. The surface roughness value increased by an average of 8.3% between 1 vol% concentration ratio and 1.5 vol% concentration ratio. This is attributed to the precipitation of nanoparticles after a certain point, prevention of cutting fluid to reach the tool-chip interface because of an extensive increase of viscosity, and consequently the insufficient cooling/lubrication function of nano-cutting fluid.
- By keeping the cutting speed of 90 m/min, feed rate of 0.12 mm/rev and machining time (9 min for each operation) in milling of Hastelloy C276, the flank wear was measured as 0.32 mm at 0.5 vol% concentration, while it was measured as 0.22 mm and 0.26 mm at concentrations of 1 vol% and 1.5 vol%, respectively. Further, in experiments carried out in same cutting parameters until the tool wear reached 0.3 mm, the tool life values recorded at 0.5 vol%, 1 vol% and 1.5 vol% concentrations were 10 min, 12.3 min and 11.2 min, respectively. Therefore, 1 vol% Al_2O_3 concentration clearly provided an improvement by up to 23% and 10% in tool life, compared to 0.5 vol% and 1.5 vol% concentration, respectively. In addition, while chipping/fracture, attrition wear and peeling of coating were observed under all cutting conditions, there was no evidence for workpiece material adhesion at 1 vol% and 1.5 vol% Al_2O_3 based nanofluid-MQL.
- The quadratic mathematical models with the coefficient of determination value of 97.38% and 84.34% for tool life and surface roughness can be used to estimate the responses at various levels of process parameters. The comparison of predicted values, obtained with linear, quadric equations, and Taguchi analysis and actual experiments proved that best fitting to the experimental results is the quadratic model responses.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgment

As the writers, we appreciate the funding of this experimental study from the fund for Research at the Duzce University (Turkey) (Project Number: 2017.07.04.523).

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