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# Multi-response optimization of minimum quantity lubrication (MQL) drilling of Ti-6Al-4V with hybrid nanofluid of $Al_2O_3$ and $SiO_2$

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**Abstract**

Minimum quantity lubrication (MQL) in drilling produces aerosol made up of mixture of air and liquid which forms a protective layer to reduce friction and tool wear to increase productivity. This study explains the drilling process performed on titanium alloy Ti-6Al-4V under minimum quantity lubrication (MQL) by hybrid nanofluid $Al_2O_3$ - $SiO_2$ blend with a ratio of 90:10 to achieve better drilling performances. The experimental study is performed with drilling control parameters i.e. speed of spindle (N), feed rate (F) and point angle (D) at mixed level with Taguchi $L_{16}$ orthogonal array to investigate optimum condition yielding minimum thrust force (TF), torque (TQ) and surface roughness (SR). Analysis of Variance (ANOVA) gives significance of control parameters on drilling performances. It was found that speed of spindle is the major significant factor contributing 78.26 %, 70.99 % and 71.53 % of thrust force (TF), torque (TQ) and surface roughness (SR) respectively. Microstructure analysis revealed dynamic transformation resulting in fine grain refinement of drilling under action of hybrid nanofluid of $Al_2O_3+SiO_2$.

**Keywords:** Minimum quantity lubrication, Nanofluid, Drilling, Titanium alloy

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## 1. Introduction

Drilling is a material removal technique that involves a multiple-pointed rotary cutter drill instrument to make cylindrical cross-sectional holes in solid materials. The drill bit is forced into the workpiece with high rotational speed. Various forces operating on drill tools throughout drilling operations are depicted in Fig.1. Lubrication such as nano-diamond particles dispersed paraffin and vegetable oils (Nam et al,2011), MQL-nano-fluid with chilly CO2 gas (Hegab et al,2018), Molybdenum disulfide ($MoS_2$) MQL-nanofluid (Zhang et al ,2015), multi walled carbon nanotube (MWCNT) nanofluid (Hegab et al,2018) are already used during machining of solid materials to reduce friction, thereby reducing mechanical energy loss to heat, removes excess heat and keeps the drill head from thermal expansion and adhesion leading to failure. The effect and optimization of MQL on wear of material as well as thrust force at the drill bit has been grossly observed by a number of researchers including Huang et al. (2016), Kishawy et al. (2019), Pal et al. (2020), Subhedar et al. (2021). Talib et al. (2015) have shown that the wear mechanism evolves from abrasion and adhesion to severe adhesion and thermal wear during drilling. Huang et al. (2016) explained that the force and torque in micro drilling and burr wear decreases with use of nanofluid with MQL system during micro drilling of 7075-T6 aluminum alloy. Waqar et al. (2017) observed that the surface roughness increases with increase in speed of spindle and decreases with feed rate. The increase in speed of spindle and feed rate increases exit burr height which is undesirable. Zhu et al. (2017) found that there is 2.5 times increase in thrust force with the increase in feed range of 0.05 to 0.13 mm/r at cutting speed of 40 m/min. Kyratsis et al. (2018) investigated the variation in the cutting torque and thrust force with change in cutting speed, feed rate, and tool diameter on drilling of aluminum AA7075 alloy using response surface methodology. Tool diameter and feed rate are the major significant parameters than cutting speed. Parida et al (2018) explained that the temperature of drill bit increases with increase in feed rate. The improved surface finish was produced with higher cutting speed and lower feed rate. Xu et al. (2019) studied that thrust forces and temperature increased suddenly while drilling CFRP/Ti6Al4V stacks instead of individual material due to the rapid drill wear. The wear rate of twist drills is rapidly occurring in the stack drilling as compared to individual CFRP and Ti-6l-4V plates. Kishawy et al. (2019) explained that the most significant parameters are feed rate and nanofluid wt. percentage influencing surface roughness quality and power consumption during machining Ti-6Al-4V with nano-additives-based minimum quantity lubrication. Subhedar et al. (2021) showed a decrease in surface roughness and increase in tool life with $Al_2O_3$ nanoparticles with cutting fluid blended with mineral oil on drill performance of SS 304.

Most of the studies on drilling of titanium alloy (Ti-6Al-4V) are conducted with $Al_2O_3$ nanoparticles rich nanofluid. However, no studies are observed on drilling of titanium alloy (Ti-6Al-4V) using hybrid nanofluid of $Al_2O_3$ blended with $SiO_2$ having ratio of 90:10 with minimum quantity lubrication. $Al_2O_3$ nanoparticles have chosen compared to graphene nanoparticles, nano-diamond particles (ND), molybdenum disulfide ($MoS_2$), multi walled carbon nanotube (MWCNT) due to the better phase stability in water dispersion, dimensional stability and it is less expensive. $SiO_2$ nanoparticles are used due to the low toxicity, better thermal stability and ease of synthesis than graphene nanoparticles, nano-diamond particles (ND), Molybdenum disulfide ($MoS_2$), multi walled carbon nanotube (MWCNT). This novel work performed with hybrid nanofluid rich $Al_2O_3$ nanoparticles blended with 0.1% wt. of $SiO_2$ to enhance performance of nanofluid. The hybrid mixture of $Al_2O_3$ and $SiO_2$ nanoparticles improved the rheological property of nanofluid due to synergistic effect. The main objective of this study is to investigate drilling performance on titanium alloy Ti-6Al-4V with minimum quantity lubrication.

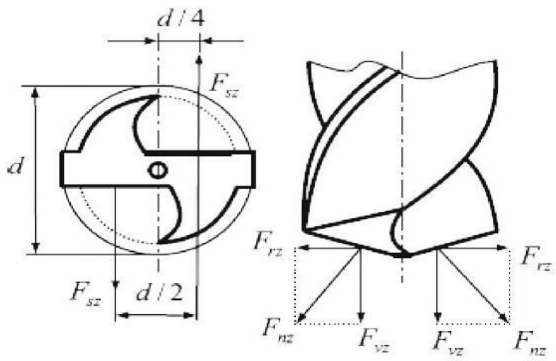



**Fig. 1** Drilling operation and forces

## 2. Materials and Methods

### 2.1. Work piece details

For the experimental trials, we used a Grade 5 titanium alloy (Ti-6Al-4V) (DOMADIA™ titanium plate provided by M/s DALI ELECTRONICS, Mumbai) plate as shown in Fig.2. The titanium alloy has excellent mechanical properties resistant to corrosion as given in Table 1. The chemical analysis of titanium alloy (Ti-6AL-4V) is given in Table 2. Titanium alloys are exceptionally robust and have high tensile strength. This metal is both lightweight and heat-resistant. An hcp crystal structure of α and bcc crystal structure of β are the two most common phases of titanium alloy. The mechanical properties vary depending on the heat treatment condition; the following table lists typical property ranges for well-processed titanium alloy (Ti-6Al-4V) as provided by the vendor.

**Fig.2** Titanium Alloy Ti6-Al4-V Plate

**Table 1.** Mechanical Properties of Titanium alloy (Ti-6AL-4V)

| Mechanical Properties | Density | Young's Modulus s | Shear Modulus | Yield Stress s | Ultimate Stress | Thermal Conductivity y | Hardness |
|---|---|---|---|---|---|---|---|
| Values | 4.43 g/cm$^3$ | 114 GPa | 44 GPa | 1100 MPa | 1170 MPa | 6.7-7.5 W/mK | 41 HRC |

**Table 2.** Chemical analysis of Titanium alloy (Ti-6AL-4V)

| Element | Ti | Al | V | Fe | Rem. |
|---|---|---|---|---|---|
| % | 88.60 | 6.00 | 4.54 | 0.24 | 0.62 |

## 2.2. Drilling Tool

Tungsten drill bits are perhaps the most popular variety of carbide, with a strong presence in a wide range of sectors. Regardless of the conventional drill bits, tungsten drill bits are among the long-life due to the better durability. Tungsten carbide (WC) is a chemical compound mostly of carbide and tungsten that has equal quantities of tungsten and carbon atoms. The drill bit having $30^0$ of helix angle, $118^0$ of point angle, 10 mm of drill diameter, drill length of 70 mm and flute length 40 mm is used for this study as shown in Fig.3.

**Fig.3** Tungsten Carbide Drill Bit

## 2.3. Cutting Fluid

The hybrid nano-fluid prepared with a mixture of nano-powder of $Al_2O_3$ and $SiO_2$ in a ratio of 90:10 blended with distilled water is used as cutting fluid to minimize friction and heating. The nanoparticle powder was dispersed into 150 ml distilled water with 1.0% w/v inside a beaker with the help of sonication at the frequency of 50 Hz for a period of 3 hours at room temperature as shown in Fig.4.


**Fig.4** Hybrid-nanofluid $Al_2O_3$ with $SiO_2$ (90:10 ratio) with ultrasonic probe sonication

## 2.4. Experimental setup

The experimental trials of drilling are performed on JYOTI PX10 vertical machining center (VMC) having spindle RPM range up to 8000 rpm, maximum load capacity of 400 Kg and maximum power of 7.5 kW. In this study, we have employed the external spray system consisting of nozzle, mixing chamber, Lubricating fluid reservoir and Compressor. The nozzle is placed at an angle of 45 degrees. Besides, the 120 ml/h of fluid flow rate and 6 bar of air supply pressure are kept constant for the study. The set up for experimental study with dynamometer (kistler) for thrust force (TF) and torque (TQ) measurement is depicted in Fig 5. The experimental trials of drill holes performed on titanium alloy are shown in Fig.6.The surface roughness (SR) is tested with surface roughness tester as in Fig. 7.

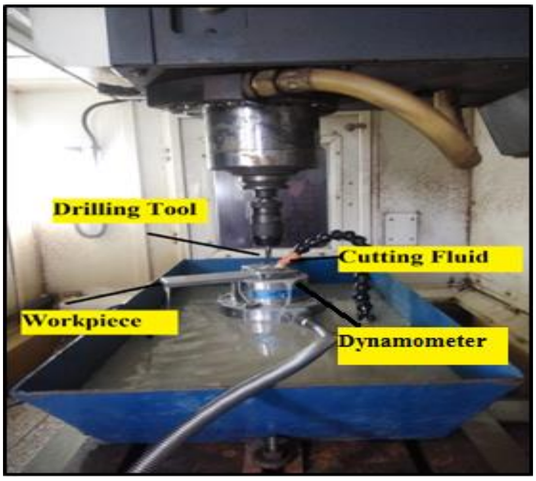



**Fig.5** Drilling of Ti-6Al-4V

**Fig.6** Experimental trials of Drilling


**Fig. 7** Surface Roughness Measurement

## 2.5. Design of Experiment with Taguchi $L_{16}$ OA

Shinde and Arakerimath (2022) explained that taguchi method could be successfully used for performance optimization of various manufacturing systems. The taguchi method reduces variation in the manufacturing process through robust design of experiments. The main objective of this method is to produce better quality products at lower cost. This method focused on investigating the optimum combination of design parameters to achieve better performance of the manufacturing system. The SN ratio gives optimum values of control parameter, and the loss function statistic provides a measurement of quality. In this study, effect of significant drilling control parameters such as speed of spindle (N), feed rate (F) and point angle (D) are analyzed on thrust force (TF), torque (TQ) and surface roughness (SR) under hybrid nanofluid made up of $Al_2O_3$ and $SiO_2$.The control parameters and their range of levels for drilling are identified from earlier studies in literature and several trial experiments. The point angles other than $118^0$ and $135^0$ have not produced better results as found in earlier studies and pilot trials.

The factor and levels used for the Taguchi $L_{16}$ orthogonal array is given in Table 3.

**Table 3.** Factors and Their levels

| Sr. No | Process Parameter | Unit | Symbol | Levels | | | |
|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 |
| 1 | Speed of spindle | rev/min | N | 900 | 1200 | 1500 | 1800 |
| 2 | Feed Rate | mm per min | F | 20 | 30 | 40 | 50 |
| 3 | Point Angle | degree | D | 118 | 135 | - | - |

## 3. Results and Discussion

Shinde and Arakerimath (2021) discussed that the SN ratio in Taguchi technique analyzes variations in the outcome of experimental study. The lower the better criteria for S/N ratio is selected in this study to achieve minimum TF, TQ and SR. The significant control parameters i.e. N, F and D during the drilling of Ti-6Al-4V were considered with different levels of operations from initial trial experiments. The experimental study of drilling Ti-6Al-4V under hybrid Nanofluid of $Al_2O_3$ and $SiO_2$ as cutting fluid is carried out with Taguchi $L_{16}$ orthogonal array (OA). The literature study shows that the response parameters TF, TQ and SR have significant effect on drilling of materials. Hence the response parameters TF, TQ and SR are measured in this study as shown in Table 6. The average values calculated for TF and its S/N ratio are 481 N and -53.50 respectively. The average values calculated for TQ and its S/N ratio are 3.21 N-mm and -9. 93. The average values calculated for SR and its S/N ratio are 0.90 µm and 1.18 respectively. The effect of each process parameter and their level on drilling performances TF, TQ and SR can be analyzed from main effect plots of SN ratio and mean as shown in Fig. 9, Fig. 10 and Fig. 11. The calculated average of SN ratio and mean for different levels of control parameters are shown in Table 8 and Table 9. The objective of this study is to achieve optimum values of control parameters that give minimum TF, TQ and SR in drilling of Ti-6Al-4V. This can be analyzed from the mean values at different levels obtained from results of experimental study. It is observed that lower surface roughness is achieved at high N of 1800 rpm due to less development of built up edge (BUE). The SR is observed to be higher at lower speed of spindle in this study because of formation of large and unstable BUE. The lower TF and TQ is observed with higher N of 1800 rpm caused by the thermal softening during drilling leading to increased temperature and lower thrust force. The TF, TQ and SR increased significantly with increased F because of the large chip size formation. There are similar results are explained in earlier studies in literature by Sharif et al. (2007), Chatterjee et al. (2016), Shunmugesh et al. (2016), Lotfi et al. (2018), Parida et al (2018) and Joy et al. (2020). Parida et al (2018) found a similar trend of the torque and thrust forces reduced with the increase of spindle speed while thrust force and torque increased with the increase of feed rate. The surface roughness value linearly increased with the increase of feed rate due to a built-up edge formation. The surface roughness value decreased with increase in spindle speed due to higher shearing action and reduction of the coefficient of friction at higher cutting speed. The lower surface roughness was observed at low feed rate and high cutting speed. The lower TF, TQ and SR are obtained at lower 20mm per min of feed rate due to small chip size formation. Sharif et al. (2007) observed that TiAlN-coated drill achieved good surface finish at different cutting speed as compared to uncoated-carbide drill. The lower surface roughness values are observed with higher cutting speed. The similar trend of results is reported in this study with a tungsten carbide (WC) tool. Chatterjee et al. (2016) observed that there is decrease in thrust force with increase in speed of spindle while it increases with diameter of drill. Lotfi et al. (2018) further explained that there is decrease in surface quality with increase in feed rate owing to formation of BUEs. This effect is enhanced with higher spindle speed. Joy et al. (2020) observed that the tool wear is sensitive with feed rate during drilling of titanium. There is increase in drill bit wear and decrease in drill bit life with increase in feed rate. Pal et al. (2020) showed that graphene nanoparticles of 1.5 % wt. decreases the thrust force of 27.4%, torque of 64.9%, surface roughness of 33.8% and coefficient of friction of 51.7% of the $30^{th}$ hole than the pure MQL state which enhanced the tool life. The TF and TQ are decreased with an increase in point angle from $118^0$ to $135^0$ while SR is increased with increase in point angle from $118^0$ to $135^0$. The lower TF, TQ and SR are obtained at point angle of $135^0$. In this study, ANOVA is carried out with 0.05 level of significance thus the factors whose values are less than 0.05 are most significant of drilling performance. The N is a major significant factor with highest F-values on responses as shown in ANOVA Table 7. The order of significant factors on drilling performances is N, F and D. The N is the most significant process parameter observed in ANOVA with 78.26 %, 70.99 % and 71.53 % percentage contribution on TF, TQ and SR respectively. The F has major influence on TF, TQ and SR with a percentage contribution of 13.57%, 21.36% and 26.24% respectively. However, D has no significant effect due to lower percentage contributions of 0.07 %, 2.27 % and 0.01 % on TF, TQ and SR respectively. The R-sq. and R-sq. (adj) values for TF, TQ and SR shown in Table 4 are high which confirms the predicted model is valid and adequate. The smaller-the-better criterion is selected for this study to achieve lower TF, TQ and SR. The optimum conditions to achieve the objective of this study are obtained from lowest levels of N, F and D. The predicted values of responses TF, TQ and SR at optimum conditions can be evaluated with below equations,

$$TF = T_{TF} + (N_4-T_{TF}) + (F_1-T_{TF}) + (D_2- T_{TF}) \quad (1)$$

$$= 481 + (362.5 - 481) + (438 - 481) + (479.3 - 481) = 317.8 \text{ N}$$

$$TQ = T_{TQ} + (N_4-T_{TQ}) + (F_1-T_{TQ}) + (D_2-T_{TQ}) \quad (2)$$

$$=3.21+ (2.493 - 3.21) + (2.798 - 3.21) + (3.110 - 3.21) = 1.981 \text{ N-mm}$$

$$SR = T_{SR} + (N_4-T_{SR}) + (F_1-T_{SR}) + (D_1- T_{SR}) \quad (3)$$

$$= 0.90+ (0.665 - 0.90) + (0.7275 - 0.90) + (0.9025 - 0.90) =0.495 \text{ µm.}$$

Terms used in eqn. (1), (2) and (3),

$T_{TF}$ = Average of Thrust Force in N

$T_{TQ}$ = Average of Torque in N-mm

$T_{SR}$ = Average of Surface Roughness in µm.

$N_4$= Speed of Spindle in revolution per min at $4^{th}$ level (1800 rpm)

$F_1$= Feed Rate in mm per min at $1^{st}$ level (20 mm per min)

$D_2$= Point angle in degrees at $2^{nd}$ level ($135^0$)

$D_1$=Point angle in degrees at $1^{st}$ level ($118^0$)

The confirmation experiments are conducted at optimum conditions to evaluate outcomes of this study. The optimum condition (N4F1D2) with N of 1800 rpm, F of 20 mm per min and D of $135^0$ gives lower TF of 296 N. The optimum condition (N4F1D2) with N of 1800 rpm, F of 20 mm per min and D of $135^0$ gives lower TQ of 2.04 N. The optimum condition (N4F1D1) with N of 1800 rpm, F of 20 mm per min and D of $118^0$ gives lower SR of 0.48 µm. The comparison of experimental and predicted results of optimum solution shows close agreement that gives confirmation of model accuracy as given in Table 5.

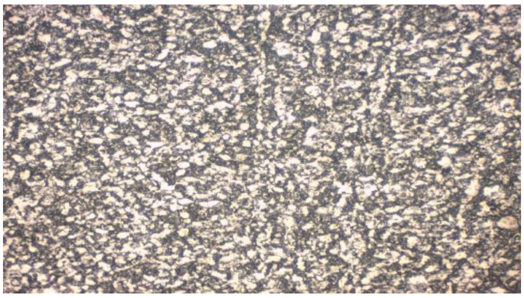
**Table 4.** $R^2$ and $R^2$ (Adjusted) values for TF, TQ, SR

| Response | TF | | TQ | | SR | |
|---|---|---|---|---|---|---|
| % Significance | $R^2$ | $R^2$(adj) | $R^2$ | $R^2$(adj) | $R^2$ | $R^2$(adj) |
| | 91.89% | 89.86% | 94.62% | 93.28% | 97.77% | 97.22% |

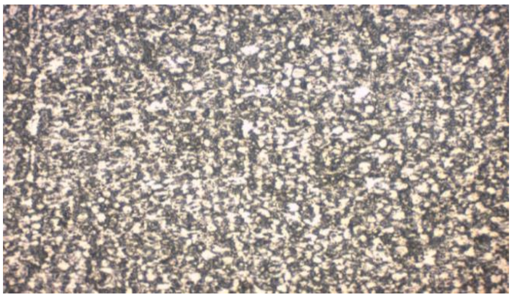
**Table 5.** Optimum Solution (Experimental and Predicted)

| Sr No | Response | Optimum condition | Experimental | Predicted | % Error |
|---|---|---|---|---|---|
| 1 | Thrust Force (TF) | N4F1D2 | 296 N | 317.8 N | -0.074 |
| 2 | Torque (TQ) | N4F1D2 | 2.04 N-mm | 1.981 N-mm | 0.029 |
| 3 | Surface Roughness (SR) | N4F1D1 | 0.48 µm | 0.495 µm | - 0.031 |

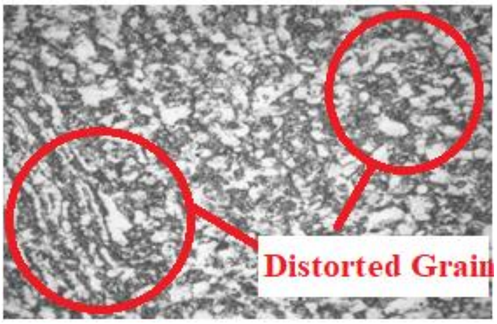
The microstructure of the drilling surface of confirmation experiments conducted with optimum condition (N4F1D2) for TF and TQ is shown in Fig.8 (a) and (c). The microstructure of the drilling surface of confirmation experiments conducted with optimum condition (N4F1D1) for SR is shown in Fig.8 (b) and (d). The drilling surface undergoes dynamic transformation which results in grain refinement. The refined grain structure is observed in drilling experiment with N=1800 rpm, F=20 mm per min and D=$118^0$ as shown in Fig. 8 (a) and (c) when compared with grain distortion with N=1800 rpm, F=20 mm per min and D=$135^0$ as shown in Fig.8 (b) and (d). Fig.8 (e) shows edge morphology of drill bit wear on cutting edge after drilling experiments conducted with hybrid Nanofluid of $Al_2O_3$+ $SiO_2$.



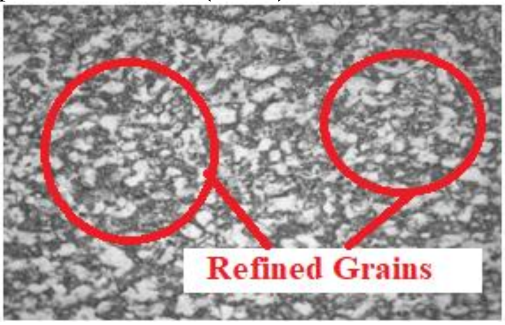
(a) Grain refinement with N=1800 rpm, F=20 mm per min, D=135$^0$ (200X)



(b) Grain refinement with N=1800 rpm, F=20 mm per min, D=118$^0$ (200X)




(c) Distorted grain structure with N=1800 rpm, F=20 mm per min, D=135$^0$ (400X)




(d) Grain structure with N=1800 rpm, F=20 mm per min D=118$^0$ (400X)

(e) Drill Bit Wear Cutting Edge

**Fig. 8** Microstructure Analysis of drilling

**Table 6.** DOE with Taguchi $L_{16}$ OA Nanofluid ($Al_2O_3$ + $SiO_2$)

| DOE NO | Speed (N) | Feed Rate (F) | Point angle (D) | Thrust Force (N) | SN Ratio | Mean | Torque (N-mm) | SN Ratio | Mean | Surface Roughness (µm) | SN Ratio | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 900 | 20 | 118 | 534 | -54.55 | 534.00 | 3.64 | -11.22 | 3.64 | 1.04 | -0.34 | 1.04 |
| 2 | 900 | 30 | 118 | 562 | -54.99 | 562.00 | 3.74 | -11.46 | 3.74 | 1.14 | -1.14 | 1.14 |
| 3 | 900 | 40 | 135 | 576 | -55.21 | 576.00 | 3.92 | -11.87 | 3.92 | 1.28 | -2.14 | 1.28 |
| 4 | 900 | 50 | 135 | 590 | -55.42 | 590.00 | 4.22 | -12.51 | 4.22 | 1.34 | -2.54 | 1.34 |
| 5 | 1200 | 20 | 118 | 470 | -53.44 | 470.00 | 3.36 | -10.53 | 3.36 | 0.78 | 2.16 | 0.78 |
| 6 | 1200 | 30 | 118 | 510 | -54.15 | 510.00 | 3.54 | -10.98 | 3.54 | 0.92 | 0.72 | 0.92 |
| 7 | 1200 | 40 | 135 | 542 | -54.68 | 542.00 | 3.72 | -11.41 | 3.72 | 1.02 | -0.17 | 1.02 |
| 8 | 1200 | 50 | 135 | 564 | -55.03 | 564.00 | 3.86 | -11.73 | 3.86 | 1.10 | -0.83 | 1.10 |
| 9 | 1500 | 20 | 118 | 452 | -53.10 | 452.00 | 2.15 | -6.65 | 2.15 | 0.61 | 4.29 | 0.61 |
| 10 | 1500 | 30 | 118 | 474 | -53.52 | 474.00 | 2.52 | -8.03 | 2.52 | 0.78 | 2.16 | 0.78 |
| 11 | 1500 | 40 | 135 | 482 | -53.66 | 482.00 | 3.24 | -10.21 | 3.24 | 0.86 | 1.31 | 0.86 |
| 12 | 1500 | 50 | 135 | 496 | -53.91 | 496.00 | 3.46 | -10.78 | 3.46 | 0.94 | 0.54 | 0.94 |
| 13 | 1800 | 20 | 118 | 296 | -49.43 | 296.00 | 2.04 | -6.19 | 2.04 | 0.48 | 6.38 | 0.48 |
| 14 | 1800 | 30 | 118 | 340 | -50.63 | 340.00 | 2.45 | -7.78 | 2.45 | 0.64 | 3.88 | 0.64 |
| 15 | 1800 | 40 | 135 | 380 | -51.60 | 380.00 | 2.64 | -8.43 | 2.64 | 0.72 | 2.85 | 0.72 |
| 16 | 1800 | 50 | 135 | 434 | -52.75 | 434.00 | 2.84 | -9.07 | 2.84 | 0.82 | 1.72 | 0.82 |

**Table 7.** Analysis of Variance for drilling titanium alloy (ANOVA)

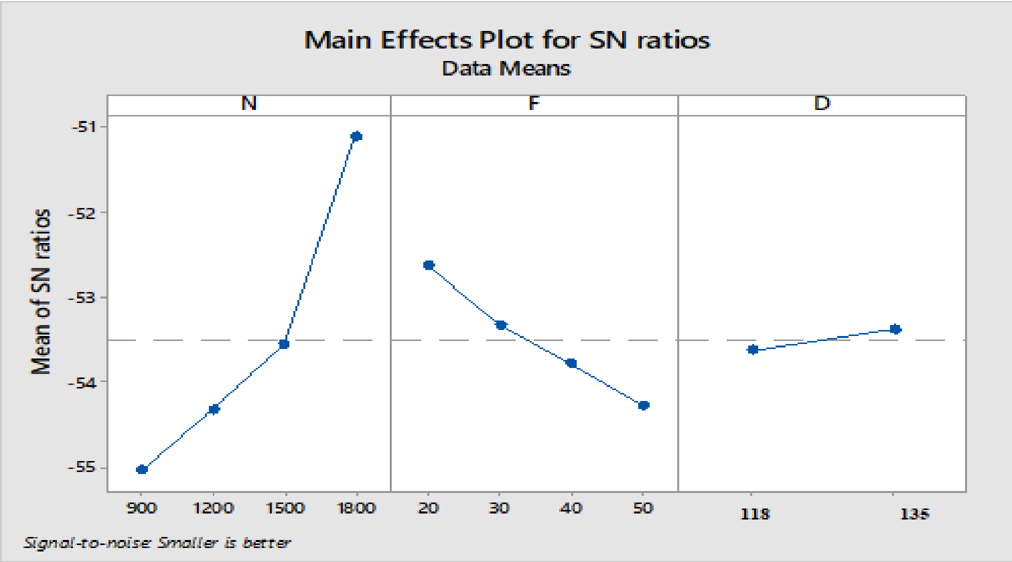
| | | **TF** | | | | | | **TQ** | | | | | | **SR** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Seq. SS** | **% contr.** | **Adj. SS** | **Adj. MS** | **F-Value** | **P-Value** | **Seq. SS** | **% Contr.** | **Adj. SS** | **Adj. MS** | **F-Value** | **P-Value** | **Seq. SS** | **% Contr.** | **Adj. SS** | **Adj. MS** | **F-Value** | **P-Value** |
| Regression | 3 | 100598 | 91.89% | 100598 | 33532.5 | 45.31 | 0.000 | 6.5056 | 94.62% | 6.5056 | 2.1685 | 70.37 | 0.000 | 0.8492 | 97.77% | 0.8492 | 0.2831 | 175.6 | 0.000 |
| N | 1 | 85674 | **78.26%** | 85674 | 85674.1 | **115.77** | **0.000** | 4.8807 | **70.99%** | 4.8807 | 4.8807 | **158.37** | **0.000** | 0.6213 | **71.53%** | 0.6213 | 0.6213 | **385.39** | **0.000** |
| F | 1 | 14851 | 13.57% | 14851 | 14851.3 | 20.07 | 0.001 | 1.4688 | 21.36% | 1.4688 | 1.4688 | 47.66 | 0.000 | 0.2279 | 26.24% | 0.2279 | 0.2279 | 141.38 | 0.000 |
| D | 1 | 72 | 0.07% | 72 | 72.2 | 0.10 | 0.760 | 0.156 | 2.27% | 0.156 | 0.1560 | 5.06 | 0.044 | 0.0001 | 0.01% | 0.0001 | 0.0001 | 0.03 | 0.855 |
| Error | 12 | 8880 | 8.11% | 8880 | 740.0 | - | - | 0.3698 | 5.38% | 0.3698 | 0.0308 | - | - | 0.0193 | 2.23% | 0.0193 | 0.0016 | - | - |
| Total | 15 | 109478 | 100.00% | - | - | - | - | 6.8754 | 100.00% | - | - | - | - | 0.8686 | 100.00% | - | - | - | - |

**Table 8.** Response Table for SN ratio for TF, TQ, SR

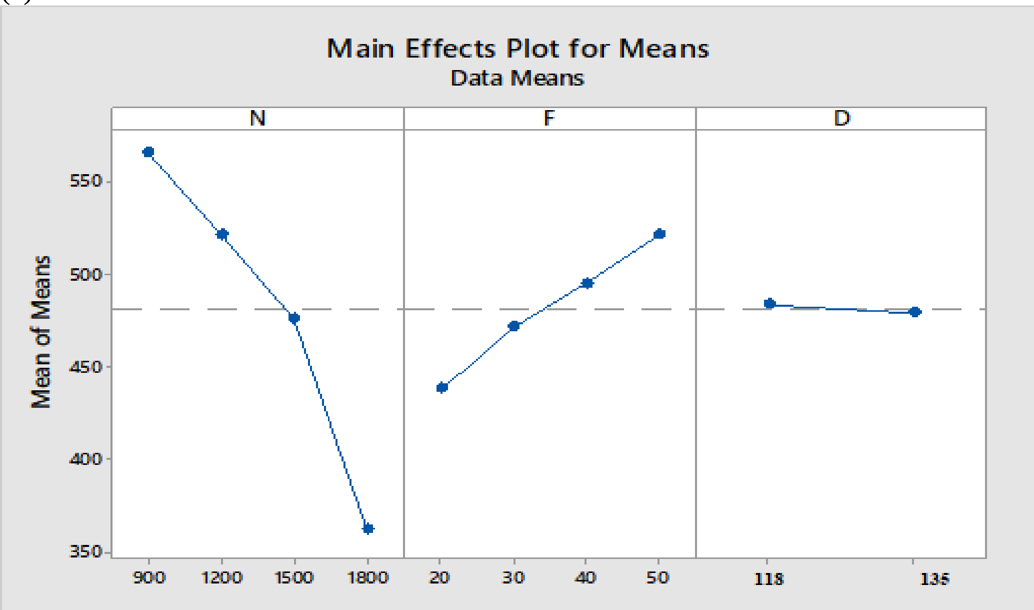
| | **TF** | | | **TQ** | | | **SR** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Level** | **N** | **F** | **D** | **N** | **F** | **D** | **N** | **F** | **D** |
| 1 | -55.04 | **-52.63** | -53.63 | -11.763 | **-8.648** | -10.335 | -1.5413 | **3.1215** | 0.9785 |
| 2 | -54.32 | -53.32 | **-53.38** | -11.162 | -9.562 | **-9.521** | 0.4706 | 1.4052 | **1.3771** |
| 3 | -53.55 | -53.79 | - | -8.917 | -10.480 | - | 2.0747 | 0.4618 | - |
| 4 | **-51.10** | -54.28 | - | **-7.869** | -11.021 | - | **3.7072** | -0.2772 | - |
| Delta | 3.94 | 1.65 | 0.26 | 3.894 | 2.374 | 0.814 | 5.2484 | 3.3987 | 0.3986 |
| Rank | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |

**Table 9.** Response Table for Mean for TF, TQ, SR

| | **TF** | | | **TQ** | | | **SR** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Level** | **N** | **F** | **D** | **N** | **F** | **D** | **N** | **F** | **D** |
| 1 | 565.5 | **438.0** | 483.5 | 3.880 | **2.798** | 3.308 | 1.2000 | **0.7275** | **0.9025** |
| 2 | 521.5 | 471.5 | **479.3** | 3.620 | 3.063 | **3.110** | 0.9550 | 0.8700 | 0.9063 |
| 3 | 476.0 | 495.0 | - | 2.843 | 3.380 | - | 0.7975 | 0.9700 | - |
| 4 | **362.5** | 521.0 | - | **2.493** | 3.595 | - | **0.6650** | 1.0500 | - |
| Delta | 203.0 | 83.0 | 4.3 | 1.387 | 0.797 | 0.198 | 0.5350 | 0.3225 | 0.0038 |
| Rank | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |

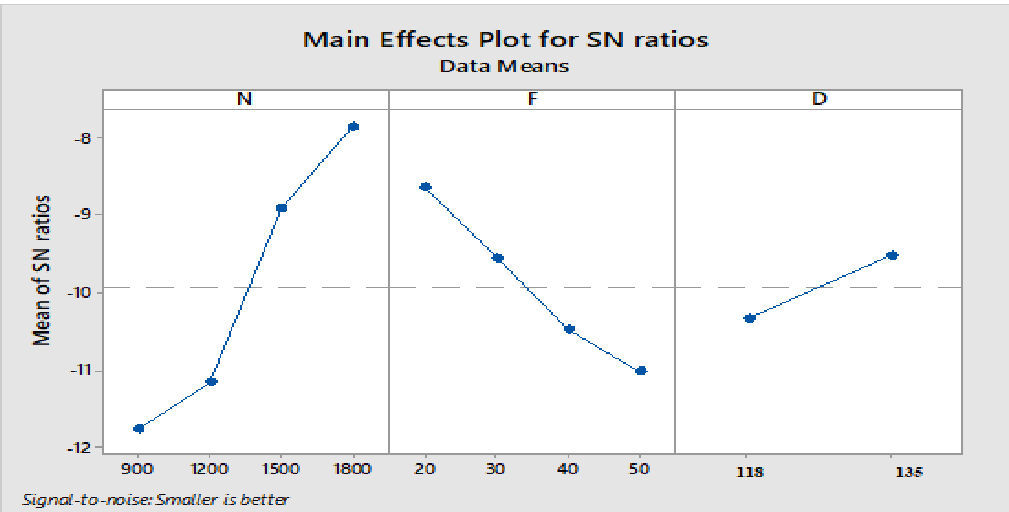



(a)

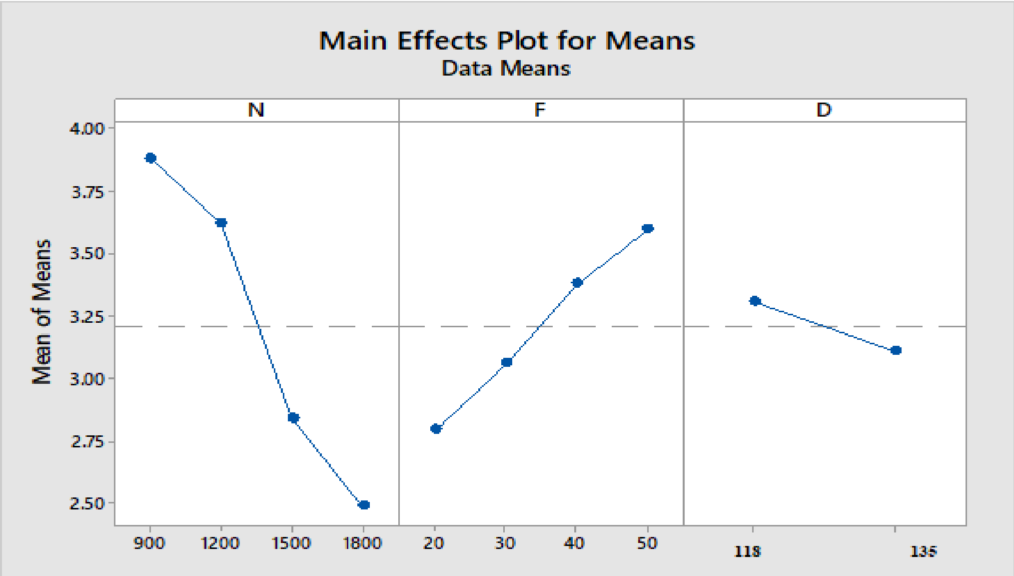



(b)

**Fig. 9** Main Effect Plots for TF (a) SN ratio (b) Means

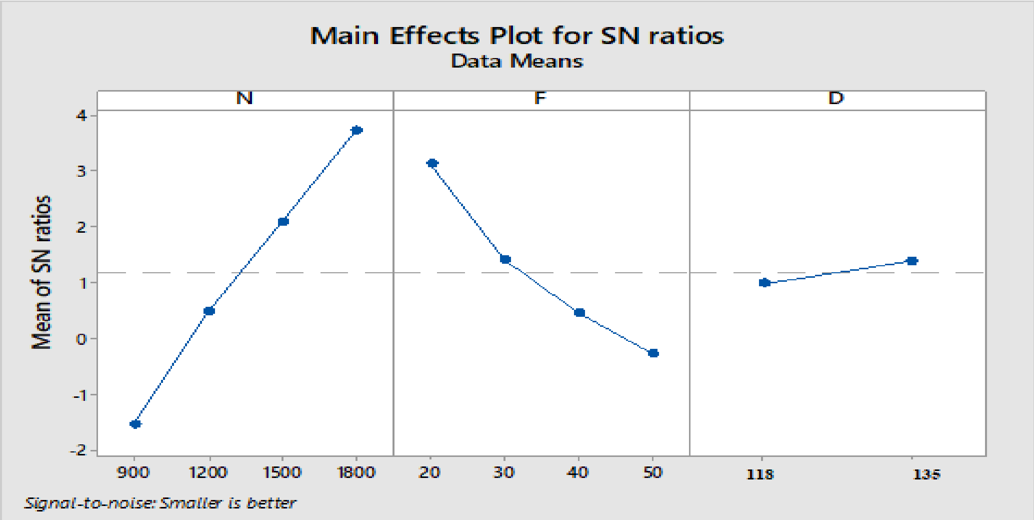



(a)

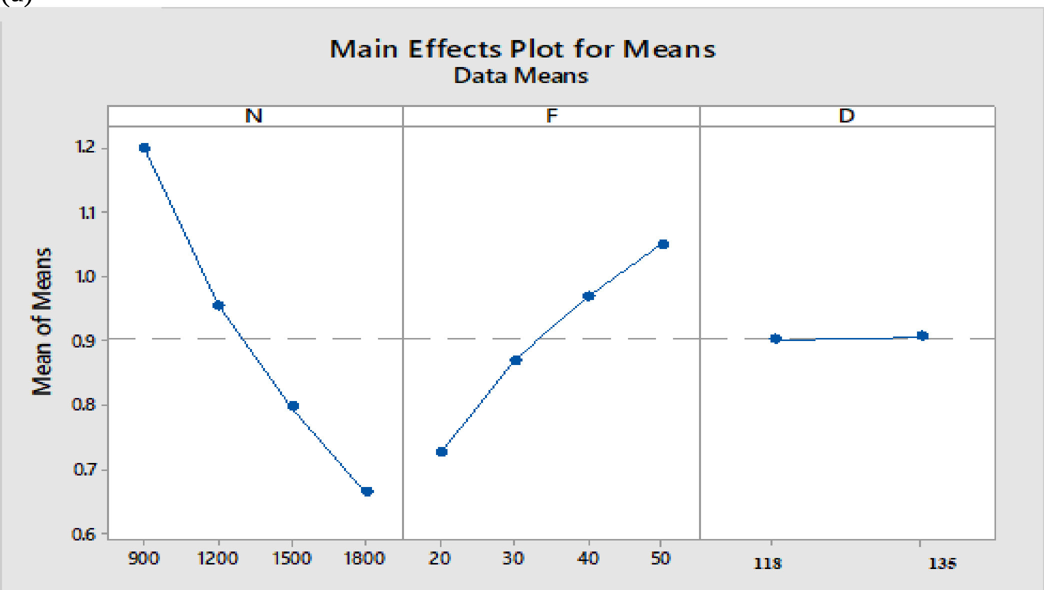



(b)

**Fig. 10** Main Effect Plots for TQ (a) SN ratio (b) Means




(a)




(b)

**Fig. 11** Main Effect Plots for SR (a) SN ratio (b) Means

## 4. Conclusions

In this study, drilling performances on Ti-6Al-4V with use of tungsten carbide (WC) tool is evaluated experimentally under minimum quantity lubrication of hybrid nanofluid of rich $Al_2O_3$ nanoparticles blended with 0.1% wt. of $SiO_2$ i.e. 90:10 ratio of $Al_2O_3$ with $SiO_2$. Taguchi mixed orthogonal array $L_{16}$ is used to understand the effect of the significant control parameters such as speed of spindle, feed rate and point angle on drilling performances thrust force, torque and surface roughness.

The use of minimum quantity lubrication of hybrid nanofluid of rich $Al_2O_3$ nanoparticles blended with 0.1% wt. of $SiO_2$ i.e. 90:10 ratio of $Al_2O_3$ with $SiO_2$ have shown better drilling performances on Ti-6Al-4V with use of tungsten carbide (WC) tool as compared to dry or lubricants such as graphene nanoparticles, nano-diamond particles (ND), molybdenum disulfide ($MoS_2$), multi walled carbon nanotube (MWCNT).The surface roughness decreases with increase in speed of spindle owing to less formation of built up edge (BUE) which results in better surface finish. The decrease in thrust force and torque is observed with increase in speed of spindle caused due to the thermal softening with rise in temperature during drilling. The thrust force, torque and surface roughness increased significantly with increase in feed rate due to the large chip size formation. The decrease in thrust force and torque are observed with increase in point angle from $118^0$ to $135^0$ while surface roughness is increased with increase in point angle from $118^0$ to $135^0$.The optimum condition (N4F1D2) with speed of spindle of 1800 rpm, feed rate of 20 mm per min and point angle of $135^0$ gives minimum thrust force of 296 N and minimum torque of 2.04 N-m. The optimum condition (N4F1D1) with speed of spindle of 1800 rpm, feed rate of 20 mm per min and point angle of $118^0$ gives minimum surface roughness of 0.48 µm. Microstructural analysis of drilling surface in experiments conducted with optimum conditions shows dynamic transformation which results in fine grain refinement under MQL-nanofluid. The refined grain structure is observed in drilling experiments with speed of spindle of 1800 rpm, feed rate of 20 mm per min and point angle $118^0$ when compared with grain distortion with speed of spindle of 1800 rpm, feed rate of 20 mm per min and point angle of $135^0$.

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