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A novel approach of applying copper nanoparticles in minimum quantity lubrication for milling of Ti-6Al-4V

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A B S T R A C T

Presently, nanoparticles are mixed into lubricants to enhance the lubricating and cooling properties. Some research works are available on minimum quantity lubrication (MQL) machining performance of nanofluids suspended with MoS2, Al2O3 and xGnP nanoparticles. However, the deficiency has been found in applying of metal particles like copper (Cu) nanoparticles. In this research, nanofluids have been prepared by mixing four types of nanoparticle (Cu, Graphite, MoS2 and Al2O3) into natural-77 vegetable oil with two concentrations (1 % and 2 %). Taguchi's orthogonal array has used for experimental design. The machining performance of nanofluids are evaluated with regard to the reduction in cutting force and surface roughness during MQL milling of Ti-6Al-4V alloys. Analysis of variance (ANOVA) has carried out to investigate the relative influence of machining parameters. From the analysis, Cu and Graphite nanoparticles have shown higher effects for reducing cutting force and surface roughness. The results of ANOVA have shown that the type and concentration of nanoparticles influence the cutting force significantly. The confirmation tests have carried out and found that copper-nanofluid reduced cutting force and surface roughness by 8.84 % and 14.74 %, respectively. Graphite-nanofluid reduced cutting force and surface roughness by 5.51 % and 21.96 %, respectively.

A R T I C L E   I N F O

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1. Introduction and literature review

Traditional manufacturing transform gradually to green manufacturing in recent years. Eco-friendly machining technique such as MQL has been promoted for its better machinability at higher cutting speed compared with conventional flood cooling. Nevertheless, its capability to carry away the heat is limited [1-3]. With the development of nanoscience and nanotechnology, some researchers mixed nanoparticles into base fluid to improve the characters, such as thermal conductivity, specific heat, and heat transfer coefficient in the field of heat transfer and this approach may provide an alternative way to improve the cooling performance of MQL [4-6].

It is obvious that the heat conductivity coefficient of solid is much higher than that of liquid. The cooling performance may be increased by adding nano-sized solid particles into lubricant, without abrasion and clogging [7]. What's more, the ball bearing effect, protective film, mending effect and polishing effect of nanoparticles also will reduce the friction coefficient and enhance the surface quality [8]. Researchers had investigated the tribological properties or machining performance of some common nanoparticles include metallic particles (Cu, Bi), metallic oxide particles (Al2O3, CuO, TiO2) and nano-diamond (ND) etc [9-11]. Meanwhile, some solid materials such as molybdenum disulfide (MoS2), graphite and boron nitride also have been used for lubricant [12-14]. For instance, MoS2 and xGnP at nano scale have a multilayer structure, which make them effective to reduce the fiction on the chip-tool or tool-workpiece contact interface [13]. However, it's questionable and doubtful that MoS2 has a low dissociation temperature, approximately at 350°C, in oxidizing environments. Compared with MoS2, xGnP has not only a much higher dissociation temperature but also the high aspect ratio, these main advantages make a better lubricity when graphite is applied into MQL process [12]. Just like graphite, hexagonal Boron Nitride (hBN) has a layered structure where each layer is weakly bonded to adjacent layers. The higher dissociation temperature and the aspect ratio of diameter/thickness can be the main advantages of the platelet form of solid lubricant [14]. Besides the tribological properties, there are also some other selection standards when researchers select the types of nanoparticle, such as the nontoxic properties [10].

The conductivity coefficient of copper is up to 401 W/(m·K), which is much higher than the base fluid. Therefore, the lubricant suspended with copper particles may reduce the temperature of cutting zone efficiently [15]. Besides, as a soft metal, the hardness of the tool and workpiece is harder than copper, so it won't scratch the machined surface. When the particles reach to the contact interfaces of cutting zone, they can shape easily, reduce the friction and even mend the surface. G. Liu et al. investigated the mending effect of copper nanoparticle added into lubricant oil [16]. They found that copper nanoparticles do display an excellent mending effect through the Pin-on-disk experiments and SEM observations. Yan J et al. explored the feasibility of four types of nanoparticles (MoS2, GF, Cu and CuO) in diamond turning of reaction-bonded SiC [17]. The results show that grease containing 10 % Cu nanoparticles produced the highest surface quality and the lowest tool wear. Researchers contributed the excellent lubrication to Cu's significantly high micro plasticity. These researches and findings make the possibility that nanofluid suspended with nano-scale copper particles can improve the MQL machining performance compared with pure lubricant, maybe even better than other types of nanoparticles.

Based on the present work, however, there are only a few evaluation papers which focus on the different MQL machining performance of different types of nanoparticle, especially for metal (Cu) nanoparticles. So further research is needed. In this paper, an orthogonal experiment are designed to explore the performance of nano-enhanced lubricant with Cu nanoparticles, as well as other three types of nanoparticles with two concentrations. Meanwhile, the effects of machining parameters such as milling speed, depth of cut and feed rate are investigated. The design of experiments is performed using the Taguchi method. Optimal process parameters are obtained using the range analysis. Moreover, ANOVA is carried out to obtain the significance of parameters influencing on the cutting force (milling force) and surface roughness in the MQL milling of titanium alloy. After the optimization, the confirmation tests are conducted.

2 Experimental procedure

2.1 Workpiece and nano-enhanced lubriacant

Titanium (Ti-6Al-4V) alloy was used as the workpiece material, with chemical composition of 6.5 %Al, 4.25 %V, 0.04 %Fe, 0.02 % C, 0.015 %N, 0.16 %O, 0.0018 %H, and the remaining amount is Ti. The nano-enhanced lubriacant (nanofluids) were prepared by adding four different types of nanoparticles with an average size of 40 nm to the natural-77 vegetable oil, followed by mechanical rabbling in order to suspend the particles homogeneously in the mixture. The four types of nanoparticles are MH-Cu, MH-Graphite, MH-MoS2 and MH-Al2O3, produced by Nanjing Emperor Nano Material CO.,Ltd (China). The natural-77 vegetable oil is the green lubricant, produced by iLC company (Italy). The concentration of each lubricant was 1 % or 2 %, measured by volume. A suspension stability experiment was performed before the machining process and the nanofluids have found stable in the machining process as desired. Fig. 1 shows the nanofluids used in MQL machining process.

2.2 Orthogonal experiment design

The technique of defining and investigating all possible conditions in an experiment involving multiple factors is known as the design of experiments (DOE). The experimental tests are designed on the basis of Taguchi's orthogonal array $L_{16}(4^4 \times 2^1)$, for four factors (types of nanoparticle, milling speed, depth of cut and feed rate) with four levels (4^4) and one factor (concentration) with two levels (2^1) [18, 19]. Range analysis and ANOVA are performed to determine the order and relative influence of the machining parameters respectively, through the SPSS software. The factors and their levels setup for the experiments have shown in Table 1.

1% Cu   2% Cu   1% C   2% C   1% MoS_2 2% MoS_2 1% Al_2O_3 2% Al_2O_3

Fig. 1 Nanofluids used in machining process

Table 1 Factors and levels setup for the experiment

Factors	Level-1	Level-2	Level-3	Level-4
(A) types of nanoparticle	MH-Cu	MH-Graphite	MH-MoS2	MH-Al2O3
(B) milling speed (m/s)	1	1.5	2	2.5
(C) depth of cut (mm)	0.2	0.4	0.6	0.8
(D) feed rate (mm/z)	0.025	0.05	0.075	0.1
(E) concentration	1 %	2 %	-	-

2.3 Experimental setup

The vertical machining centre (VMC 0850B, Shenyang, China) was employed for the slot milling process. This machining centre has three-axis with a maximum rotational spindle speed of 6000 rpm. The milling tool fitted with two teeth inserts ACM300 and diameter of 16 mm have used for experiments. The experimental setup, machining spot and the MQL device are shown in Fig. 2. The MQL device was designed by Beihang University and its related parameters are shown in Table 2 [20, 21].

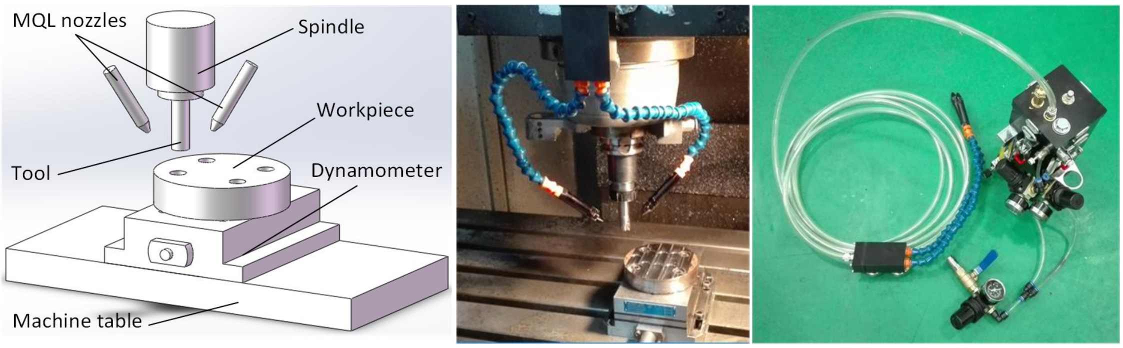

Fig. 2 Experimental setup, machining spot and the MQL device

Table 2 The parameters of MQL device

Nano-enhanced lubricant flow rate	$Q = 24$ mL/h
Air pressure	$p = 0.4$ Mpa (4.0 bar)
Distance from the nozzle tip to the cutting zone	$d = 20$ mm
Nozzle elevation angle	$\alpha = 60°$
Nozzle direction in relation to feed direction	$\beta_1 = 0°$ and $\beta_2 = 120°$

The cutting force measuring system (9257B, Kistler, Switzerland) fitted with high speed precision dynamometer, 5070A charge amplifier and Dyno Ware V2.41 have applied and the cutting forces have recorded in graphical signal. The signal of cutting force were analysed by Dyno Ware software. The resultant of force, F related to the force in X, Y, Z directions has been found from Eq. 1. The surface roughness (S_a) were measured by a 3D optical profiler (CCI MP, TAYLOR HOBSON, England). This equipment is an advanced type of measurement interferometer (a noncontact 3D Profiler), which can measure polished or rough, curved, flat or stepped surfaces. The resultant of surface roughness (S_a) is the average of values got from three measurements. The orthogonal array and the experiment data have recorded in the Table 3.

$$F = \sqrt{F_X^2 + F_Y^2 + F_Z^2} \tag{1}$$

Table 3 Orthogonal array and experimental data

Exp. num	Factors					Experimental parameters					Experimental results	
	A	B	C	D	E	A	B (m/s)	C (mm)	D (mm/z)	E (%)	F(N)	S_a (μm)
1	1	1	1	1	1	Cu	1	0.2	0.025	1	175.49	0.359
2	1	2	2	2	1	Cu	1.5	0.4	0.05	1	251.55	0.422
3	1	3	3	3	2	Cu	2	0.6	0.075	2	376.17	0.464
4	1	4	4	4	2	Cu	2.5	0.8	0.1	2	444.18	0.519
5	2	1	2	3	2	Graphite	1	0.4	0.075	2	345.84	0.489
6	2	2	1	4	2	Graphite	1.5	0.2	0.1	2	251.84	0.452
7	2	3	4	1	1	Graphite	2	0.8	0.025	1	329.05	0.493
8	2	4	3	2	1	Graphite	2.5	0.6	0.05	1	320.80	0.310
9	3	1	3	4	1	MoS2	1	0.6	0.1	1	420.08	0.592
10	3	2	4	3	1	MoS2	1.5	0.8	0.075	1	421.13	0.538
11	3	3	1	2	2	MoS2	2	0.2	0.05	2	323.05	0.537
12	3	4	2	1	2	MoS2	2.5	0.4	0.025	2	336.99	0.482
13	4	1	4	2	2	Al2O3	1	0.8	0.05	2	416.72	0.860
14	4	2	3	1	2	Al2O3	1.5	0.6	0.075	2	301.23	0.358
15	4	3	2	4	1	Al2O3	2	0.4	0.1	1	316.09	0.607
16	4	4	1	3	1	Al2O3	2.5	0.2	0.075	1	237.90	0.353

3 Results and discussion

3.1 Milling force

Fig. 3 indicates the influence on milling force of the factors at different levels. The 3D response surface plots in Fig. 4 have been drawn for all the levels of the five factors, by taking the two factors as variable at the same time. From the main effect plot in Fig. 3(a), the higher influence of MH-Cu, MH-Graphite and MH-Al2O3 particles have been found in reducing the milling force. The application of these three types of nanoparticles has shown reduced milling force more than 60 N as compared to MH-MoS2 particles. Moreover, the flat line between MH-Cu and MH-Graphite has indicated the similar effects on milling force (milling force of 310 N in both cases). Besides the types of nanoparticles, the concentration also remains a dominant factor in the milling process in Fig. 3(e). The illustration shows that the milling force don't always decrease with higher concentration. It has found that nanofluids with 1 % concentration decrease the milling force by 11.6 % as compared to the nanofluids with the concentration of 2 %. From the 3D response surface plot in Fig. 4(d), the smallest milling force has found that factor A (types of nanoparticle) with Cu and factor E (concentration) with 1 % for MQL milling process.

From Fig. 3(b), the milling force found decreased up to 35 N with the increase of milling speed from 1 m/s to 1.5 m/s. However, the milling force found increased again when the milling speed increased to 2 m/s and 2.5 m/s. Finally, this force has reduced slightly in comparisons with the force recorded at 1 m/s. Regarding to this fact, some research contribute this phenomenon to the synthetic and complex influence of cutting temperature and vibration in the milling process [22].

The milling force has found increased with the increase of the cutting depth and the feed rate as shown in Fig. 3(c) and (d), respectively. From Fig. 4(c), it has found that the smallest depth of cut and feed rate results the smallest milling force. Moreover, the difference of the tilt of the plate for each factor in Fig. 4(a), (b) and (c) also shows that the depth of cut has more influence on the milling force as compared to feed rate.

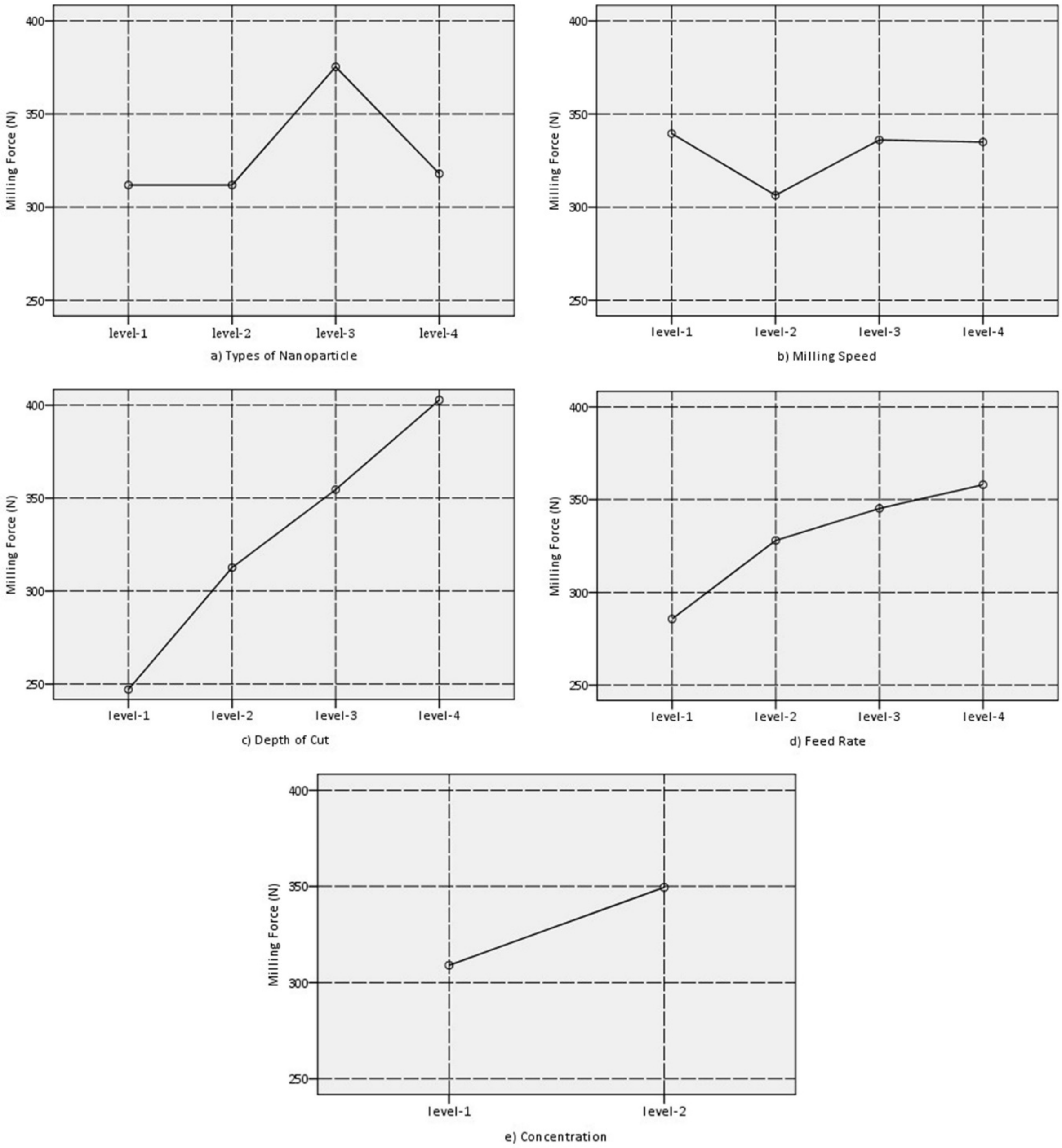

Fig. 3 The milling force and related factors with different levels

Range analysis for milling force

The results of range analysis for milling force have recorded in Table 4. According to the R volume (155.700>72.3575> 63.4650>40.4910>33.0950), the influence order of five controllable factors on milling force has found as C→D→A→E→B. From the range analysis, factor C (depth of cut) has found with the maximum influence and factor B (milling speed) has found with the lowest influence on the force. The tilt of the plot for milling speed and depth of cut (shown in Fig. 4(a), (b) and (c)) indicate the similar results.

From the range analysis in Table 4, the optimal cutting parameters for F were determined as A1B2C1D1E1. Considering the little difference between level 1 (MH-Cu) and level 2 (MH-Graphite) of the type of nanoparticles (factor A), just 0.035, the optimal cutting parameters could also be A2B2C1D1E1.

ANOVA for milling force

The ANOVA has carried out to analyse the effects of types and concentrations of nanoparticle, milling speed, depth of cut and feed rate on the milling force. The results of this analysis have recorded in Table 5.

Table 4 Results of range analysis for milling force

factor\level	Level 1	Level 2	Level 3	Level 4	R
A	311.8475	311.8825	375.3125	317.9850	63.4650
B	339.5325	306.4375	336.0900	334.9675	33.0950
C	247.0700	312.6175	354.5700	402.7700	155.700
D	285.6900	328.0300	345.2600	358.0475	72.3575
E	309.0110	349.5030	--	--	40.4910

Table 5 Results of ANOVA for milling force

Variation of source	Sum of squares(SS)	Degree of freedom(DOF)	Mean of squares(MS)	F ratio	Significance
A	11412.524	3	3804.175	55.99	significant
B	2822.461	3	940.820	13.85	non-significant
C	52305.940	3	17435.313	256.60	highly significant
D	11938.312	3	2186.055	32.17	significant
E	6558.165	1	6558.165	96.52	significant
Error(e)	135.895	2	67.948		
Total	85173.297	15			

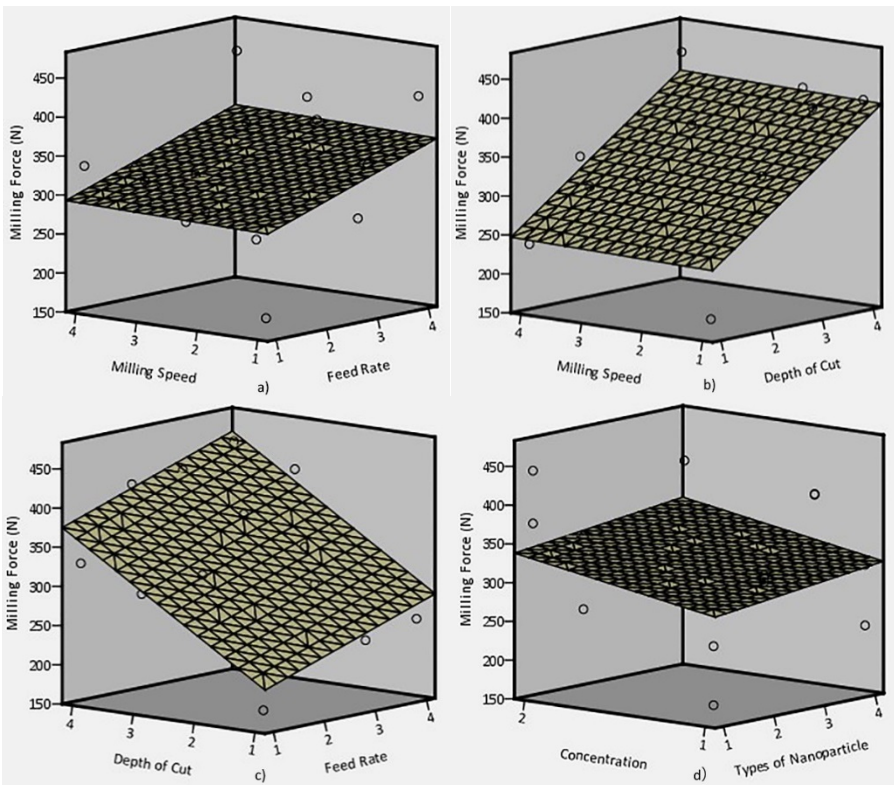

Fig. 4 The 3D response surface plot on the milling force

The data of F Distribution Table as follows: $F_{0.05}(3,2) = 19.2$, $F_{0.05}(1,2) = 18.5$, $F_{0.01}(3,2) = 99.2$, $F_{0.01}(1,2) = 98.5$. The statistical significance of each factor for the milling force are gained by comparing the data with the F ratio in Table 5 as follows: $F_A = 55.99 > F_{0.05} = 19.2$, $F_B = 13.85 < F_{0.05} = 19.2$, $F_C = 256.60 > F_{0.05} > F_{0.01} = 99.2$, $F_D = 32.17 > F_{0.05} = 19.2$, $F_E = 96.52 > F_{0.05} = 18.5$. From the ANOVA analysis, we can conclude that the depth of cut has a highly significant influence on the milling force, while the types of nanoparticle, the concentration and the feed rate significantly influence the milling force. The milling speed has shown non-significant influence as compared to the other factors on the force.

3.2 Surface roughness

Fig. 5 has shown the influence of factors on surface roughness with different levels. The 3D response surface plots have shown in Fig. 6. From the main effect plot in the Fig. 5(a), (e) and 3D response surface plot in Fig. 6(d), it has been found that the types of nanoparticles (factor A) and the concentration (factor E) have a remarkable influence on the surface roughness. The little difference has been found for MH-Cu and MH-Graphite with the value of S_a=0.44 μm. This value is lower than the value of S_a=0.54 μm that is found by adding MH-MoS2 and MH-Al2O3. With the increase of concentration from 1 % to 2 %, S_a found increased correspondingly by 13.2 %. The surface roughness has found change within the scope of 0.3-0.6 μm for all the experiment.

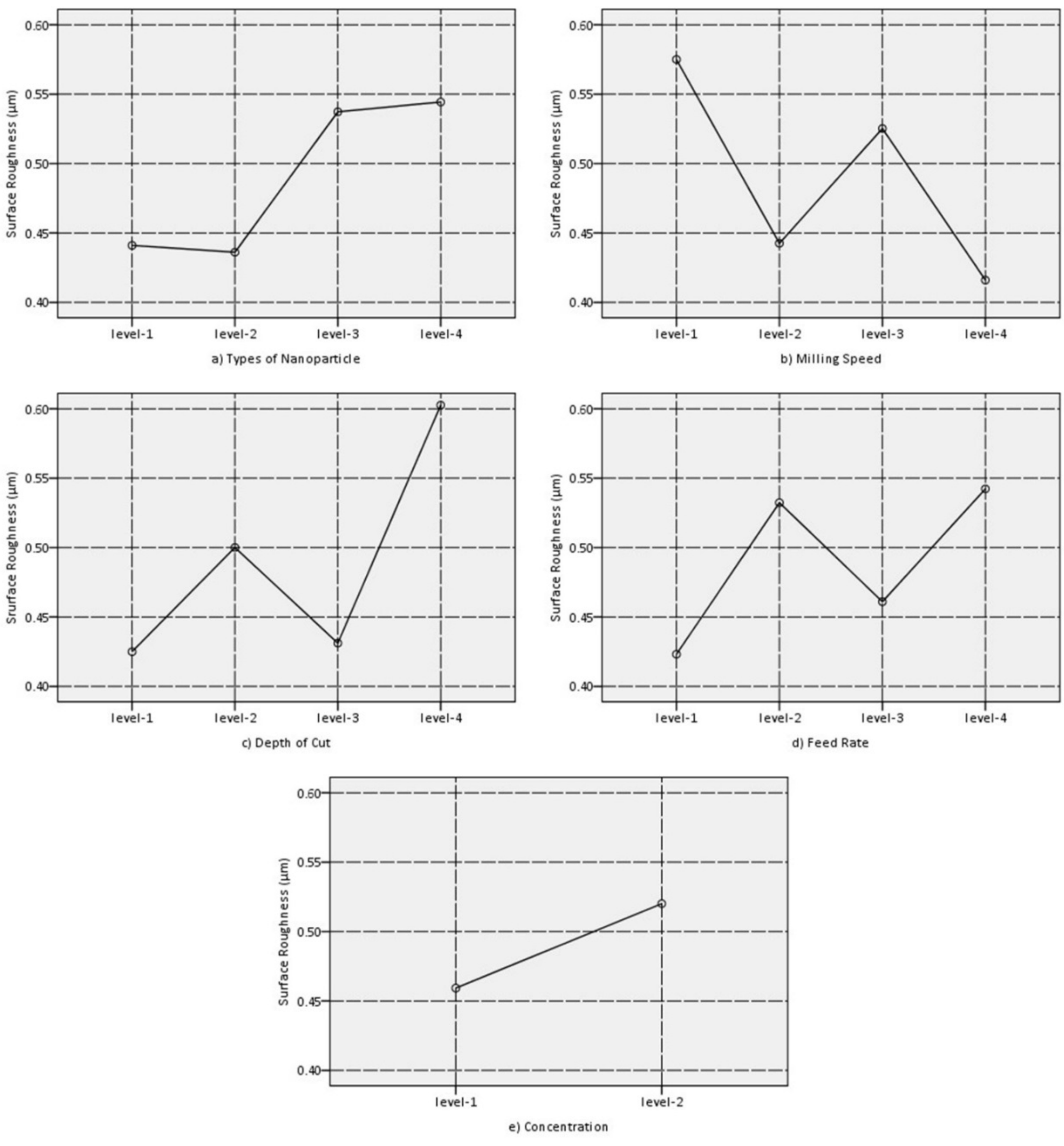

Fig. 5 The surface roughness and related factors with different levels

From the 3D response surface plot shown in Fig. 6(a), (b) and (c), the surface roughness has found increased with the increase of depth of cut and feed rate. With the increase of milling speed from 1 m/s to 2.5 m/s, the surface roughness has observed to decrease. But it may not be monotone seen from the main effect plot in Fig. 5(b), (c) and (d). The difference between the tilt of the plot for milling speed, depth of cut are not greater and is slightly higher than the feed rate. From Fig. 6, it has found that the combination of the milling speed set at level 4, depth of cut set at level 1 and feed rate set at level 1, the best surface quality (the smallest surface roughness) can be achieved.

Range analysis for surface roughness

The results of range analysis for surface roughness have reported in Table 6. According to the R volume (0.17762>0.15896> 0.11915> 0.10822> 0.06081), the influence order of five controllable factors on surface roughness has found as C→B→D→A→E. From the range analysis, it can be found that the depth of cut has the highest influence on S_a, the types and concentration of nanoparticle don't influence the roughness much. The result is different from some other research which indicate that the feed rate rank first in the influence order [23]. We may contribute this phenomenon to the influence of nanoparticles or the unreasonable choice of depth of cut, which cause excess vibration in the machining process.

From Table 6, the optimal cutting parameters for surface roughness have been found as A2B4C1D1E1. Considering the little difference between level 1 and level 2 of the type of nanoparticles (factor A), just 0.00493, the optimal cutting parameters could also be A1B4C1D1E1.

ANOVA for surface roughness

In this section, the ANOVA has carried out to analyse the effects of types and concentrations of nanoparticle, milling speed, depth of cut and feed rate on the surface roughness. The results of this analysis have tabulated in Table 7.

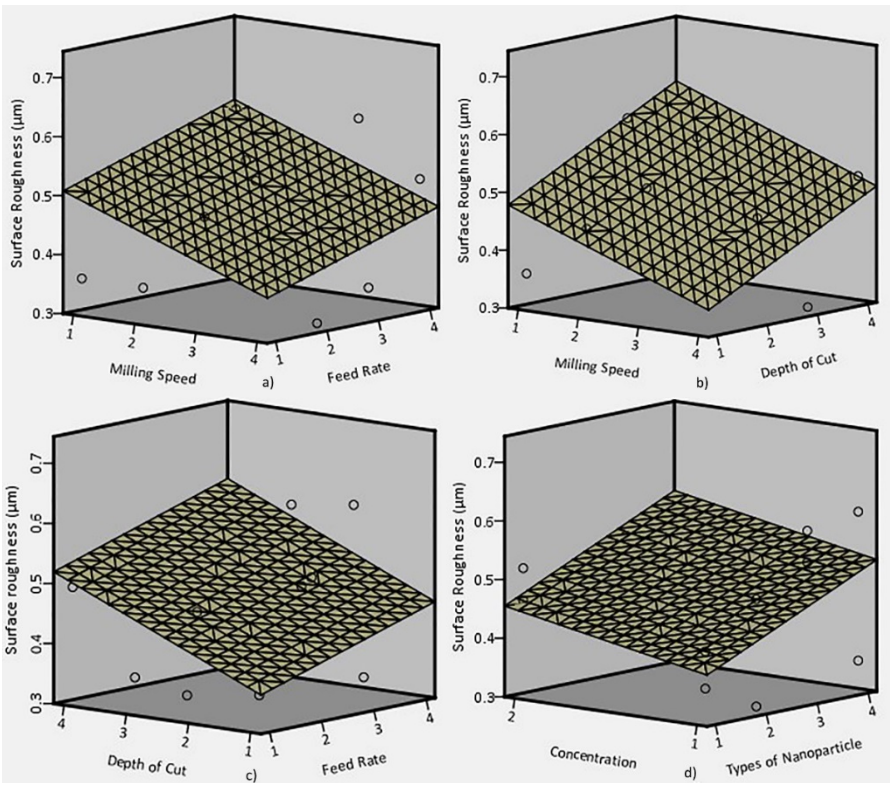

Fig. 6 The 3D response surface plot on the surface roughness

Table 6 Results of range analysis for surface roughness

factor\level	Level 1	Level 2	Level 3	Level 4	R
A	0.44105	0.43612	0.53729	0.54434	0.10822
B	0.57499	0.44254	0.52525	0.41603	0.15896
C	0.42499	0.50004	0.43116	0.60261	0.17762
D	0.42316	0.53233	0.46100	0.54231	0.11915
E	0.45930	0.52011	--	--	0.06081

Table 7 Results of ANOVA for surface roughness

Variation of source	Sum of squares(SS)	Degree of freedom(DOF)	Mean of squares(MS)	F ratio	significance
A	0.04195	3	0.01398	1.753	non-significant
B	0.06476	3	0.02159	2.706	non-significant
C	0.08188	3	0.02729	3.421	non-significant
D	0.03935	3	0.01312	1.644	non-significant
E	0.01479	1	0.01479	1.854	non-significant
Error(e)	0.01596	2	0.00798		
Total	0.25868	15			

The data of F Distribution Table follows as:$\mathrm{F}_{0.05}(3,2) = 19.2$, $\mathrm{F}_{0.05}(1,2) = 18.5$. The statistical significance of each factor for surface roughness is obtained by comparing the data with the F ratio in Table 7 as follows:$\mathrm{F}_\mathrm{A} = 1.753 < \mathrm{F}_{0.05} = 19.2$, $\mathrm{F}_\mathrm{B} = 2.706 < \mathrm{F}_{0.05} = 19.2$, $\mathrm{F}_\mathrm{C} = 3.421 < \mathrm{F}_{0.05} = 19.2$, $\mathrm{F}_\mathrm{D} = 1.644 < \mathrm{F}_{0.05} = 19.2$, $\mathrm{F}_\mathrm{E} = 1.854 < \mathrm{F}_{0.05} = 19.2$. From the ANOVA, it has found obviously that the types of nanoparticles, milling speed, depth of cut, feed rate and the concentration have non-significant influence on the surface roughness.

For the Mean of squares(MS) of factor A and D and E is smaller than the double of error, it's better to classify them into the error, the results of ANOVA analysis after the adjustment is shown in Table 8.

We can get the following data from F Distribution Table: $\mathrm{F}_{0.05}(3,9) = 3.86$. By comparing the data with the F ratio in:$\mathrm{F}_\mathrm{B} = 2.706 < \mathrm{F}_{0.05} = 3.86$, $\mathrm{F}_\mathrm{C} = 3.421 < \mathrm{F}_{0.05} = 3.86$, we can get the same conclusions that the five factors have non-significant influence on the surface roughness. Previous researchers claimed the similar results about effect of cutting parameters on the surface roughness [24].

Table 8 Results of ANOVA for surface roughness after the adjustment

Variation of source	Sum of squares(SS)	Degree of freedom(DOF)	Mean of squares(MS)	F ratio	significance
B	0.06476	3	0.02159	2.706	non-significant
C	0.08188	3	0.02729	3.421	non-significant
Error(e)	0.11205	9	0.01245		
Total	0.25868	15			

4. Confirmation tests

In order to confirm the accuracy of the optimal parameters got by the orthogonal experiments, the confirmation tests are arranged. The confidence interval (CI) is employed to verify the quality characteristics of the confirmation experiment. The confidence interval for the predicted optimal values is calculated using Eq. 2, Eq. 3 and Eq. 4 [18, 19, 25]:

$$\mathrm{C.\,I.} = X_0 + \sqrt{\frac{F_\alpha(f_1, f_2)}{n_e} V_e} \tag{2}$$

$$X_0 = \overline{X_0} + \sum_{i=1}^{k} (\overline{X_i} - \overline{X_0}) \tag{3}$$

$$n_e = \frac{n}{1 + \sum_{i=1}^{k} DOF} \tag{4}$$

Where $F_\alpha(f_1, f_2) =$ variance ratio for DOF f_1 and f_2 at the level of significance α. The confidence level is $(1 - \alpha)$. $f_1 =$ DOF of mean (which always equals 1), $f_2 =$ DOF of error term, $V_e =$ variance of error term, $n_e =$ number of equivalent replications, $n =$ number of the orthogonal experiments ($n = 16$), $k =$ level number of each factor ($k = 4$ or 2). The optimal parameter is A1B2C1D1E1 for milling force and A2B4C1D1E1 for surface roughness. The 95 % and 99 % confidence interval for the milling force are $\mathrm{C.I.} = 143.016 \pm 33.165$ and $\mathrm{C.I.} = 143.016 \pm 76.526$, respectively. The 95 % and 99 % confidence interval for the surface roughness are $\mathrm{C.I.} = 0.2008 \pm 0.1670$ and $\mathrm{C.I.} = 0.2008 \pm 0.2403$, respectively. Moreover, the feasibility of nano-MQL is determined compared with the performance of MQL. If there are no nanoparticles in the lubricant, the parameters are defined as A0B×C×D×E0. The experimental setup and the results have shown in the Table 9. 3D view of the surface of an experiment has shown in Fig.7.

Table 9 Experimental setup of confirmation tests

Condition	Parameters	Results	
		F(N)	Sa(μm)
MQL	A0B2C1D1E0	128.05	-
	A0B4C1D1E0	-	0.346
Nano-enhanced MQL	A1B2C1D1E1	116.73	-
	A1B4C1D1E1	-	0.295
	A2B2C1D1E1	121.0	-
	A2B4C1D1E1	-	0.270

It's seen that nano-copper has the best machining performance with regard to cutting force and nano-Graphite has the best machining performance with regard to surface roughness in the experimnt. Compared with MQL machining, nanofluid suspended with nano-copper can reduce the cutting force and surface roughness by 8.84 % and 14.74 %, respectively. Nanofluid suspended with nano-Graphite can reduce the cutting force and surface roughness by 5.51 % and 21.96 %, respectively. Compared with MQL machining, nano-enhanced MQL got better machining performance both on cutting force and surface roughness. Besides, the results of the confirmation tests all located in the range of 95 % and 99 % CI, which indicated that the optimal combination of the parameters are effectively.

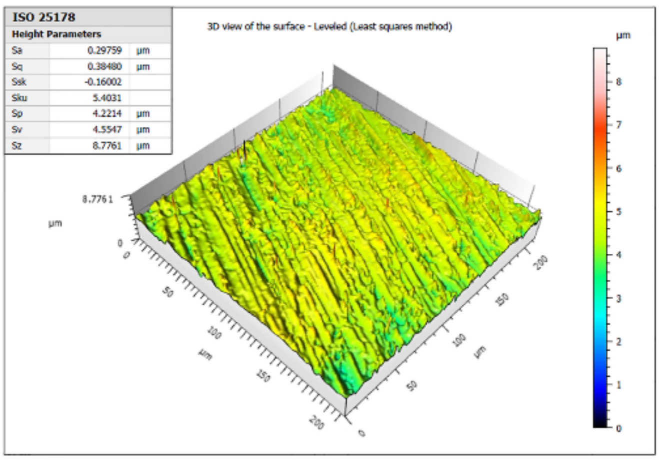

Fig. 7 3D view of the surface of an experiment

5. Conclusion

In this paper, Cu nanoparticles, as well as other three types of nanoparticles were applied into the research and the optimal of cutting parameters in nano-enhanced MQL milling Ti-6Al-4V to improve machining performance were investigated. The conclusions have been drawn as follows:

- Nanoparticles of copper and graphite have a distinct and similar effect on reducing the cutting force and the surface roughness. The types of nanoparticles play a more important role than the concentration for better machining performance. What's more, higher concentrations didn't lead to better machining performance.
- It can be seen from the range analysis that the types and the concentration of the nanoparticles have much more influence than the milling speed on the cutting force. But the contrary is the case for surface roughness. And obviously, depth of cut always play a key role both on the cutting force and surface roughness.
- From the ANOVA analysis, we can conclude that depth of cut has a highly significant influence on the milling force, the types of nanoparticles, the concentration and the feed rate influence the cutting force significantly. The milling speed doesn't have much effect on the force. While the all five factors have non-significant influence on the surface roughness.
- The confirmation tests show that compared with MQL machining, copper nanofluid reduced the cutting force and surface roughness by 8.84 % and 14.74 %, respectively. Graphite nanofluid reduced the cutting force and surface roughness by 5.51 % and 21.96 %, respectively.

The combination of different types of particles as additives added into pure lubricant may be explored as future work. This research work has good application for practical machining at industry level.

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