

# Optimization of Cutting Parameters for Surface Roughness under MQL, using Al<sub>2</sub>O<sub>3</sub> Nanolubricant, during Turning of Inconel 718

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**Abstract.** Inconel 718 is a nickel-based alloy commonly used due to its excellent mechanical properties at high temperatures and its elevated corrosion resistance. This material however is difficult to machine due to the high temperature generated during machining, which requires efficient lubrication system. Minimum quantity lubrication (MQL) technique is a more efficient and a more environmentally friendly alternative to conventional flooding lubrication technique. The efficiency and efficacy of this lubrication technique can be further enhanced by adding nano particles and surfactant into the base lubricant. There are currently limited number of studies on the application of minimum quantity lubrication (MQL) technique using nanolubricant with added surfactant in the machining of hard-to-machine materials such as Inconel 718. Consequently, this paper aims to optimize the cutting parameters for surface roughness under minimum quantity lubrication (MQL) condition using surfactant-added Al<sub>2</sub>O<sub>3</sub> nanolubricant during the turning of Inconel 718. The effects of cutting speed, depth of cut and feed rate and their two-way interactions on surface roughness are investigated on the basis of the standard Taguchi's L9 orthogonal array (OA) design of experiment and the results are assessed using analysis of variance (ANOVA) and signal to noise (S/N) ratio methods to determine the optimal cutting parameter settings as well as the level of significance of the cutting parameters. The optimal surface finish can be observed at the cutting speed of 70 m/min, depth of cut of 0.05 mm and feed rate of 0.05 mm/rev with feed rate being the most significant factor to affect surface finish. Through this study, the application of minimum quantity lubrication (MQL) technique using surfactant-added Al<sub>2</sub>O<sub>3</sub> nanolubricant, has been shown to produce desirable surface finish quality on Inconel 718 with additional economic and ecological benefits.

## 1. Introduction

Environmental issues have become a major concern around the world and many nations are taking the efforts to reduce the negative impacts of production on the environment. The extensive and overuse of lubricant in metal working industries greatly contributes to environmental pollution and causes detrimental effects on the health of operators [1]. The purpose of lubrication in machining is to



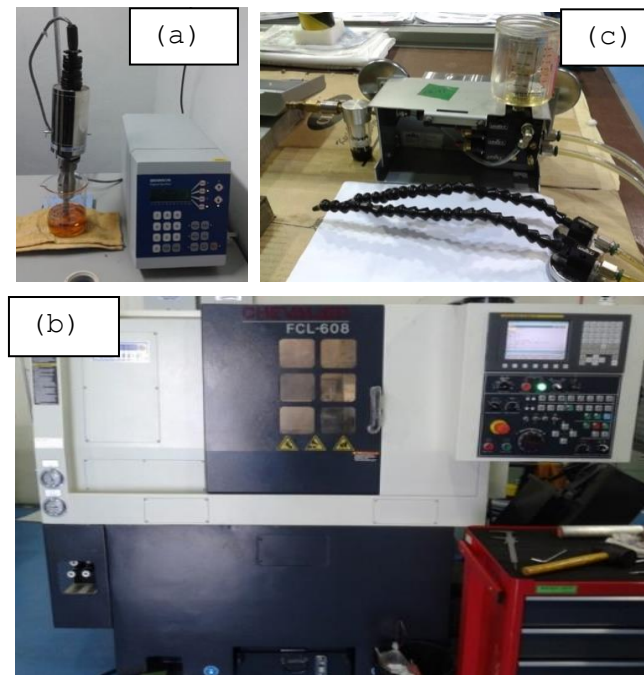
prolong the life of mechanical tools, reduce friction, flush away chips and slow down the wear of cutting tools. Minimum quantity lubrication system (MQL) minimizes the usage of cutting fluids during machining. In a minimum quantity lubrication system, small oil droplets mixed with compressed air are sprayed directly into the cutting zone providing efficient lubrication while at the same time improving cutting performance. It has been reported that MQL technique improves tool life and increases surface quality while minimizing waste disposal at the same time [2]–[4].

Nanofluids or nanolubricants offers better thermal stability during machining than normal cutting fluids. Nanolubricants are produced by dispersing small amounts of nano-sized (less than 100 nm) materials in a base fluid. Based on previous researches, lubricants with nanoparticles suspended in the base oils exhibits greater reduction in friction and wear than base oil lubricants on its own. The addition of nanoparticles (NP) in base oil creates anti-wear mechanism by the tribo-sintering layer of NPs which is generated on the wear surfaces causing a reduction of metal to metal contact [5], [6]. However, the nanoparticles in the base oil tend to agglomerate or coagulate after a period of time. This can be prevented simply by adding surfactant into the nanolubricant. The addition of surfactant in nanolubricants has also been shown to further improve machining performance. In a machining test conducted on titanium alloy, nanolubricants with surfactant managed to enhance machining performance in terms of surface quality, power consumption and tool wear resistance of the cutting insert [7].

Nickel-based super alloys are gaining substantial attention around the world due to their high hot strength, high hardness and high toughness properties. They also have many other favourable properties which include high temperature resistance and anti-corrosion properties. Inconel 718 is one of these super alloys that is widely used in manufacturing sectors particularly in aerospace, nuclear, defence and power industries. This high toughness, low plasticity and small thermal conductivity material is difficult to machine [8]. Currently, there are limited number of studies on the application of MQL using nanolubricant with added surfactant in the machining of hard-to-machine materials. Therefore, the objective of this paper is to optimize the cutting parameters of surface roughness when turning Inconel 718 by using Taguchi method under surfactant-added minimum quantity nanolubrication condition.

## **2. Preparation of Nanolubricant**

Aluminum oxide nanoparticles, which is commercially available and supplied by Sigma Aldrich, were used for preparing the nanolubricant with the soluble cutting oil (SolCut). The nanoparticles have a particles size of <50 nm (under DLS). A concentration of 0.4 % in weight percentage was suspended in soluble cutting oil (SolCut). Ultrasonics liquid processor was used to mix the particles in SolCut for a period of 4 hours with 25 % amplitude. The output power was set at 100 W at 18–23°C. 1% of sodium dodecyl benzene sulfonate or SDBS was added to the lubricant in order to minimize agglomeration in the mixture.



**Figure 1.** (a) Preparation of  $\text{Al}_2\text{O}_3$  Nanolubricant using sonication process, (b) Experiments conducted by using 3-axis CHEVALIER FCL-608 CNC Turning Machine, (c) UNIST Minimum quantity lubricant device.

**Table 1.** Experimental Condition

Items	Description
Machine Tool	CHEVALIER FCL-608 CNC Turning Machine
Work specimen:	
Material	Inconel 718
Size (mm)	50 mm diameter
Cutting tool (insert):	
Cutting insert	Finishing coated carbide insert (nose radius: 2 mm)
Process parameters:	
Cutting speed	30, 50 and 70 m/min
Depth of cut	0.05, 0.1 and 0.15 mm
Feed rate	0.05, 0.1 and 0.2 mm/ rev
MQL supply Air:	6.0 bar, lubricant: 40 ml/h (through external nozzle)
Environment:	MQL nanolubricant (<50 nm) with SDBS

**Table 2.** Cutting parameters

Machining parameters	Level 1	Level 2	Level 3
Cutting speed, $v$ (m/min), A	30	50	70
Depth of cut, $a$ (mm), B	0.05	0.10	0.15
Feed, $f$ (mm/rev), C	0.05	0.10	0.20

**Table 3.** L9 Taguchi orthogonal arrays

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

### 3. Experimental procedure

The aim of this experiment is to investigate the optimum cutting parameters of surface roughness when turning Inconel 718 by using Taguchi experimental design approach. MQL system was employed using  $\text{Al}_2\text{O}_3$  nanoparticles and SDBS added nanolubricant. The experimental runs were carried out in accordance to L9 Orthogonal Array design of experiment which consists of three independent variables, namely; cutting speed,  $v$ , depth of cut,  $a$ , and feed rate,  $f$  at three levels; Level 1, Level 2 and Level 3. It has been reported on numerous occasions that, the Taguchi orthogonal array layout is capable of providing full information upon all factors that affect the performance parameter. Results obtained from the experimental runs performed were converted into appropriate signal to noise (S/N) ratio in order to measure the deviation from the desired value of quality characteristic or output. In this experiment, smaller values of surface roughness are preferred for the optimum cutting conditions. Therefore, smaller the better approach was chosen. Table 1 shows the details of experimental condition for the different environment. While Table 2 and 3 shows the cutting parameter details and L9 Taguchi orthogonal array experimental design respectively. Picture of device and machine used for experimentation purpose shown in Figure 1.

### 4. Results and Discussion

Table 4 shows the values of surface roughness obtained from the Taguchi L9 Orthogonal Array experimental runs. The output data were recorded three times, and the average value was taken in order to minimize experimental errors. These data were then used to calculate the S/N ratio values (Table 5). As stated earlier, smaller values of surface roughness were preferred for the optimum cutting conditions. Regardless of the category of the performance characteristics, higher value of S/N ratio corresponds to better performance. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio. The difference between maximum and minimum values of S/N ratio (main effect) are shown in S/N ratio table (Table 6). For a better representation, data from this table (Table 6) are plotted in figure 2. Maximum value for factor A occurs at level 3 with S/N ratio of 12.230, while the maximum value of S/N ratio for both factors B and C occur at level 1 at 12.171 and 14.328 respectively. Therefore, the combination of parameters for the better surface finish can be observed at level A3, B1 and C1 (70 m/min, 0.05 mm and 0.05 mm/ rev).

Based on the rank observed in table 6, it can be implied that the feed rate is the factor that influences surface roughness most, followed by the cutting speed and the depth of cut respectively. The delta value and the steep slope in figure 2 clearly shows that the feed rate is the dominant factor influencing the value of surface roughness. This is because, the rise of friction and contact between the workpiece and tool interface, will eventually increases the temperature in the cutting zone. The changes of cutting tool geometry due to friction and heat will affect the quality of surface finish [9].

**Table 4.** Surface finish results

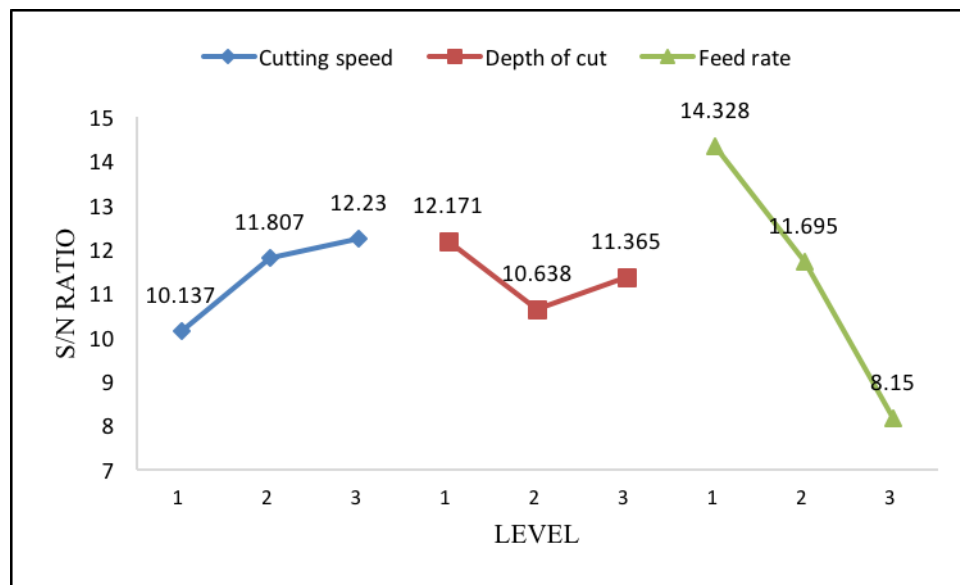
Exp No.	Cutting Parameters			Surface( $\mu\text{m}$ )			
	Speed (m/min)	Doc (mm)	Feed (mm/rev)	R1	R2	R3	R <sub>a</sub> (avg)
1	30	0.05	0.05	0.210	0.198	0.201	0.203
2	30	0.10	0.10	0.327	0.298	0.344	0.323
3	30	0.15	0.20	0.457	0.469	0.454	0.460
4	50	0.05	0.10	0.234	0.245	0.211	0.230
5	50	0.10	0.20	0.403	0.396	0.422	0.407
6	50	0.15	0.05	0.185	0.178	0.180	0.181
7	70	0.05	0.20	0.328	0.295	0.337	0.320
8	70	0.10	0.05	0.197	0.183	0.199	0.193
9	70	0.15	0.10	0.232	0.276	0.203	0.237

**Table 5.** Result calculation S/N value of surface finish

Exp. No	Cutting Parameter Level			S/N Ratio
	A. Speed (m/min)	B. Doc (mm)	C. Feed (mm/rev)	
1	30	0.05	0.05	13.850
2	30	0.10	0.1	9.816
3	30	0.15	0.2	6.745
4	50	0.05	0.1	12.765
5	50	0.10	0.2	7.808
6	50	0.15	0.05	14.846
7	70	0.05	0.2	9.897
8	70	0.10	0.05	14.289
9	70	0.15	0.1	12.505

**Table 6.** Rank for different cutting parameters

Level	A	B	C
1	10.137	<u>12.171</u>	<u>14.328</u>
2	11.807	10.638	11.695
3	<u>12.230</u>	11.365	8.150
$\Delta$	2.093	1.533	6.178
Rank	2	3	1



**Figure 2.** S/N ratio for Surface Roughness.

**Table 7:** ANOVA analysis for surface finish

Factors	Degree of Freedom	Sum of Square	Mean of Square	F Ratio	P Value	Contribution (%)
A	2	7.349	3.675	76.252	0.013	10.7%
B	2	3.529	1.765	36.615	0.027	5.1%
C	2	57.677	28.838	598.403	0.002	84.0%
Model	6	68.555	11.426			
Error	2	0.096	0.048			0.2%
Total	8	68.651				

**Table 8:** Optimum cutting parameter for minimum surface finish

Speed (m/min)	Depth of Cut (mm)	Feed (mm/rev)	Ra (mm)	S/N Ratio
70	0.05	0.05	0.188	14.517

The significance and contribution of each process parameter on the performance characteristics were found out using Analysis of variance (ANOVA) method. From the percentages of influence, factors which are not significant can be easily spotted out so that adjustments and improvements for increasing machining performance can be suggested. ANOVA analyses for surface roughness are presented in table 7. It has been shown that factor C (feed rate) is the dominant factor, which devotes the highest contribution of 84 % followed by factor A (cutting speed) with 10.7 % contribution. Factor B (depth of cut) only contribute to about 5.1 %. A conformation test was conducted in order to validate of result produced based on the setting suggested by Taguchi. The conformation test result is recorded in table 8.

## 5. Conclusion

In this study, the optimal values of cutting parameter of surface roughness under MQL nanolubrication approach during CNC turning of Inconel 718 using Taguchi method was investigated. The results show that surface finish is most influenced by the feed rate at 84 % contribution, followed by cutting speed at 10.7 % contribution and depth of cut at 5.1 % contribution. The optimal combination of parameters for the best surface finish when machining Inconel 718 under MQL system using SDBS added  $\text{Al}_2\text{O}_3$  nanolubricant can be obtained at the cutting speed of 70 m/min, depth of cut of 0.05 mm and feed rate of 0.05 mm/rev. The optimum parameters obtained from the experiment can be applied in real machining industries. This alternative of the application of minimum quantity nanolubricant in machining process reduce coolant consumption, promote sustainable manufacturing and minimize the manufacturing cost.

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## References

- [1] M. N. Sharif, S. Pervaiz, and I. Deiab, Potential of alternative lubrication strategies for metal cutting processes: a review. *The International Journal of Advanced Manufacturing Technology*, 2016.
- [2] A. Garg, S. Sarma, B. N. Panda, J. Zhang, and L. Gao, "Study of effect of nanofluid concentration on response characteristics of machining process for cleaner production," *J. Clean. Prod.*, vol. 135, pp. 476–489, 2016.
- [3] Y. Wang, C. Li, Y. Zhang, M. Yang, X. Zhang, N. Zhang, and J. Dai, "Experimental evaluation on tribological performance of the wheel/workpiece interface in minimum quantity lubrication grinding with different concentrations of  $\text{Al}_2\text{O}_3$  nanofluids," *J. Clean. Prod.*, 2016.
- [4] A. K. Sharma, A. K. Tiwari, and A. R. Dixit, "Effects of minimum quantity lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A review," *J. Clean. Prod.*, vol. 127, pp. 1–18, 2015.
- [5] W. Xia, J. Zhao, H. Wu, S. Jiao, and Z. Jiang, "Effects of oil-in-water based nanolubricant containing  $\text{TiO}_2$  nanoparticles on the tribological behaviour of oxidised high-speed steel," *Tribol. Int.*, vol. 110, no. January, pp. 77–85, 2017.
- [6] T. Bakalova, L. Svobodová, P. Rosická, K. Borůvková, L. Voleský, and P. Louda, "The application potential of  $\text{SiO}_2$ ,  $\text{TiO}_2$  or Ag nanoparticles as fillers in machining process fluids," *J. Clean. Prod.*, vol. 142, pp. 2237–2243, 2017.
- [7] M. A. Mahboob Ali, A. I. Azmi, A. N. Mohd Khalil, and K. W. Leong, "Experimental study on minimal nanolubrication with surfactant in the turning of titanium alloys," *Int. J. Adv. Manuf. Technol.*, 2017.
- [8] M. K. Sinha, R. Madarkar, S. Ghosh, and P. V. Rao, "Application of eco-friendly nanofluids during grinding of Inconel 718 through small quantity lubrication," *J. Clean. Prod.*, vol. 141, pp. 1359–1375, 2017.
- [9] Sulaiman, M.A., Che Haron, C.H., Ghani, J.A. and Kasim, M. S, "Optimization of Turning Parameters for Titanium Alloy Ti-6Al-4V ELI Using the Response Surface Method (RSM)," *Journal of Advanced Manufacturing Technology*, vol. 7, pp. 11–28, 2013.