SURFACE ROUGHNESS OPTIMIZATION AND STATISTICAL MODELLING IN QUATERNARY HYBRID NANOFLUID MQL MILLING OF TI-6AL-4V

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Abstract : A key surface-integrity indicator for Ti-6Al-4V components is Surface roughness which is used in biomedical and aerospace applications. It directly influences sealing performance, fatigue life, and post-processing requirements. A statistical optimization of surface roughness parameters (Ra, Rz, Rt) generated during minimum quantity lubrication (MQL) milling of Ti-6Al-4V using a novel hybrid nanofluid with four nanoparticles (quaternary) is presented in this study. According to Taguchi L9 orthogonal array design, experiments were carried out by differing depth of cut, feed rate, cutting speed, and MQL pressure. Each roughness parameter applied Signal-to-noise (S/N) ratio analysis and analysis of variance (ANOVA) to rank the statistical significance of each process parameter. To predict Ra, Rz, and Rt from the four input parameters empirical regression models were developed. The outcomes identified that feed rate is the most significant factor as a dominant contributor in Ra, Rz, and Rt . It has Percentage Contribution Ratio (PCR) as 80.99%, 80.31%, and 63.46% in Ra, Rz, and Rt respectively. In Ti-6Al-4V milling, these key learnings provides both a practical parameter selection guideline and a mechanistic explanation for the surface-finish-improving effect of the quaternary hybrid nanofluid in Ti-6Al-4V milling.

IndexTerms **- Surface roughness, Ti-6Al-4V, Statistical Optimization, Minimum Quantity Lubrication (MQL), Taguchi technique, ANOVA, Percentage Contribution Ratio (PCR), Regression Modeling.**

INTRODUCTION

While machining Ti-6Al-4V parts, surface roughness stands out as a heavily scrutinized quality metric in aerospace and biomedical uses, since fatigue performance, resistance to fretting, and assembly tolerances respond strongly to the character of the surface. While excessive surface irregularity in biomedical implants can impair Osseointegration and raise the danger of bacterial colonization, poor surface finish produces stress concentration areas that can start fatigue fractures. Therefore, in the production of titanium components, achieving consistently low surface roughness is not just a cosmetic need but also a functional and safety-critical one.

Surface Roughness in milling emerges from a combination of the geometric feed-mark pattern left by the material-dependent and cutting-edge effects such as elastic recovery, chip-tool sliding friction, and built-up edge (BUE) formation. The alloys's low thermal conductivity concentrates heat at the tool-chip interface, promoting adhesion and BUE formation for Ti-6Al-4V specifically. While its low elastic modulus permits spring-back of the machined surface behind the tool, both of which degrade surface finish beyond what the geometric feed-mark pattern alone would predict.

By suppressing BUE production and lowering tool-chip friction, minimum quantity lubrication (MQL) improves surface quality. This effect is further enhanced when nanoparticles are added to the MQL base fluid. In Ti-6Al-4V milling, hybrid nanofluids in particular have shown significant improvements in surface-finish: Lotfi et al. [3] reported a reduction in surface roughness of up to 61.2% when using a hybrid Al_2O_3-CuO nanofluid compared to dry machining, Aydın et al. [4] reported a 65.8% improvement when using a hBN/MWCNT hybrid nanofluid, and Jamil et al. [1], [2] consistently lower roughness under Al_2O_3-MWCNT hybrid nanofluid MQL compared to dry and conventional flood conditions.

Despite these advancements, surface-roughness studies of hybrid nanofluids on Ti-6Al-4V are still limited to binary nanoparticle systems [1]–[4], with tripartite systems only recently investigated for Ti-6Al-4V [5] and other alloys [6]. Additionally, the surface-roughness behaviour of quaternary (four-nanoparticle) hybrid nanofluids has not been statistically characterized for Ti-6Al-4V milling. The current work fills this obvious research need.

The three goals of this study, which examines quaternary hybrid nanofluid MQL milling of Ti-6Al-4V, are to: (1) use Taguchi-based S/N and ANOVA analysis to statistically determine the impact of feed rate, depth of cut, cutting speed, and MQL pressure on Ra, Rz, and Rt; (2) create empirical regression models that predict each roughness parameter from the four process parameters; and (3) use surface morphology analysis to explain the observed surface-finish trends.

LITERATURE REVIEW

A. Surface Roughness Generation Mechanisms in Ti-6Al-4V milling

During milling of Ti-6Al-4V, surface roughness is generated which is theoretically governed by tool nose radius and feed-mark geometry. As Ti-6Al-4V exhibits high chemical affinity with tool materials, low thermal conductivity, and relatively low elastic modulus, the actual roughness produced in titanium alloy machining deviates significantly from the theoretical prediction. Heat accumulation at the tool-chip interface, chip adhesion, built-up edge (BUE) formation, and severe friction resulting in deterioration of surface integrity [2] are promoted by these characteristics. In addition, the low stiffness-to-strength ratio of the alloy makes it susceptible to vibration and elastic recovery behind the cutting edge, further affecting the generated surface profile.

During milling, high localized temperatures are produced by the tribological contact between the work piece and cutting tool which speeds up wear and boosts frictional resistance. To reduce friction, stop BUE generation, and effectively dissipate heat in addition to feed geometry, surface roughness is dependent on the lubrication strategy's capacity. As a result to obtain better surface smoothness efficient cooling and lubrication are now crucial in Ti-6Al-4V machining.

Further experimental studies have proved the significance of lubrication for control of the surface roughness while milling Ti-6Al-4V. Eltaggaz et al. [18] have proved that the use of nanofluids-based minimum quantity lubrication system helped to improve the surface quality by reduction of friction, decreasing the wear of the tool and improving the heat dissipation from the chip-tool interface.

Roushan et al. [20] have also explored the effect of the tool coating and use of nanofluids for minimum quantity lubrication in the micromachining of Ti–6Al–4V. It was found that the combination of the two techniques is very effective in reducing friction and wear in addition to improving the machining accuracy by reducing burr formation. This clearly highlights the importance of both the lubrication technique and the properties of the cutting tool in determining the surface roughness produced while machining the titanium.

B. Nanofluid-MQL Effects on Surface Roughness

An environmentally friendly alternative to flood cooling owing to its reduced fluid consumption and improved sustainability has emerged as Minimum quantity lubrication (MQL). However, due to the excessive heat generated in the cutting zone, the cooling capability of traditional MQL becomes insufficient during titanium machining. To enhance thermal conductivity and tribological properties, nanoparticles have been dispersed into base oils which addresses this limitation.

Ma et al. [15] have provided an exhaustive review on the use of nanofluid-assisted minimum quantity lubrication in different machining operations and found that nanoparticles increase the thermal conductivity and lubricating properties of traditional cutting fluids. Nanofluid-assisted MQL was found to reduce cutting temperature, friction, wear of tools, and surface roughness, thus proving to be a sustainable technique as compared to traditional flood cooling technique.

Abellán-Nebot et al. [16] have also shown that hybrid nanofluids provide better results as compared to mono nanofluids because of the synergic effects of nanoparticles of different types. They have stated in their review paper that the combined effect of rolling action, tribofilm, polishing, mending, and heat transfer results in better lubrication efficiency.

Timbadia V. and Vasudevan H. [19] reviewed the emerging application of hybrid nanofluid-assisted MQL in machining difficult-to-cut alloys and highlighted its potential for improving sustainable manufacturing. Their review emphasized that the enhanced thermal conductivity and tribological properties of hybrid nanofluids, combined with the reduced fluid consumption of MQL, contribute to lower cutting temperatures, improved lubrication, and enhanced surface quality. The authors also identified the need for further experimental investigations on Ti–6Al–4V machining to establish optimum machining parameters and hybrid nanofluid compositions.

A comparative study of flood cooling, conventional minimum quantity lubrication (MQL), and MQL using nanofluids was conducted by Taha-Tijerina and Edinbarough [21] on the machining of Ti–6Al–4V alloy. From their study, it became clear that MQL utilizing nanofluids had better surface finish and machining performance due to higher cooling and lubrication capabilities. It was found from their study that nanoparticles increased lubrication of the cutting zone.

While considering surface roughness, energy consumption, and tool wear during milling of Ti-6Al-4V, Jamil et al. [1] looked into hybrid Al_2O_3-MWCNT nanofluids under MQL conditions. Hybrid nanofluids significantly reduced tool wear and improved surface quality in comparison with traditional lubrication methods. Microscopic observations revealed reduced chip adhesion and improved surface topography, while multi-objective optimization resulted in a surface roughness of 0.529 µm. The authors concluded that between surface quality, sustainability, and productivity, the hybrid nanofluid-assisted MQL provided an effective compromise.

Later on in another research, Jamil et al. [2] used a Taguchi L16 orthogonal array to change flow rate, air pressure, and concentration to examine the machinability and tribological performance of Al203-MWCNT hybrid nanofluids. The minimum resulting cutting temperature, surface roughness and cutting force were 148.7 °C, 0.67 µm and 24.3 N respectively at ideal MQL conditions. For the enhanced performance, the combination of cylindrical MWCNTs and spherical Al203 particles was responsible. MWCNTs offered outstanding inter-tuular slip and thermal conductivity while AL203 nanoparticles improved wettability and dispersion. Additionally, by forming a stable tribological coating at the tool-chip interface, the hybrid system reduced friction and inhibited the creation of built-up edges.

Lotfi et al. [3] compared dry and conventional cooling to mono and hybrid nanofluid MQL conditions during Ti-6Al-4V milling. In their findings, the best overall machining properties were obtained by AL203-Cu0 hybrid nanofluids. Hybrid nanofluid MQL decreased surface roughness by 61.2% and cutting force by around 46.5% in comparison to traditional cutting settings. Confirming the beneficial role of hybrid nanoparticles in improving tribological behavior and surface integrity, superior surface topography and lower subsurface microhardness were achieved.

Aydin et al. [4] observed significant increases in sustainability and machining performance, when Hexagonal boron nitride's (hBN)/MWCNT hybrid nanofluids were introduced for MQL milling of Ti-6Al-4V. In comparison to dry cutting, surface roughness and cutting force were reduced by 65.8% and 63.5%, respectively. Fewer flaws and enhanced surface integrity were shown by analysis of surface topography. MWCNTs enhanced tribofilm formation and load bearing capacity while hBN easy-shear layered structure which functioned as a solid lubricant, was credited with the better performance. Additionally, from experiencing significant wear mechanisms the hybrid nanofluid reduced work hardening and stopped the cutting tool.

Likewise, Namlu et al. [17] conducted research on Ti–6Al–4V milling with the help of hybrid nanofluid-assisted minimum quantity lubrication in conjunction with multi-axis ultrasonic vibration. It is seen from their work that the performance of the hybrid nanofluids in terms of cooling and lubrication is much better in comparison to traditional machining.

The machinability of Ti–6Al–4V was studied by Makhesana et al. [23] through experiments under dry machining, flood machining, minimum quantity lubrication (MQL), and nanofluids-assisted MQL with the use of textured tools. It is shown from their findings that nanofluid MQL always achieves lower surface roughness and higher machining efficiency than other methods of machining such as dry, flood, and MQL.

Dambatta et al. [5] further investigated the impact of increasing nanoparticle complementarity by creating a tripartite hybrid nanofluid made of Al2O3, graphene oxide (GO), and ZnO nanoparticles for grinding Ti–6Al–4V under MQL conditions. When compared to monotype nanofluids, their tribological research showed that the hybrid lubricant had better physicochemical properties. The tripartite nanofluid decreased tangential force by 41.5 percent, grinding force ratio by 16.5 percent, and surface roughness by 42 percent. The three nanoparticles' synergistic tribological interactions, improved viscosity, and improved heat transfer capacity were all linked to the improvement.

Even though the research conducted by Guerra et al. [22] was carried out on CFRP/Ti-6Al-4V stacks, they have proved that nanofluid-based MQL is effective in improving the efficiency of the milling operation and ensuring better hole integrity in helical milling.

During the end milling of Al6061-T6, Safiei et al. [6] studied a SiO_2-Al_2O_3-ZrO_2 tri-hybrid nanofluid. The investigation showed the significance of nanoparticle complementarity in improving heat transmission and lubrication, even if the workpiece material was different from titanium alloys. Improvements in cutting temperature and surface roughness ranging from 16% to 76% were noted. The machining responses were strongly impacted by interactions between MQL parameters and nanoparticle concentration, according to statistical analysis utilising response surface methods and ANOVA. These results imply that better tribological and thermal performance may be achieved by increasing the quantity of complimentary nanoparticles.

Because each nanoparticle provides a distinct mechanism, such as rolling action, load-carrying capability, tribofilm creation, mending effect, and increased heat dissipation, the literature as a whole shows that hybrid and tri-hybrid nanofluids perform better than mono nanofluids. These synergistic actions results into lower friction, inhibition of built-up edge development, lower cutting temperature, and ultimately better surface polish.

C. Statistical Optimization Approaches for Surface Roughness

Statistical optimization techniques are widely adopted to reduce experimental effort and identify optimum parameter combinations due to the large number of process variables involved in machining operations. The most commonly employed approaches are Taguchi orthogonal arrays, analysis of variance (ANOVA), signal-to-noise ratio analysis, and regression modeling.

Along with Taguchi-based optimization, Response Surface Methodology (RSM) coupled with Central Composite Design (CCD) has also been widely accepted for machining optimization. During the dry milling of Inconel 625, Rajguru and Vasudevan employed CCD, RSM and ANOVA to optimize machining parameters demonstrating that these statistical techniques effectively predict machining responses such as surface roughness and micro-hardness while reducing the number of experimental trials [12], [13]. To optimize the machinability characteristics of GFRP/vinyl ester composites highlighting the effectiveness of statistical experimental design in mavhining studies, Rajguru et al. [14] applied a Design of Experiments (DoE) approach.

Toprak et al. [24] have formulated the regression equations to predict surface roughness in milling of Ti–6Al–4V material. The research shows that second order regression equations can be successfully used to formulate the correlation between the processing parameters and surface quality, where the feed rate is the most important parameter.

To study the influence of nanofluid concentration, MQL flow rate, and air pressure on machining responses, Jamil et al. [2] employed a Taguchi L16(43) design. To determine parameter significance signal-to-noise ratio analysis and ANOVA were used. To predict cutting force, surface roughness, and temperature empirical models were developed.

Similarly, to simultaneously minimize energy consumption and surface roughness while maximizing material removal rate, Jamil et al. [1] utilized regression models and desirability-function-based optimization. Their research demonstrated that optimization techniques and statistical modeling provide an effective framework for balancing multiple machining objectives.

The conclusion in the research done by Safliei et al. [6] noted that two intersecting factors have a great deal to do with cutting temperature and surface roughness in machining processes. Since statistical methods are often the only way to get to grips with relationships that are not immediately obvious this is an argument in favor of applying statistics to machinability studies. These findings are consistent with the observations reported by Rajguru and Vasudevan [12], [13], where statistical analysis successfully identified the significant machining parameters influencing surface integrity during dry milling.

Altogether, for optimizing machining performance while minimizing experimental cost and time Taguchi Design, Design of Experiments (DoE), signal-to-noise-ratio analysis, ANOVA, regression modelling, Central Composite Design (CCD) and Response Surface Methodologies (RSM) have proven to be effective tools.

D. Research gap identification and problem definition:

Some constraints still remain despite of significant development in nanofluid-assisted MQL machining of Ti-6Al-4V. Previous studies has mostly focused on binary hybrid systems and mono nanofluids like Al_2O_3-MWCNT [1], [2], Al_2O_3-CuO [3], and hBN-MWCNT [4]. But the current works have studied tripartite hybrid systems like Al_2O_3-GO-ZnO [5] and SiO_2-Al_2O_3-ZrO_2 [6]. However, no research have investigated at the machining behavior of Ti-6Al-4V in a quaternary nanofluid MQL environment.

Mukhopadhyaya and Kundu [25] optimized grinding parameters for Ti–6Al–4V and demonstrated that statistical optimization techniques effectively improve machining performance under different lubrication conditions. However, similar optimization studies focusing specifically on hybrid nanofluid-assisted MQL during Ti–6Al–4V milling remain limited, particularly for surface roughness prediction using Taguchi-based experimental design.

Also, the previous studies have focused on average surface roughness (Ra), while comprehensive surface characterization involves Ra, Rz and Rt has received limited attention. In addition, to explain the mechanisms responsible for surface generation in multi-particle hybrid systems, statistical optimization results have rarely been correlated with surface morphology evidence.

By exploring Ti-6Al-4V milling in a quaternary hybrid nanofluid MQL environment these research gaps are addressed in the current works. To give both statistical optimization and a mechanistic knowledge of surface roughness formation, Taguchi design, signal-to-noise ratio analysis, ANOVA, surface morphology characterization, and regression modelling are used. The work can help to create new hybrid nanofluid lubrication solutions for long-term titanium alloy machining.

MATERIALS AND METHODS:

A. Workpiece, Cutting Tool, and MQL System

To carry out slot milling operations a mirror finish block of Ti-6Al-4V (grade 5 titanium alloy) of 75mm x 175mm x 30mm with two holes 150mm apart has been used. For milling trials, a Sandvik Coromant CoroMill® 390 indexable end mill (R390-012A16-11L) with a single R390-11 T3 16M-PM S30T carbide insert was used. The cutter's greatest axial depth of cut was 10 mm, and its diameter was 12 mm. The S30T insert grade was chosen because it is appropriate for machining titanium alloy. High strength alloy tool steel with a precision ground shank and PVD-coated contact surface is used to make the holder body. Fine grain cemented carbide substrate (WC-Co), PVD coating tailored for titanium and HRSA machining, high edge toughness, and strong resistance to notch and crater wear make up the insert grade S30T. Ti-6Al-4V was milled using a Kenco Mist Lubrication System that was based on the Minimum Quantity Lubrication (MQL) technology. The KNPMB200 MQL type, which has a 3-liter oil reservoir capacity, was utilised for the experiments. For an air pressure range of 0.5 to 2 bar, the MQL unit has a flow rate of 210 to 496 ml/hr.

B. Preparation of Hybrid Nanofluid

The quaternary hybrid nanofluid employed in the present investigation consisted of Aluminium Oxide (Al_2O_3), Zinc Oxide (ZnO), Graphene Oxide (GO), and Multi-Walled Carbon Nanotubes (MWCNTs) dispersed in a water-glycol-based lubricant. The formulation and preparation methodology adopted in this work were based on the authors' preliminary investigation reported in [7], while the present study extends the previous work towards experimental machining performance evaluation and statistical optimization. The selection of the constituent nanoparticles was motivated by their complementary thermo-physical and tribological characteristics reported in earlier investigations [1]–[6]. Purity greater than 99% was controlled by the nanoparticles engaged in the current work. While GO was made up of nanosheets with thicknesses between 0.8 and 2 nm and average particle size D50 below 10 µm, Al2O3 and ZnO nanoparticles had almost spherical shape and average particle sizes below 100 nm. MWCNTs have typical lengths near 1µm and widths ranging from 10 to 30 nm [7]. Soluble oil, ethylene glycol, Deionized water and Sodium Lauryl Sulfate (SLS) were mixed with four earlier mentioned nanoparticles and hybrid nanofluid was prepared via a two-step method. Based on the authors' earlier work, the volume-fraction order was Al_2O_3 > ZnO > MWCNT > GO [7].

C. Design of Experiments

The experimentations were planned using a Taguchi L9 orthogonal array to reduce the number of experimental runs while assuring a methodical assessment of the impact of cutting settings on surface roughness responses. As the Taguchi technique can determine the comparative importance of process factors with fewer tests, it has been repeatedly used in machining research [2]. Research on hybrid nanofluid assisted machining of Ti-6Al-4V and other manufacturing alloys has successfully used similar statistical techniques [3]–[5].

Since they have a main impact on chip formation, heat production, lubrication efficiency, and surface integrity, four process parameters - cutting speed, feed rate, depth of cut, and MQL pressure were selected as control variables. Three levels of each factor - low, medium, and high operating conditions were studied. Initial testing, machine tool restrictions, and suggestions from earlier research on hybrid nanofluid assisted machining of Ti-6Al-4V [3], [4] were used to control the selected ranges.

Table 3: Factor levels for Cutting Speed, Depth of Cut, Feed Rate, and MQL Pressure

Parameters	Levels		
	1	**2**	**3**
Cutting Speed (m/min)	60	95	130
Feed Rate (mm/rev.)	0.12	0.24	0.36
DOC (mm)	0.2	0.4	0.6
MQL Pressure (bar)	0.5	1.0	1.5

Table 4: Taguchi L9 Array

Cutting Speed (m/min)	Feed Rate (mm/rev.)	DOC (mm)	MQL Pressure (bar)
60	0.12	0.2	0.5
60	0.24	0.4	1
60	0.36	0.6	1.5
95	0.12	0.4	1.5
95	0.24	0.6	0.5
95	0.36	0.2	1
130	0.12	0.6	1
130	0.24	0.2	1.5

130	0.36	0.4	0.5

D. Surface Roughness Measurement

Surface roughness measurements were performed using a Taylor Hobson Surtronic series portable surface roughness tester in order to assess the impact of cutting speed, depth of cut, feed rate, and MQL pressure on the surface integrity of Ti-6Al-4V machined under quaternary hybrid nanofluid assisted MQL conditions. Using a cut-off length (λc) of 0.80 mm and an evaluation length of 4.00 mm, the roughness parameters - arithmetic average roughness (Ra), mean peak-to-valley height (Rz), and maximum peak-to-valley height (Rt) were measured [8], [9]. To promise reproducibility and reduce random errors, measurements were taken perpendicular to the feed marks at three distinct positions on each machined surface. Each experimental run was repeated three times. The average values were then utilized for multi-response optimization, regression modelling, analysis of variance (ANOVA), and signal-to-noise ratio analysis. Also, in line with earlier research on hybrid nanofluid assisted MQL machining of Ti-6Al-4V [2]–[4], the impact of MQL pressure on lubrication efficiency, heat dissipation, and surface generation processes was related with the observed surface roughness responses. To promise accurate estimation of surface integrity and process performance, similar measuring techniques and statistical methods have been widely used in machining research [10], [11].

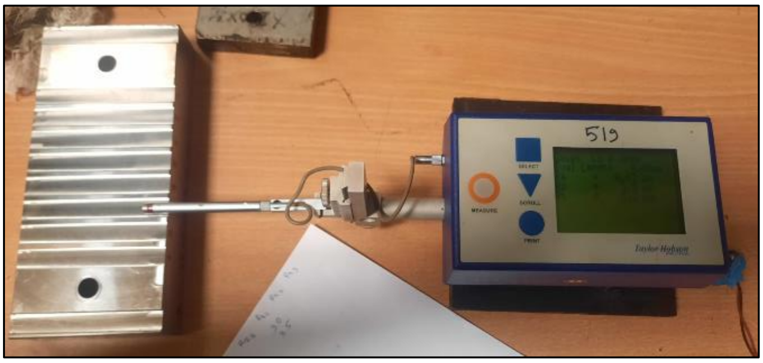

Fig. 1 Taylor Hobson Surtronic Duo Surface Roughness Tester

STATISTICAL METHODOLOGY

A. Theoretical Roughness Reference

As a theoretical reference, the kinematic surface roughness produced by feed-mark geometry alone is approximated by:

$$R_{a\,(theoretical)} = f^2 / (32 \,.\, R_n) \ldots\ldots (I)$$

Where f represents the feed rate, while Rn is the nose radius of the tool. Deviation of Ra from its theoretical value serves as an indicator of how much non-geometrical factors affect the actual surface roughness created under various lubrication conditions.

B. Signal – to – Noise Ratio Analysis

Smaller-the-better S/N ratio was applied to each roughness component as minimum surface roughness is desired.

$$S/N = -10 \log_{10}[(1/n)\, \Sigma\, y_i^2] \ldots\ldots (II)$$

where y_i is the measured roughness value for the i-th repetition of a given run and n is the number of repetitions. Mean S/N ratios were tabulated by factor level to identify the parameter combination yielding minimum R_a, R_z and R_t individually.

C. Analysis of Variance (ANOVA)

ANOVA was performed on R_a, R_z and R_t to quantify the percentage contribution of machining parameters i.e. cutting speed, feed, depth of cut and MQL pressure to assess statistical significance at the p value less than 0.05 (95% confidence level).

D. Empirical Regression Modeling

Regression model of the general power-law form was developed to express each roughness parameter as a function of machining parameters:

$$R = K.\, V^a.\, f^b.\, d^c.\, p^d$$

Where R is the roughness parameter, V, f, d and p are cutting speed, feed, depth of cut and MQL pressure respectively. K is a proportionality constant and a, b, c and d are exponents determined by regression model.

RESULTS AND DISCUSSION

A. Surface Roughness Data

Following table shows the number of runs and roughness values R_a, R_z and R_t obtained for each run.

Table 5: Surface Roughness for 27 Experimentation

Run	Parameters				Roughness		
	Cutting Speed (m/min)	Feed (mm/ rev)	Depth of Cut (mm)	Pressure (bar)	R_a	R_z	R_t
1	60	0.12	0.2	0.5	0.32	2.3	3
2	60	0.12	0.2	0.5	0.26	1.9	2.4
3	95	0.36	0.2	1	1.02	4.8	5
4	60	0.36	0.6	1.5	1.12	5.4	6.8
5	95	0.24	0.6	0.5	0.62	3.5	5.2
6	130	0.24	0.2	1.5	0.84	4.4	5
7	60	0.24	0.4	1	0.72	3.9	4.6
8	95	0.24	0.6	0.5	0.9	4.1	4.6
9	60	0.36	0.6	1.5	1.62	7.1	8.7
10	95	0.12	0.4	1.5	0.54	3.1	3.8
11	130	0.12	0.6	1	0.46	2.8	4.2
12	60	0.24	0.4	1	0.6	3.5	4
13	130	0.12	0.6	1	0.42	2.5	3.6
14	130	0.36	0.4	0.5	1.54	6.3	6.9
15	60	0.24	0.4	1	0.64	3.5	4.2
16	95	0.12	0.4	1.5	0.5	2.3	2.9
17	130	0.24	0.2	1.5	0.88	4.8	7.4
18	130	0.36	0.4	0.5	1.56	7.1	7.6
19	130	0.36	0.4	0.5	1.26	6.8	8.3
20	95	0.36	0.2	1	1.04	5.4	8.8
21	95	0.24	0.6	0.5	0.74	3.5	3.9
22	95	0.12	0.4	1.5	0.54	3.1	4.7
23	60	0.36	0.6	1.5	1.36	6.7	8
24	130	0.12	0.6	1	0.36	2.3	3.1
25	130	0.24	0.2	1.5	0.94	4.6	6.1
26	60	0.12	0.2	0.5	0.52	3.3	4.8
27	95	0.36	0.2	1	0.94	4.3	4.7

B. S/ N Ratio and ANOVA Results

Minitab used to analyse the data and following are the statistical output obtained. Table 6 indicates response table for S /N Ratio followed by Main effects plot and table 7 indicates Analysis of Variance followed by model summary and residual plot.

Table 6: Response Table for S/ N Ratio

Smaller is better				
Level	**Speed**	**Feed**	**DOC**	**Pressure**
1	3.214	7.298	3.216	2.636
2	2.671	2.418	2.01	3.829
3	1.843	-1.987	2.503	1.264
Delta	1.371	9.286	1.206	2.565
Rank	**3**	**1**	**4**	**2**

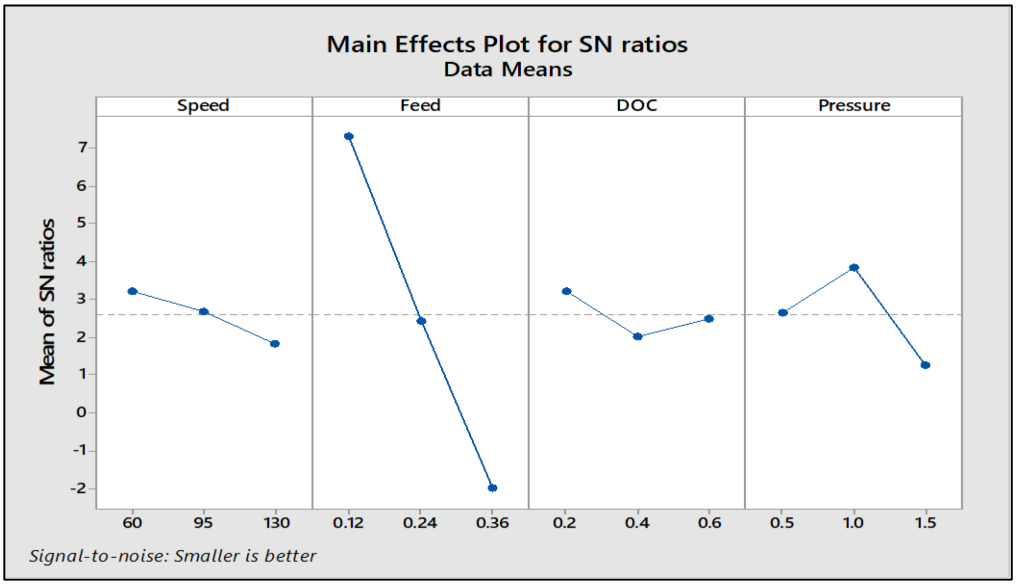

Fig. 2 Main Effect Plot for SN ratio

A plot showing the effects of S/N ratio indicates the effect of machining parameters on the surface roughness (R_a). As the objective for surface roughness is " smaller is better," then the machining condition for maximum S/N ratio is considered as the optimum because it is the one having the least variation and smallest Ra.

As compared to other process parameters, the impact of cutting speed on Ra is found to be relatively low. S/N ratio decreases gradually as the cutting speed increases implying that the cutting speed should be as low as possible. Therefore, the optimal cutting speed is 20 m/min.

Feed rate is found to have the greatest impact on surface roughness from the plot above showing a steepest slope of main effects. The S/N ratio decreases drastically as feed rate increases from 0.12 mm/rev to 0.36 mm/rev implying that higher feed rates lead to roughness of the surface owing to feed marks and cutting force. Therefore, feed rate of 0.12 mm/rev is the best choice for achieving the minimum surface roughness.

Depth of cut also plays a moderately important role since the ratio decreases from 0.2mm to 0.4mm and improves slightly at 0.6mm. However, the highest signal-to-noise ratio is at 0.2 mm depth of cut implying that the lower depth of cut results in smoothness of the surface.

However, the MQL pressure gives an optimum performance curve rather than being linearly related. The S/N ratio is seen to rise when the MQL pressure goes from 0.5 bar to 1.0 bar, showing improvement in lubrication and cooling, thus improving the surface finish. However, the rise in MQL pressure from 1.0 bar to 1.5 bar sees the S/N ratio fall significantly, showing that there is a poor surface quality, most likely caused by excessive mist velocity and unstable lubrication. Thus, the optimum value of MQL pressure is 1.0 bar. From the main effects plot, the optimum machining parameters in order to reduce surface roughness (R_a) are a cutting speed of 20 m/min, feed rate of 0.12 mm/rev, depth of cut of 0.2 mm, and MQL pressure of 1.0 bar.

Table 7: Analysis of Variance and Model Summary

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed	2	0.12329	0.06164	3.93	0.038
Feed	2	3.20702	1.60351	102.3	0
DOC	2	0.0776	0.0388	2.48	0.112
Pressure	2	0.26942	0.13471	8.59	0.002
Error	18	0.28213	0.01567		
Total	26	3.95947			

Model Summary

S	0.1252
R-Sq	92.87%
R-Sq (adj)	89.71%
R-Sq (Pred)	83.97%

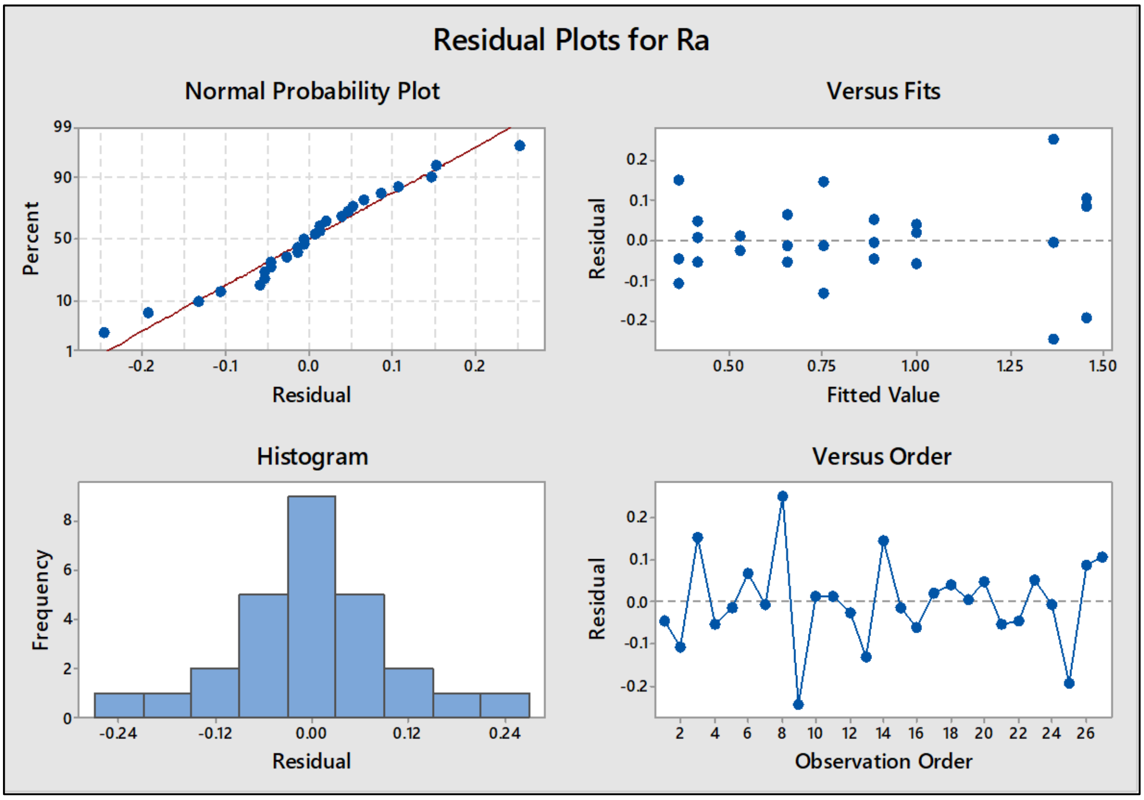

Fig. 3 Residual Plots for Cutting Force

To examine the suitability of the generated statistical model and validate the ANOVA assumptions, residual analysis was used. It's represented by normal probability plot, residual versus fits, histogram of residuals and residuals versus order. In normal probability plot residuals are scattered along/ nearer to the straight reference line with just minor variations at the ends. This indicates that created model accurately represents the experimental data with residuals roughly distributed and having no substantial violations of the normality assumption. Similarly, for residuals versus fits graph also represents randomly distributed residuals around the zero with no obvious pattern, funnel form or curvature. This suggests, constant variance is maintained, no systematic errors in model and the regression model are statistically acceptable. The histogram shows bell-shaped distribution centered on zero. This indicates the residuals are symmetrically distributed and mean residual is close to zero without subsequential skewness. From the residual versus order plot, it is clear that the residual values are randomly scattered around the zero value without any trend or cycle. The random distribution of the residuals indicates the independency of the residuals. There is no systematic error in the experiment as there is no pattern with respect to time. Even some of the residual values have relatively larger magnitude, but they are still randomly scattered. Therefore, it can be said that the constructed regression equation meets the criteria of error independency.

Table 8: Regression Model Summary and Coefficient Output

Model Summary			
S	**R-sq**	**R-sq (adj)**	**R-sq (pred)**
0.125196	92.87%	89.71%	83.97%

Coefficients						
Term		**Coef**	**SE Coef**	**T-Value**	**P-Value**	**VIF**
Constant		0.8244	0.0241	34.22	0	
Speed	60	-0.0289	0.0341	-0.85	0.408	1.33
	95	-0.0644	0.0341	-1.89	0.075	1.33
Feed	0.12	-0.3889	0.0341	-11.41	0	1.33
	0.24	-0.06	0.0341	-1.76	0.095	1.33
DOC	0.2	-0.0733	0.0341	-2.15	0.045	1.33
	0.4	0.0533	0.0341	1.57	0.135	1.33
MQL Pressure	0.5	0.0333	0.0341	0.98	0.341	1.33
	1	-0.1356	0.0341	-3.98	0.001	1.33

The positive coefficient implies that as there is an increase in the machining parameter under consideration, there will be an increase in the value of Ra, resulting in a rough machined surface. On the other hand, a negative coefficient implies the opposite.

CONCLUSION

This paper presented a statistical analysis and optimization of cutting forces generated due to milling of Ti-6Al-4V under quaternary hybrid nanofluid using MQL technique. The following conclusions can be drawn:

1. Feed and MQL pressure are the most significant factors contributing 81% and 7% respectively.
2. Optimal parameter combination for minimum cutting force is: cutting speed 60m/ min with feed rate of 0.12mm/ rev and DOC 0.2mm at 1.0 bar MQL pressure.
3. The regression model summary generated using Minitab indicates percentage value of R^2 as 92.87, R^2(adj) 89.71 and R^2(pred) 83.97 for surface roughness.
4. The empirical evidence confirms that the Quad-HNF MQL technique significantly enhances the integrity of the machined surface in Ti-6Al-4V through milling, and the results obtained are statistically and technically meaningful.

FUTURE SCOPE

The current study considers Ra, Rz and Rt only. Future research needs to take surface integrity parameters into account, such as 3D surface roughness, residual stresses, microhardness and changes in material microstructure in order to carry out a complete surface integrity characterization. Researchers can also assess the impact of surface finish improvement achieved through various combinations of nanoparticle with MQL technique on fatigue life, biocompatibility, resistance to wear and corrosion of titanium alloy used in aerospace and biomedical applications. The preparation of nanofluid should be optimized in future in order to establish correlations between properties of nanofluids and surface roughness. In addition, surface morphology may be studied by means of SEM, AFM, 3D optical profilometer etc. to identify the relation between quantitative roughness parameters and surface defects.

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