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ORIGINAL ARTICLE

Experimental study on minimal nanolubrication with surfactant in the turning of titanium alloys

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Abstract The superiority of minimal nanolubrication for effective, efficient and cleaner machining environment has been widely discussed in the literature. However, due to their high surface energy, nanoparticles coagulate or agglomerate easily, which makes it difficult to disperse them in the base fluid. Hence, the addition of a small amount of surfactant should be able to overcome this issue. This research elucidates and extends fundamental knowledge regarding the effect of a sodium dodecyl benzene sulfonate surfactant mixed with different nanoparticle concentrations towards the sustainable machining of titanium alloy using design of experiment methodology. The experimental results indicate that the inclusion of a sodium dodecyl benzene sulfonate surfactant in aluminium oxide nanolubricant provides the best lubricating properties for the machining of the titanium alloy. At 0.4 wt% of nanoparticles and a feed rate of 0.1 mm/rev, minimum values of surface roughness and power consumption can be achieved. Meanwhile, minimal tool wear can be attained by application of a 0.6 wt% nanoparticle concentration and 0.1 mm/rev feed rate. Further statistical analyses emphasized that the feed rate was the most significant factor that influenced the surface roughness and power consumption, while the mixture of nanoparticles with surfactant and feed rate has the greatest effect on the tool wear resistance of the cutting insert.

Keywords Nanolubrication · Tool wear · Surface roughness · Power consumption · Turning · Titanium alloy

1 Introduction

The function of a lubrication system in the metal machining process is to serve as a coolant as well as a lubricant. The application of cutting fluids can generally improve the tool wear resistance and results in a good surface finish by reducing thermal distortion and flushing away machined chips. The main aim of all conventional metal-removal operations is to increase productivity and reduce costs by machining under the most practical conditions along with the longest tool life, fewest rejects and lowest downtime. However, excess lubrication in machining activities increases machining cost due to the difficulties of disposing and recycling excess lubricant. Repeated use of a cutting lubricant under the conditions of extreme heat and pressure may induce chemical changes in the cutting fluids. Chemically changed lubricants containing chlorinate are not easily and legally disposed of in the environment. In addition, exposure of machine operators to chlorinated paraffin lubricants could lead to chlorine acne, skin reactions and respiratory problems. The effectiveness of the recycled and chemically altered lubricants for machining certain alloys is often reported to be reduced and can cause corrosion of the machined surfaces [1]. Due to these environmental and health concerns, it is becoming a strict requirement of most manufacturers to reduce the volume of lubricant waste. According to Lawal et al. [2], any attempt to minimize or avoid the use of coolants or lubricants can only be addressed by replacing the functions normally assigned to the coolants with other methods or techniques. Debnath et al. [3] provided a comprehensive review of environmentally friendly cutting fluids and cooling techniques for the machining processes.

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Table 1 Chemical compositions of the Ti-6Al-4V

Type	Al	V	C	N	O	H	Fe	Y	Other	Ti
Min	5.5	3.5	–	–	–	–	–	–	–	–
Max	6.75	4.5	0.08	0.5	0.2	0.0125	0.3	0.005	0.1	Balance

Table 2 Detail specifications of the tool insert

Brand	Kennametal
ANSI catalogue number	VBMT 3305F
Grade	K10U
Insert material	Carbide-PVD Coated
Coating description	TiN
Nose radius	0.2 mm
Insert type	Positive
Hardness	2300 (Vickers)

The main aim of that article was to systematically review various approaches of past researchers to determine the minimum amount of cutting fluid that can be used in machining. The minimized cutting fluids have a similar or even better cutting performance compared to the wet cooling methods. The authors asserted that future research should concentrate on the optimum utilization of high-performance nano-based lubricant productivity in the machining industry.

Nanolubricants are an alternative that are being explored in an attempt to replace the conventional technique of cutting fluid application as well as a response to environmental concerns. In the modern manufacturing era, nano-integrated manufacturing has gained a wide impetus to grant sustainability and result in ecologically harmless engineering processes. Nanolubricants are a type of new engineering material consisting of nanometre-sized particles dispersed in ordinary heat transfer fluids, such as water, glycol and oil-based fluid [4]. Metal, metal oxides, ceramics and non-metals, such as carbon nanotubes and graphene, are common types of nanoparticles. The ability of nanolubricants to reduce friction, reduce cutting forces, improve surface roughness, prevent workpiece burning and transfer heat effectively have made this fluid well-suited for machining purpose. The nano-size of the particles makes it easy for the fluid to slide over the cutting area and produce a rolling effect. This rolling effect works as a ball-bearing function, reducing direct metal contact, alleviating friction and heat generation. In addition, the enhancement of the thermal conductivity of the base fluid with the inclusion of nanoparticles has been reported to be directly proportional to the volume concentration [5]. This enhancement is believed to produce hydrodynamic interactions and lead to a better thermal transport ability.

With its outstanding properties and low cost, this novel engineering nanolubricant shows a great potential as an alternative to the conventional lubrication method. In addition, in some review articles on sustainable metal working fluids for the machining domain [2, 3, 5], the authors highlighted the extended benefits of nanolubricants when channelled through a minimal quantity lubrication (MQL) system. This new concept of lubrication is an eco-friendly and efficient solution because the machining process is enhanced with a very low consumption of lubricants. Sayuti et al. [6], for instance, reported a novel application of nanolubricants in an MQL system for the turning process of AISI4140 hardened steel. In their study, applications of SiO_2 nanolubricants in a mist condition along with other parameters, such as air pressure and nozzle orientation, were attempted to improve tool wear resistance and at the same time produce a good surface quality. The authors asserted that introduction of the SiO_2 nanolubrication system would provide much less friction and a superior surface quality. This result is mainly attributed to the tribological properties of SiO_2 that reduce the coefficient of friction at the

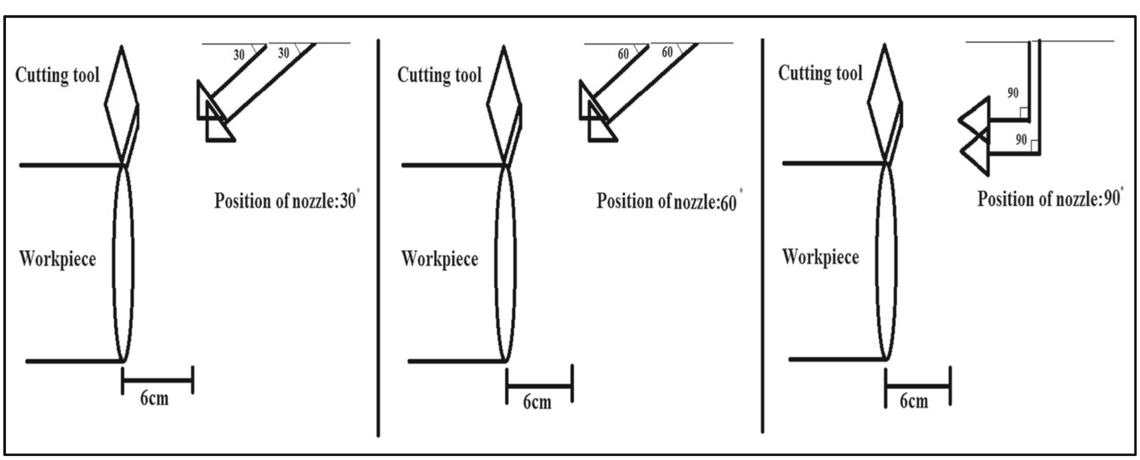


Fig. 1 Position of nozzle angle

Table 3 Detail specifications of SolCut cutting fluids

Appearance/description	Clear re-brown fluid with mild odour (opaque white when emulsified)
Boiling point	<316°C
Solubility in water	Soluble. Product forms an emulsion when added to water.
Specific gravity	Typically 0.89 g/ml
Vapour pressure	Expected to be <0.0005 kPa @ 20°C
Flash point	>150°C
Flammability	Classified as a Class C2 combustible
Viscosity @ 40°C	30–40 mm^2/s
RI	1.0
pH	8.17

tool-chip interface during machining, acting as billions of nano-scale quasi-spherical structural rolling elements [6]. The authors believed that the cutting zone temperature would be diminished, leading to lower tool wear and, consequently, improved surface quality. In another study, [7] explored the wear mechanism of a tungsten carbide insert in the end milling of an aluminium alloy, Al6061-T6 with water-based TiO_2 nanofluids. The authors claimed that the major benefit of the water-based nanofluids MQL was evident in terms of the edge integrity of the cutting insert, which was seen in very few cases, especially with a higher depth of cut [7]. The authors attributed this finding to the cooling effect produced by the latent heat of vaporization of water, which results in reducing the cutting zone temperature.

In an earlier study, Rahmati et al. [8] reported the effects of molybdenum disulphide (MoS_2) nanoparticles suspended in ECOCUT HSG 905S base oil for end milling aluminium alloy Al 6061-T6. The nanolubricant was supplied to the cutting zone through an MQL system with a nozzle that had an orifice diameter of 1 mm. The presence of MoS_2 nanoparticles in the tool-workpiece interfaces was reported to improve the quality of the machined surface [8]. This improvement was attributed to the rolling, filling and polishing action at the tool-workpiece interface. Extending on the work of Rahmati et al. [8], Uysal et al. [9] employed the same type of nanoparticle in machining AISI 420 martensitic stainless steel using an uncoated tungsten carbide tool in the milling operation. The author asserted that minimum tool wear and surface roughness values were obtained in the nano MQL milling at a 40 ml/h MQL flow rate.

Setti et al. [10] recently reported the performance of grinding Ti-6Al-4V under the influence of nanofluids. According to the authors, in the grinding process, the friction between the abrasive grains and workpiece is a key issue that governs the main grinding output, namely, the grinding force, power, specific energy and wheel wear. The existence of a high friction force increases heat generation and leads to thermal damage in the surface layer of the ground work. Therefore, the authors attempted to use various concentrations of Al_2O_3 and CuO nanoparticles (40-nm particle size) in water for grinding the aforementioned titanium alloys. For the sustainability of the grinding process, the MQL approach was employed. The main result that the authors claimed was in terms of the significant roles of the type of nanoparticles and concentrations in reducing friction during grinding. The authors also asserted that the application of nanofluid leads to the reduction of tangential forces and grinding zone temperature, and this reduction was evident from the short C-type chip formation. In another interesting study, Padmini et al. [11] reported the improvement of the cutting force, tool wear and surface roughness by using vegetable oil-based nanofluids during machining of AISI 1040.

In all of the aforementioned studies, the authors failed to highlight any occurrence of agglomeration of nanoparticles in the base liquid after a period of time. Several previous studies suggested that agglomeration of nanoparticles often limits the superiority of nanolubricants. Due to the high surface energy

Table 4 Orthogonal array L9

Experiment	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 5 Experimental setting of the controlled factors

	L1	L2	L3
Per cent of nanoparticles, % (A)	0.2	0.4	0.6
Cutting speed, m/min (B)	75	85	95
Feed rate, mm/rev (C)	0.10	0.15	0.20
Angle of nozzle, ° (D)	30	60	90

Table 6 Surface roughness and its calculated S/N ratio

Experiment	A	B	C	D	R_a (μm)	S/N ratio
1	1	1	1	1	1.285	−2.178
2	1	2	2	2	2.991	−9.516
3	1	3	3	3	5.855	−15.351
4	2	1	2	3	2.898	−9.242
5	2	2	3	1	3.552	−11.009
6	2	3	1	2	1.314	−2.372
7	3	1	3	2	4.675	−13.396
8	3	2	1	3	1.401	−2.929
9	3	3	2	1	3.001	−9.545

of nanoparticles, it is easy for them to coagulate in and difficult to disperse in the base fluid [4]. These reactions cause sedimentation of nanoparticles, which makes nanolubricants unstable and ineffective. One of the solutions used to address this issue is an additive known as a surfactant. A surfactant, which stands for 'surface acting agent', is a compound that lowers the surface tension of a liquid, increasing the contact between the liquid and another substance. This additive interacts with the surface of a liquid to change its properties. It is imperative to emphasize that some studies carried out with respect to nanolubricant stability have proven that the presence of a surfactant can stabilize the nanolubricant [12–14].

In addition to the aforementioned research gap, previous studies by [6, 8, 15] did not include all of the possible factors that can influence the machinability performance using nanolubricants. The cutting speed and feed rate were not considered in their study and were set to be constant. Furthermore, their experimental investigations were limited to other types of materials, namely, aluminium alloys and hardened steel with SiO_2 nanoparticles in a base fluid. Hence, in the present study, empirical investigations on the effect of controlled parameters and the determination of the optimum parameters for machining titanium Ti-6Al-4V under Al_2O_3 nanolubricants with surfactant (in an MQL setting) have been explored. For a systematic experimental investigation, a Taguchi Design of the Experimental methodology was employed.

Table 7 Response table for surface roughness

Level	A	B	C	D
1	−9.015	−8.272	−2.493	−7.578
2	−7.541	−7.818	−9.435	−8.428
3	−8.623	−9.089	−13.252	−9.174
Δ	1.474	1.271	10.759	1.596
Rank	3	4	1	2

2 Experimental procedure

2.1 Preparation of nanolubricants

Nanolubricants of Al_2O_3 with a (<50 nm) particle size of 0.2, 0.4 and 0.6 wt%, suspended in soluble cutting oil (SolCut), were prepared using an ultrasonic liquid processor for 4 h at a 25% amplitude. The output power set at 100 W at 18–23°C. The additional sodium dodecyl benzene sulfonate (SDBS) of 1 wt% was used to alleviate any agglomeration in the mixture. This percentage of surfactant was found to be a suitable proportion based on our earlier experimental investigations [16, 17] and also the study by Debnath et al. [3].

2.2 Workpiece material and experimental measurement procedure

As mentioned above, Ti-6Al-4V, one type of titanium alloy, was used as the workpiece for the cutting process. This titanium alloy is classified as Grade 5 material and is the most common type being used in the aerospace industries. This alloy has a low thermal conductivity, low modulus of elasticity and high chemical affinity. Due to these characteristics, it is a very difficult and challenging material to cut or machine. The workpiece used was in a round bar shape, with a length of 100 mm and diameter of 50 mm. Table 1 summarizes the chemical composition of the workpiece. During the cutting process, a 5-mm diameter of material was removed in each cutting to a 45-mm length. The process was continued until 30 mm of the diameter of the workpiece had been removed. For each cutting process, the surface roughness and tool wear were measured. A surface roughness tester, Mitutoyo F-3000, was used for the surface roughness measurement. Several positions on the workpiece were selected to measure the surface roughness to ensure the consistent and reliable measurement of the surface roughness. A Leica microscope with Dino capture software was used to measure the growth of tool wear on the flank face of the insert. The wear on the flank face of the cutting insert was selected as the main tool failure mode. Scanning electron microscopy (SEM) was employed for the further enhancement or understanding of the tool wear mechanism. SEM was carried out on selected cutting inserts under different machining conditions. Meanwhile, in recent studies, it has been reported that the power consumption data can be used to indicate the machining performance and also the sustainability index. To obtain the power consumption data, the electrical current was measured and recorded during the cutting process using a Picolog data logger. Then, this measurement was converted into power based on Eq. 1, as follows.

$$\text{Power (watt)} = IV\sqrt{3} \quad (1)$$

where I is the current (A) measured and V is the voltage (415 V) for a three-phase machine.

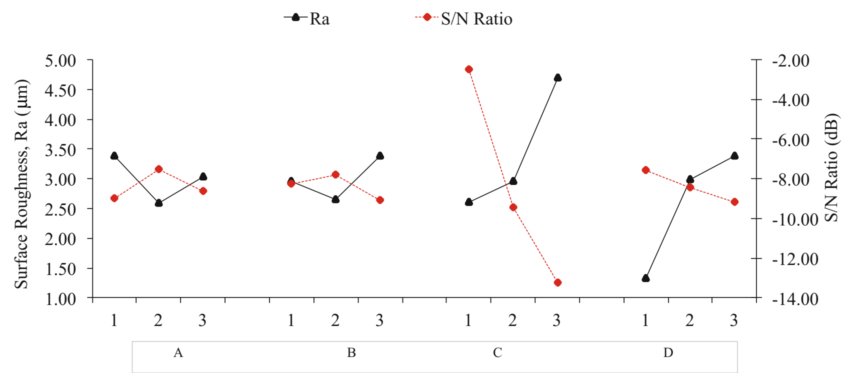


Fig. 2 Average R_a values and its *S/N* ratio

Another possible influence on the machinability performance is the position of the MQL nozzle. Thus, in this study, the positions of the nozzle were based on the angles shown in Fig. 1. This range of angles was within the range of nozzle angles tested by [15]. These MQL orientations are anticipated to efficiently and effectively supply the mist nanolubricants to the tool-chip interface area. MQL supplies the air and lubricant at a pressure of 6 Bar and flow rate of 40 ml/h. Meanwhile, the type of cutting insert used and the cutting fluids specifications are tabulated in Tables 2 and 3, respectively.

2.3 Experimental design

Design-of-experiment (DoE) is a widely employed statistical technique that is often applied to simultaneously evaluate individual and/or interactive effects of controlled parameters on the product or process performance. In this research, the Taguchi fractional factorial approach was employed as the experimental method. The optimization process was conducted using orthogonal array L9 (Table 4). For this type of orthogonal array, there are three levels of settings for each factor, which are levels 1, 2 and 3. The parameters or control factors are the volumetric percentage of nanoparticles, cutting speed, feed rate and angle of nozzle, as shown in Table 5. As the desired output (surface roughness, tool wear and power consumption) is focused on the smaller value, 'the smaller the better characteristic' was chosen. The *S/N* ratio was calculated as

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}x^2\right) \quad (2)$$

where n is the number of trials for the experiment and x is the experimental output.

Apart from the *S/N* ratio analyses, analysis of variance (ANOVA) was used as a statistical tool by means of the table and a Fisher test to explore the significant contribution of each parameter towards the machinability performance. The variation of the calculated *S/N* ratio for each parameter and the associated error were applied to generate the ANOVA table, and a critical Fisher value with a 95% confidence level was selected for the *F*-test.

Table 8 Tool wear and its calculated S/N ratio

Experiment	A	B	C	D	TW (mm)	*S/N* ratio
1	0.2	75	0.10	30	0.195	14.199
2	0.2	85	0.15	60	0.216	13.311
3	0.2	95	0.20	90	0.234	12.616
4	0.4	75	0.15	90	0.19	14.425
5	0.4	85	0.20	30	0.186	14.610
6	0.4	95	0.10	60	0.149	16.536
7	0.6	75	0.20	60	0.147	16.654
8	0.6	85	0.10	90	0.12	18.416
9	0.6	95	0.15	30	0.142	16.954

3 Results and discussion

3.1 Surface roughness

Experimental values of surface roughness and its calculated *S/N* ratio are tabulated in Table 6. Based on the results, the lowest surface roughness was observed in the first experiment, 1.285 μm, while the highest surface roughness value was found in the third experiment, 5.855 μm. As the feed rate and cutting speed increase, the surface roughness deteriorates. This finding is in line with the metal-cutting theory, which can be explained by the formula given below [18]. From this formula, we can postulate that the amount or value of surface roughness is directly proportional to the feed rate. The formula for surface roughness is given according to Eq. 3, as follows.

$$R_a = \frac{f^2}{31.2 r_n} \quad (3)$$

where f is the feed (mm/rev) and r_n is the tool tip radius (mm).

Surprisingly for the cutting speed, the results obtained were somewhat contrary to the metal cutting theory, in which a

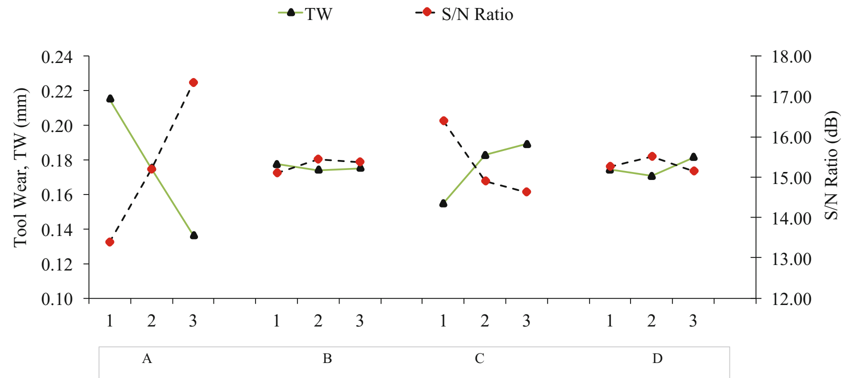


Fig. 3 Average TW values and its *S/N* ratio

higher cutting speed is supposed to cause less damage to the surface finish due to the low contact time between the tool and material. For the titanium alloy, a different case occurs. When cutting this material, even at a low cutting speed, a significant increase in the temperature at the cutting edge of the tools is observed. The increase in temperature can result in a loss of strength as well as plastic deformation and weakening of the cutting tool material. Therefore, as the cutting speed or spindle speed is elevated, more wear is propagated to the tool. Hence, this wear leads to defects on the surface finish or poor surface qualities [19]. With regard to the nozzle angle, it was determined that at 30°, the nozzle angle had the potency to effectively spread nanolubricants into the cutting region. This effective penetration of nanolubricants was suspected to promote a better cooling and lubrication effect. This result is in line with the reported study by [15] which studied end milling of the AISI4140 alloy with SiO_2 nanolubrication. This angle orientation is able to accelerate the flow of fluids into the cutting zone and obtain a better surface finish. Meanwhile, previous literature has reported that the increase of the nano-oil concentration increases the growth of the thin protective film on the machined surface that increases the quality of the machine surface [20]. However, this study may not be true when other factors, such as feed rate and cutting speed, are taken into consideration. The results of our research clearly showed that the concentration of the nanoparticles plays only a small role in the surface roughness compared to the feed rate and nozzle angle. It is worth noting that in previous research, the feed rate factor was maintained as constant, while the percentage concentration was varied. Thus, their results may not comprehensively evaluate the influence of the controlled factors on the surface roughness of the machine workpiece. Table 7 shows the response table for surface roughness. Based on the rank observed from this table, it can be implied that feed rate was the factor that most influenced surface roughness, followed by the nozzle angle and concentration of nanoparticles. This conclusion was reached by observing the value of delta, which shows that the feed rate was the dominant factor influencing the surface roughness result compared to the other three factors. Cutting speed has the least effect on the surface roughness.

Table 9 Response table for tool wear

Level	A	B	C	D
1	13.375	15.093	16.384	15.254
2	15.190	15.446	14.897	15.500
3	17.341	15.369	14.626	15.152
Δ	3.966	0.353	1.758	0.348
Rank	1	3	2	4

For a better representation, the data from this table are plotted in Fig. 2. The maximum value for factors A and B belongs to level 2, with *S/N* ratio values of −7.541 and −7.818, respectively, for factors A and B. The maximum value for factor C and D belongs to level 1, with *S/N* ratio values of −2.493 and −7.578, respectively. Therefore, the combination of the parameters for the best surface finish can be observed at level A2, B2, C1 and D1. This level corresponds to the nanoparticle percentage concentration of 0.4 wt%, cutting speed of 85 m/min, feed rate of 0.10 mm/rev and nozzle angle of 30°. Here, we highlight that the desired percentage concentration of nanoparticles, 0.4 wt%, and an orientation angle of 30° for improved surface roughness are somewhat close to the results reported by [15] during end milling of AISI4140 steel with SiO_2 nanoparticles. In their study, the surface roughness was enhanced with a 0.5 wt% concentration in mineral oil and a 30° nozzle orientation angle. However, because their study was limited to a constant cutting speed and feed rate, a comparison of these cutting conditions (feed and speed) on the surface roughness with our findings cannot be made.

3.2 Tool wear

In normal occurrence, the pattern of tool wear that can be observed on the tool insert after the turning process can be divided into three types, namely, crater wear, flank wear and corner or nose wear. Among the aforesaid types of wear, the

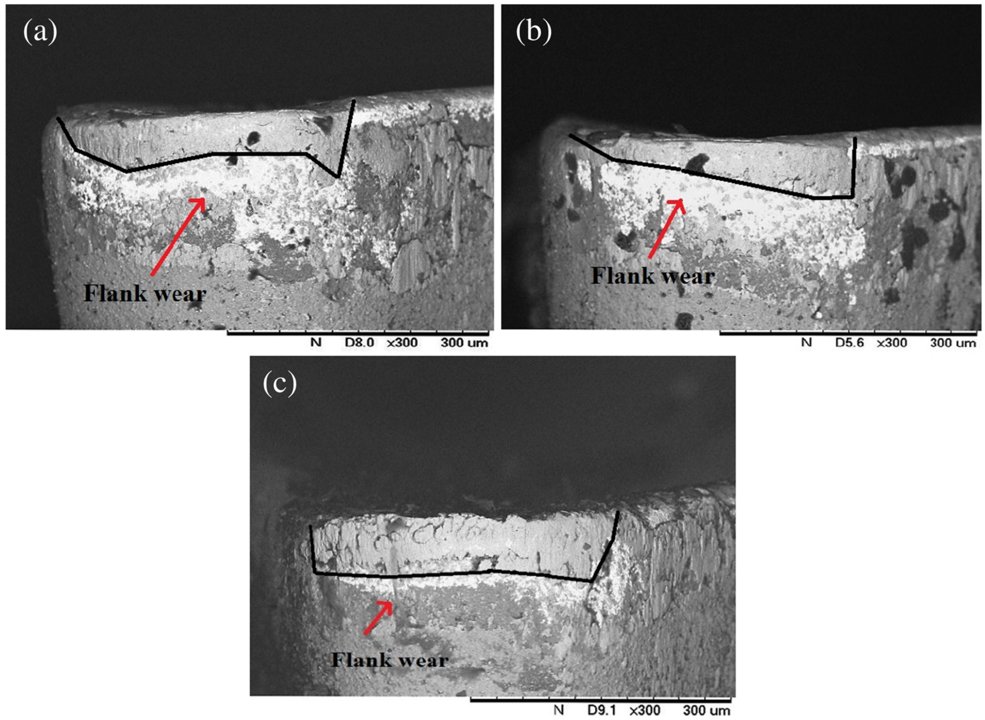


Fig. 4 Tool wear images under SEM. **a** 0.2% nanoparticles concentration. **b** 0.4% nanoparticles concentration. **c** 0.6% nanoparticles concentration

principal flank wear (V_B) was given the most priority in the present study, as this wear has a direct influence on the machining cost and product quality. The experimental results and calculated values of the *S/N* ratio for the tool wear are found in Table 8. Based on this table, it is evident that the amount of tool wear was the lowest for experiment number 8, with 0.12-mm flank wear, while the highest tool wear was recorded in experiment number 3, with 0.234-mm flank wear. Figure 3 shows the main effect plot, which gives a better understanding of the experimental results. It is apparent that the value of the *S/N* ratio for the tool wear increases with the change in the concentration of nanoparticles, directly implying that a higher concentration of nanoparticles leads to a lower tool wear during machining, possibly because, as claimed by Rahmati et al. [8], at a high concentration of nanoparticles, more kinetic energy can be transferred into the workpiece surface and more heat can be dissipated. The low-friction behaviour of nanoparticles is effective in minimizing the frictional effects on the tool-workpiece interface, hence reducing the cutting force. With respect to the feed rate, experimental analyses showed that the tool wear becomes excessive as the feed rate increases. Practising a high feed rate generates a greater cutting force per unit area of the chip-tool contact on the rake face and the work-tool contact on the flank face [21]. Additionally, the effect of the feed rate on the tool wear mechanism has also been explained in the tool life equation as in Eq. 4 (extended Taylor's equation). Clearly, the tool life is inversely proportional to the feed rate. As the feed rate increases, the tool life decreases [22]. The decrease in tool life is mainly attributed to the acceleration of the tool wear on either the flank face, rake face or nose of the cutting insert.

Table 10 Power consumption and its calculated S/N ratio

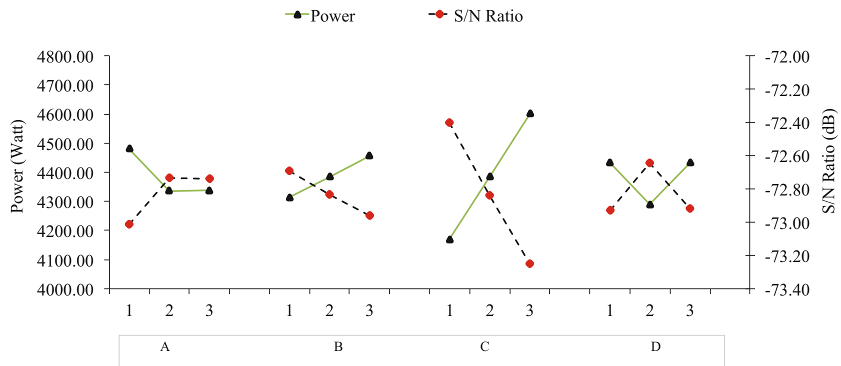
Experiment	A	B	C	D	Power (Watt)	*S/N* ratio
1	0.2	75	0.10	30	4241	−72.549
2	0.2	85	0.15	60	4385	−72.839
3	0.2	95	0.20	90	4816	−73.654
4	0.4	75	0.15	90	4313	−72.695
5	0.4	85	0.20	30	4600	−73.256
6	0.4	95	0.10	60	4097	−72.250
7	0.6	75	0.20	60	4385	−72.839
8	0.6	85	0.10	90	4169	−72.401
9	0.6	95	0.15	30	4457	−72.980

$$T = \frac{C}{v^x f^y d^z} \tag{4}$$

where C is a constant, v is the cutting speed (m/min), f is the feed rate (mm/rev), d is the depth of cut (mm), and x, y and z are constants based on the type of material.

The contribution of the cutting speed on the tool wear appears marginal compared to the contributions of the feed and nanoparticle concentration, possibly due to the use of a low and narrow range of cutting speeds, which were below 100 m/min. Theoretically, the tool wear grows exponentially as the cutting speed increases. However, the change of cutting speed in this study cannot discriminatively influence the tool wear above that of other controlled factors. Table 9 gives the response table for tool wear after the machining process. For

Fig. 5 Average power consumption and its *S/N* ratio



factor A (nanoparticle % concentration), the highest *S/N* ratio value was at level 3, with 17.341, whereas factor B (cutting speed) and D (nozzle angle) were at level 2, with 15.446 and 15.500, respectively. For factor C, which is the feed rate, the highest value of the *S/N* ratio is at level 1, with 16.384. Thus, the optimum setting suggested by the *S/N* ratio for tool wear can be achieved at level A3, B2, C1 and D2, corresponding to a percentage concentration of 0.6 wt%, 85 m/min speed, feed rate of 0.1 mm/rev and angle of 60°. Apparently, these results more or less agree with Sayuti et al. [15], where the minimum tool wear was obtained with a 0.5 wt% nanoparticle concentration in mineral oil, 2-Bar air stream pressure and a 60° nozzle orientation angle. Based on the ranking of the *S/N* ratio (determined from the delta value), the concentration of nanoparticles was the factor that had the greatest effect, followed by the feed rate, cutting speed and nozzle angle. Figure 4 shows the tool wear images captured under a scanning electron microscope. These images obviously indicate that the tool was affected by two- or three-body abrasion of the hard titanium alloy workpiece on the carbide insert.

3.3 Power consumption

The third machining output that was selected in this study was power consumption. Table 10 represents the results and the *S/N* ratio for power consumption. Experiment number 3 apparently consumed the highest power of 4.82 kW, while experiment number 6 consumed the least power, 4.10 kW. The graph in Fig. 5 shows that increasing the feed rate leads to higher power consumption. When a higher value of feed rate is selected, the axes motors need to move faster and hence consume more power. The same situation occurs when a higher value of cutting speed is used due to the movement of the spindle [23]. At 60° of the nozzle angle, lubrication was believed to be supplied effectively into the cutting region. The effective penetration of the nanolubricants between the cutting regions reduces the contact between the tool and material. Thus, the nanolubricant provides efficient cooling and lubrication effects. Concerned with the nanoparticle concentration, a higher amount of nanoparticles should lead to lower friction, which, as a result, can reduce power consumption during the cutting process. It is quite surprising that the result is not as expected. Therefore, further explanation or experimental validation is required to understand the theory behind this phenomenon. Table 11 shows a response table for power consumption. For factors A and D, level 2 seems to be dominant, with values of −72.734 and −72.642, while for factors B and C, the highest value belongs to level 1, with values of −72.694 and −72.400, respectively. Therefore, the optimum setting suggested by the *S/N* ratio for low power consumption can be achieved at level A2 (0.4 wt%), B1 (75 m/min), C1 (0.1 mm/rev) and D2 (60°). Focused on the rank of the *S/N* ratio, the feed rate was the strongest affecting factor, followed by the nozzle angle, nanoparticle concentration and cutting speed. This conclusion was reached according to the delta value shown in the response table (Table 11).

Table 11 Average S/N ratio for power consumption

Level	A	B	C	D
1	−73.014	−72.694	−72.400	−72.928
2	−72.734	−72.832	−72.838	−72.642
3	−72.740	−72.961	−73.249	−72.917
Δ	0.280	0.267	0.850	0.286
Rank	3	4	1	2

4 Evaluation of significant factors

Analysis of variance is a statistical tool that can be used to identify the effectiveness of machining parameters on the performance evaluation. From the percentages of influence, a factor that is not significant can easily be spotted so that adjustment and improvement of the machining performance can be made or suggested. *F*-tests were performed to prove the significance of each factor. In the present study, this analysis was carried out with a significance level of 0.05 (confidence level of 95%). If the F value for a factor exceeds the $F_{0.05}$ from the Fisher table, the contribution of that factor is significant.

Table 12 ANOVA analysis for surface roughness

Source	DOF	Sum of square	Mean square	F ratio	F value	Contribution (%)
A	2	3.497	1.748			1.857
B	2	2.490	1.245			1.322
C	2	178.5	89.257	59.641	6.944	94.789
D	2	3.827	1.913	1.279	6.944	2.032
Error	0	0	–			0
Total	8	188.3				100
(Error)	4	5.986	1.497			

Due to zero errors, combining the two lowest factors as pool error created a dummy error. Hence, in this analysis, only the significance of two dominant factors is focused on. The ANOVA results for surface roughness, tool wear and power consumption are presented in Tables 12, 13 and 14, respectively. For the surface roughness, factor C (feed rate) is the dominant factor, which shows the highest contribution of 94.8% followed by factor D (nozzle angle) with 2.03%. Factor A (nanoparticle concentration) only contributes approximately 1.86%, and the last is factor B (cutting speed), with 1.32%. From the two dominant factors, factors C and D, calculation of the *F*-test shows that only factor C is significant. This finding is in line with that of several previous studies [21, 24, 25] that claimed that the feed rate was the factor that had the greatest effect on the surface roughness compared to the other factors.

For tool wear, factor A (nanoparticle concentration) was the dominant factor with the greatest contribution of 80.38%, followed by factor C (feed rate), with 18.26%, while factor B (cutting speed) and factor D (nozzle angle) contributed only a small effect, 0.70 and 0.65%, respectively. The *F*-test shows that both of the dominant factors, factors A and C, are significant. Previous study conducted by Najihah et al. [7] suggested similar results, in which the concentration of nanoparticles affects the tool wear. For the power consumption, factor C (feed rate) was the dominant factor, with highest contribution of 72.17%, followed by factor D and A, with 10.47 and 10.25%, respectively. B contributed marginally at 7.11%. The *F*-test also indicated a similar conclusion. This finding is in line with [23, 26]. They reported that the feed rate is one of the most important factors for power consumption during the machining process.

5 Conclusions

Applications of nanolubricant in the machining domain have been undertaken by researchers in recent years to achieve the goal of a sustainable production environment. Similarly, in this research work, a novel understanding of the effects of nanolubricants with a surfactant and various cutting parameters while turning the Ti-6Al-4V alloy were investigated. The important following conclusions can be drawn from the results obtained:

- The comprehensive parameter settings suggested by the Taguchi method produced the optimal surface roughness, tool wear and power consumption conditions for a more sustainable use of nanolubricants in turning the titanium alloy.
- A parametric combination of A2, B2, C1 and D1, which are 0.4%, 85 m/min, 0.1 mm/rev and 30°, respectively, for the nanoparticle concentration, cutting speed, feed rate and nozzle angle, respectively, is the optimum setting for the superior surface roughness. The increase of the nanoparticle concentration was supposed to increase the growth of the thin protective film on the machined surface so that the quality of the machine surface could be improved. However, in this study, the feed rate was more

Table 13 ANOVA analysis for tool wear

Source	DOF	Sum of square	Mean square	F ratio	F value	Contribution (%)
A	2	23.652	11.826	118.631	6.944	80.380
B	2	0.207	0.103			0.703
C	2	5.4	2.687	26.957	6.944	18.265
D	2	0.192	0.096			0.652
Error	0	0	–			0
Total	8	29.4				100
(Error)	4	0.399	0.100			

Table 14 ANOVA analysis for power consumption

Source	DOF	Sum of square	Mean square	F ratio	F value	Contribution (%)
A	2	0.154	0.077			10.246
B	2	0.107	0.053			7.114
C	2	1.1	0.541	8.315	6.944	72.174
D	2	0.157	0.079	1.206	6.944	10.466
Error	0	0	–			0
Total	8	1.5				100
(Error)	4	0.260	0.065			

influential on the surface quality, which more or less agrees or is in line with the metal cutting theory.

- The enhancement of tool wear resistance can be achieved through the MQL setting and controlled settings of A3, B2, C1 and D2 (0.6%, 85 m/min, 0.1 mm/rev and 60°). A high concentration of the nanoparticles appears to have transferred more kinetic energy into the workpiece surface and dissipated more heat. Furthermore, the low-friction behaviour of the nanoparticles is very effective in minimizing the frictional effects on the tool-workpiece interface, hence reducing the cutting force and tool wear growth.
- Minimal power consumption for machining the titanium alloy can be obtained at settings of A2, B1, C1 and D2, which are nanoparticle concentration of 0.4%wt, cutting speed of 75 m/min, feed rate of 0.1 mm/rev and nozzle angle of 60°, respectively. The ANOVA results showed that the feed rate had more effect on power consumption because as the feed rate increases, the motor and drive axis move faster and hence consume more power during the machining process.

As a final note, we can conclude that application of Al_2O_3 nanoparticles with the inclusion of SDBS surfactant in a base lubricant is an effective method to machine titanium alloy. The use of the MQL technique in the machining of the titanium alloy has shown an appreciable approach towards environmentally friendly machining, as reported in previous research studies.

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