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# WCO/$TiO_2$ Nanofluids to Machine Inconel 718 Super Alloys for Better Finish

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## Abstract

Nanofluids play a wide role in the metal machining processes. Now-a-days use of difficult to cut materials rapidly increases to ensure the reliability of the critical product at elevated operating temperature, low wear rate, high strength, etc., usually special machining processes were involved in machining such materials. But mass production is time consuming and rapidly increases the cost of manufacturing. For overcome such difficulties this investigation preferred computer numerical control (CNC) machining especially CNC turning centre. As high cutting velocity and strong tools involved in this process the cooling plays a vital role. In this investigation preferred refined waste cooking oil as base fluid and titanium dioxide ($TiO_2$) nanoparticles as additives to boost up cooling effects, apart from these other key factors like spindle speed, tool feed rate, and depth of cut set for finish the components were considered to maximize the surface finish or minimize the surface roughness. Taguchi route was employed. The results revealed that the optimized process parameters were 3000 rpm spindle speed, low feed rate of 0.05 mm per revelation, 0.02 mm depth of cut, and 0.75 wt.% $TiO_2$ concentration of refined waste cooking oil (WCO).

## Keywords

Taguchi route, Titanium dioxide, CNC turning, Waste cooking oil, Nanoparticles

## Introduction

The aerospace industry has seen a rise in the use of nickel-based alloys like Inconel 718 due to its improved mechanical qualities, excellent weldability, and great oxidation and corrosion resistance. Many different elements of aviation and land-based turbine engines, as well as rings and casings for liquid-fueled rockets, are manufactured using Inconel 718 [1]. Inconel alloy 718 is also utilized in cryogenic tankage, which operates at extremely low temperatures. Inconel 625 is regarded as a difficult-to-machine material due to its low thermal conductivity, tendency to produce built-up edges, and increased tendency to stick or weld along cutting edges.

Inconel 625 has a low heat transfer rate; therefore, a lot of the cutting energy is turned into heat that stays at the tool-workpiece interface for a longer period of time during machining. Heat generation leads to high localized temperatures in the machining region, which in turn leads to softening of the tool material and rapid tool wear, which in turn reduces tool life and compromises the integrity of the machined surface. These problems can only be fixed by employing the usage of cutting fluids. Most conventional machining fluids are composed of toxic chemicals that pose health risks to employees, contaminate soil and water during disposal, and are bad for the environment. In addition, only 8% of the total machining cost is accounted for by the price of tools, with cutting fluids being responsible for the remaining 17%. There have been numerous efforts to minimize cutting fluids in order to make material removal operations greener [2]. The primary problem facing the metal-based sector is improving the quality and productivity of machined products. This has led to an increased focus on monitoring every step of the material removal process. Dry cutting, or machining without the use of cutting fluid, is a viable solution for producing environmentally friendly products. However, Inconel binds strongly to the tool surface during dry machining, leading to premature tool failure and subpar surface quality. When Inconel is machined without a coolant, the material's strong mechanical strength and low thermal conductivity cause undesirable residual stresses, surface imperfections, and burning/overheating in the cutting zone. Gentle friction, heat generation, the capacity to distribute and hold a lubricant, wear, and a material's fatigue resistance can all be affected by the surface roughness of the machined product. Cutting tools made of special materials like ceramic, PCD, or PCBN, as well as precise geometry and carefully chosen coatings, are required for dry cutting. Therefore, these sticky alloys are often machined under wet cutting conditions to enhance heat transfer from the tool-chip contact, which leads to high manufacturing costs, worker health concerns, and significant environmental difficulties. Vegetable oils are viewed as a replacement for mineral oils because of their unique intrinsic qualities and their ability to biodegrade [3].

Vegetable oils are preferable to mineral oils because they have a higher flash point, viscosity index, and lubricity while also having a lower evaporative loss. Squeezing the appropriate plant portion under pressure is how oil is extracted. Oils from plants (both edible and non-edible) can be extracted in a variety of ways, including by dissolving plant parts in water, distilling the oil, or infusing the plant components with a base oil. Several studies have shown that coconut oil, palm oil, soya bean oil, and canola oil are effective as ecologically friendly lubricants for machining. The novelty of this study rests on the premise that productivity results from the interplay of three factors: product quality; resource utilization; and operational efficiency; with cooling/lubrication conditions and depth of cut serving as input variables. There has been a lot of focus on using nanoparticles in different base fluids during the past decade. Nanoparticles distributed in water, for example, can increase the thermal conductivity, making it an ideal heat transfer fluid, especially for solar collectors. Since the early 2000s, researchers have looked into the potential benefits of nano-coolants (the dispersion of nanoparticles in water or ethylene glycol) for solving real-world challenges. It is believed that the lubricant's antifriction and anti-wear characteristics come from the nanoparticles put to it.

However, the enhanced properties depend solely on the specifics of the nanoparticles themselves, such as their shape, size, and concentration. In addition, it has been claimed that enhancing lubricating oil's antifriction and anti-wear properties by adding a suitable number of nanoparticles. Surface roughness, material removal rate, and spindle vibration are all terms used throughout the manufacturing process that are encompassed by this lexicon. Constructive process parameters, such as feed speed and cutting depth, are tuned to produce optimum reactions. Since the input parameters could react differently depending on the response, the Taguchi Design of Experiment is utilized to optimize the system as a whole. The objective is to adjust the input values such that they produce the most helpful and long-lasting results. Because of its ease of use and effectiveness, Taguchi's Design of Experiment is a great optimization tool. Taguchi is useful for determining which combination of control variables minimizes the influence of noise. In order to keep manufacturing costs low, it is essential to keep tool costs to a minimum.

Superalloys, also known as high-performance alloys, are a class of metals distinguished by their exceptional resistance to thermal creep deformation, strong resistance to corrosion and oxidation, and high strength at elevated temperatures. In addition to nickel, chromium, and iron, Inconel 718 also contains sizable amounts of niobium and molybdenum, making it a nickel-based superalloy. Niobium's presence age-hardens the alloy, giving it superior strength and fatigue resistance. Inconel 718 is a superalloy that retains its mechanical qualities even at high temperatures, often exceeding 700 °C, making it a member of the family of HRSAs. Turbine engines, cryogenic tankages, aircraft components, and liquid rockets are just some of the many uses made possible by the alloy's unique combination of characteristics. The welding qualities of Inconel 718, such as its resistance to post-weld cracking, are second to none. Due of its austenitic face-cantered cubic crystal structure, this alloy has superior mechanical properties. Inconel 718 has several uses; however, its poor machinability is a key negative. It is a member of the family of abrasive materials. Even when subjected to high temperatures, Inconel 718 maintains its hot strength. Due to its high work-hardening propensity and sensitivity to strain rate, the alloy causes quick tool wear. Because of its microstructure containing hard carbide particles (very abrasive in nature), it causes abrasion wear on the cutting tool. Inconel 718 has a high cutting zone temperature (up to 1200 °C) due to its low thermal conductivity (15 W/m/K). Due to its high chemical affinity (toward tool materials/co-binders), Inconel 718 experiences diffusion wear [4].

Modifications to tool geometry are brought on by phenomena such as chip welding, adhesion, notching, and peel off tool material (called pull out). Inconel 718's high-temperature strength causes a significant magnitude of cutting forces to be developed, which in turn generates excessive vibration (chatter) in the machine tool and, ultimately, poor surface quality in the machined work component. Machining without the application of cutting fluid is always criticized, especially when machining difficult-to-cut materials, despite the fact that conventional dry machining has advantages such as cost effectiveness, environmental friendliness, and compliance with requirements for occupational health and safety issues. Instead, cutting fluid is used in wet machining to increase the efficiency of the process by cooling and lubricating the workpiece. There are a few distinct types of wet cooling methods, including flood cooling, minimum quantity lubrication (MQL), and nanofluid MQL. Since the cutting zone temperature remains relatively low when machining is carried out at reduced cutting speeds, flood cooling emerges as a viable alternative with improved tool life.

The flushing action of the coolant removes chips from the machining area and offers corrosion protection for the finished product. When the cutting speed and temperature are both high, the cutting fluid will often evaporate, creating a steam barrier that prevents enough fluid from entering the cutting zone. An effective solution to this issue is to inject a high-pressure jet of coolant into the cutting zone, which will then generate a hydrodynamic wedge at the interface between the tool chip and the tool work, and ultimately lift the developed chips off the rake face of the tool. An increase in tool life is directly proportional to the efficiency with which the cutting fluid penetrates the material being cut. Despite these benefits, flood cooling has a negative effect on the environment and consumes a lot of coolant, which drives up production costs. Therefore, it seems that the MQL method is a good option. In MQL, cutting fluid is sprayed over the cutting zone combined with compressed air in the form of air-oil mist, but only in extremely small quantities (usually 10 - 100 ml/h). When it comes to machining, MQL offers a cooling/lubrication solution that is both economical and gentle on the planet. The poor thermal conductivity of vegetable oil based MQL limits its use despite its lower toxicity, environmental friendliness (biodegradable), and cost-effectiveness. The use of nano-sized additives, disseminated within a base cutting fluid, is advised in the literature as a means of overcoming them.

To make nanofluid, a base cutting fluid is mixed with nano-sized particles of metals/ceramics/carbon nanotubes in an appropriate ratio. There are many benefits to using a base fluid that contains nanoparticles. When nanoparticles in a base cutting fluid undergo Brownian motion, the resulting fluid's dispersion stability is improved. Because of their increased specific surface area, nanoparticle dispersions lead to better heat transmission. By dispersing nanoparticles throughout the base fluid, the thermal conductivity and wettability of the fluid can be enhanced.

There is sufficient data in the literature to suggest that nanofluid has superior thermal conductivity to standard cutting fluid. According to a study by [5], the thermal conductivity of a nanofluid made by dispersing graphene oxide in water is improved by a significant amount (48.15%) in comparison to the base fluid (water). When the nanoparticles $SiO_2$, ZnO, $TiO_2$, MgO, and $Al_2O_3$ were introduced to the base fluid (ethylene glycol), It was found that the thermal conductivity of the nanofluids was enhanced. An increase in thermal conductivity of 40.6% was seen in nanofluids based on MgO. The thermal property of nanofluid (multi-walled carbon nanotubes dispersed PAO6) was found to be significantly enhanced by [5].

In this research address the research gap of Inconel 718 machining with $TiO_2$ nanofluid with refined WCO in flood cooling environment to improve the surface finish. This investigation aims to prepare the nanofluid at different $TiO_2$ nanoparticles concentration. To conduct the multiple trail runs to fix the range of variables, to experiment as per L16 orthogonal array experimental design. To optimize the parameters including the nanoparticles concentrations to minimize the surface roughness. To conduct the confirmation experiments to validate the prediction of process parameters.

### Materials and Method

The standard work materials obtained from the Chennai Metals (Tamil Nadu, India), and cut them in to 40 mm long work pieces. The rod diameter was 16 mm. the cutting was carried out in Wire cut electric discharge machine. The nanofluid preparation involved mixing of refined WCO with $TiO_2$ nanoparticles with different concentration like 0.25 wt.%, 0.5 wt.%, 0.75 wt.%, and 1 wt.%. Hence 4 different cutting fluid prepared. 1 kg of refined WCO used for each kind of nanofluid. CNC turning center was utilized to conduct the experiments. Many pre-trails were conducted to fix the rage of variables. The range and level of variables depicted in the table 1.

The L16 orthogonal array employed as this investigation decided to vary 4 factors including the coolant grades at 4 different levels in ascending order. Table 2 shows the Taguchi experimental design. The coolant flow was set as 4 L/min. This was decided based on non-fuming condition and ensuring the flush of machined chips and to proving lubrication for better shearing. The nanofluids mixed well this was ensured 48 h storage and found no considerable sedimentation at the bottom of the beaker. The experiments were carried out at the CNC Turning center shown in figure 1. The machined work materials were tested surface roughness tester of make surftest sJ-410 series at cut off length 0.8 mm (see figure 2). the average surface roughness was measured in each specimen after machining and recorded the average surface roughness values. Table 2 last column shows the experiments wise recorded observations.

## Results and Discussion

The experiments were conducted as per Taguchi experimental design of orthogonal array form and observed the average surface roughness, for analysing the results Taguchi analysis was used. The observations were fed into the Minitab 18. Table 3 shows the Taguchi analysis results on the observation of surface roughness. Table 3 ranked the factors which involved in machining feed rate influenced high o it yielded high delta value of 5.02. similarly, the depth of cut was rank 2 (Delta = 4.26), the nanofluids concentration was rank

**Table 1:** Range and levels of variables to test machinability if Inconel 718 work materials.

| Factor | Levels | Values |
|---|---|---|
| Spindle Speed (rpm) | 4 | 1200, 1800, 2400, 3000 |
| Feed rate (mm/rev) | 4 | 0.05, 0.10, 0.15, 0.20 |
| Depth of cut (mm) | 4 | 0.01, 0.02, 0.03, 0.04 |
| $TiO_2$ concentration (wt.%) | 4 | 0.25, 0.50, 0.75, 10.00 |

**Table 2:** Experimental design and surface roughness observations on Inconel 718.

| Exp. No. | Spindle speed (rpm) | Feed rate (mm/rev) | Depth of cut (mm) | $TiO_2$ concentration (wt.%) | Surface roughness |
|---|---|---|---|---|---|
| 1 | 1200 | 0.05 | 0.01 | 0.25 | 0.104 |
| 2 | 1200 | 0.1 | 0.02 | 0.5 | 0.15 |
| 3 | 1200 | 0.15 | 0.03 | 0.75 | 0.16 |
| 4 | 1200 | 0.2 | 0.04 | 10 | 0.23 |
| 5 | 1800 | 0.05 | 0.02 | 0.75 | 0.075 |
| 6 | 1800 | 0.1 | 0.01 | 10 | 0.165 |
| 7 | 1800 | 0.15 | 0.04 | 0.25 | 0.16 |
| 8 | 1800 | 0.2 | 0.03 | 0.5 | 0.34 |
| 9 | 2400 | 0.05 | 0.03 | 10 | 0.11 |
| 10 | 2400 | 0.1 | 0.04 | 0.75 | 0.083 |
| 11 | 2400 | 0.15 | 0.01 | 0.5 | 0.13 |
| 12 | 2400 | 0.2 | 0.02 | 0.25 | 0.112 |
| 13 | 3000 | 0.05 | 0.04 | 0.5 | 0.109 |
| 14 | 3000 | 0.1 | 0.03 | 0.25 | 0.12 |
| 15 | 3000 | 0.15 | 0.02 | 10 | 0.08 |
| 16 | 3000 | 0.2 | 0.01 | 0.75 | 0.108 |

**Figure 1:** CNC turning center at SIMATS University.

**Figure 2:** Surftest sJ-410 series surface roughness tester, SIMATS University.

**Table 3:** Taguchi analysis results on the observation of surface roughness on machined surface of Inconel 718.

| Level | Spindle speed (rpm) | Feed rate (mm/rev) | Depth of cut (mm) | $TiO_2$ concentration (wt.%) |
|---|---|---|---|---|
| 1 | 16.21 | 20.15 | 18.09 | 18.25 |
| 2 | 15.86 | 18.04 | 19.98 | 15.71 |
| 3 | 19.38 | 17.87 | 15.72 | 19.84 |
| 4 | 19.73 | 15.12 | 17.39 | 17.38 |
| Delta | 3.88 | 5.02 | 4.26 | 4.14 |
| Rank | 4 | 1 | 2 | 3 |

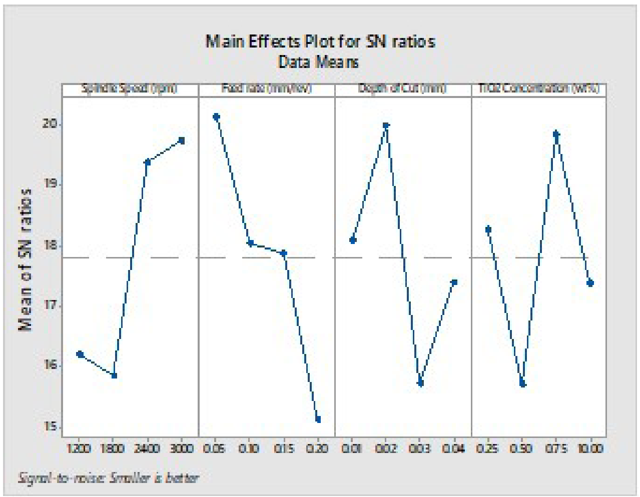

**Figure 3:** Taguchi analysis results in terms of effects of means of S/N ratios yielded by the different factors and their levels.

3 (Delta = 4.14) and spindle speed was rank 4 (Delta = 3.88). the signal to noise (S/N) ratios in table 3 found positive as the smaller is better.

The higher signal is favorable; hence the high S/N ratio is preferred as optimal parameters. According to this in figure 3 the spindle speed reduces the surface roughness rapidly from 1800 rpm then it reaches high at 3000 rpm. The 300 rpm is optimal speed. Similarly, low feed of 0.05 mm per revolution was optimal feed rate. 0.02 mm depth of cut and 0.75 wt.% $TiO_2$ concentration was optimal.

The effects of means of surface roughness is demonstrated in the figure 4. Here the mean surface roughness is minimum is better. According to this higher rpm of spindle speed recorded minimum mean surface roughness that is 3000 rpm. Similarly, 0.05 mm per revolution feed rate, 0.02 mm depth of cut and 0.75 wt.% $TiO_2$ concentration were optimal processing condition.

Analysis of variance (ANOVA) results are two kinds such as for factors and their levels. Table 4 shows the results of

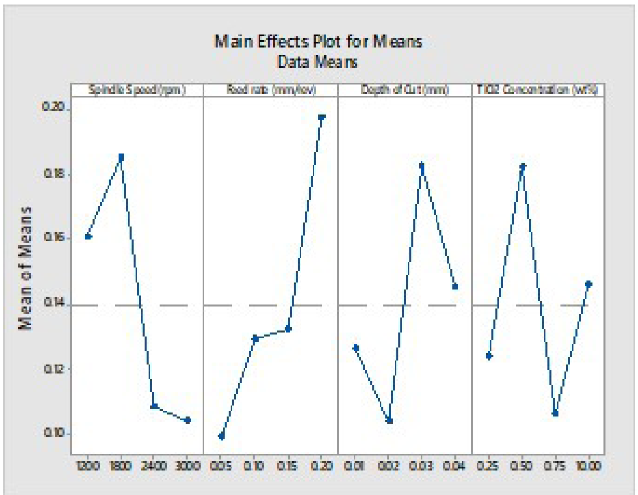

**Figure 4:** Taguchi analysis results in terms of effects of means of surface roughness observations at the different factors and their levels.

ANOVA for the surface roughness observations for factors. The F values shows the contribution factors and p-values shows the level of significance. The F-vales for spindle speed (rpm), feed rate (mm/rev), depth of cut (mm) and $TiO_2$ concentration (wt.%) are 21.89, 23.71, 15.26, and 14.8. The p-value greater than 0.1 are said to be in significant and p-value which secure less that 0.05 is significant. Hence the p-values for spindle speed (rpm), feed rate (mm/rev), depth of cut (mm) and $TiO_2$ concentration (wt.%) are 0.015, 0.014, 0.025 and 0.026. As all p-values are less than 0.05 the model is good.

Table 5 shows results of ANOVA for the of surface roughness observations at the levels of different factors. the p-value greater than 0.1 are said to be in significant and p-value which secure less that 0.05 is significant. Hence the p-values for spindle speed of 1200 rpm, 1800 rpm and 2400 rpm and feed rate (mm/rev) of 0.05, 0.10 and 0.15, depth of cut (mm) of 0.01, 0.02 and 0.03 and the $TiO_2$ concentration (wt.%) of 0.25, 0.50 and 0.75 are 0.063, 0.009, 0.024, 0.012, 0.257, 0.396, 0.175, 0.017, 0.010, 0.121, 0.010, 0.020 in which the $TiO_2$ concentration 0.25 wt.%, depth of cut 0.1 mm, feed rates like 0.1 mm/rev and 0.15 mm/rev and low speed of 1200 rpm are insignificant. These values and omitted levels in the tables shall not considered for better finish. Equation 1 is mathematical model to predict the surface roughness.

Surface Roughness = 0.13975 + 0.02125 Spindle Speed (rpm)_1200 + 0.04525 Spindle Speed (rpm)_1800 − 0.03100 Spindle Speed (rpm)_2400 − 0.03550 Spindle Speed (rpm)_3000 − 0.04025 Feed Rate (mm/rev)_0.05 − 0.01025 Feed Rate (mm/rev)_0.10 – 0.00725 Feed Rate (mm/rev)_0.15 + 0.05775 Feed Rate (mm/rev)_0.20 – 0.01300 Depth of Cut (mm)_0.01 − 0.03550 Depth of Cut (mm)_0.02 + 0.04275 Depth of Cut (mm)_0.03 + 0.00575 Depth of Cut (mm)_0.04

**Table 4:** Results of ANOVA for the of surface roughness observations at the different factors.

| Source | DF | Adj SS | Adj MS | F-value | p-value |
|---|---|---|---|---|---|
| Spindle speed (rpm) | 3 | 0.018881 | 0.006294 | 21.89 | 0.015 |
| Feed rate (mm/rev) | 3 | 0.020451 | 0.006817 | 23.71 | 0.014 |
| Depth of cut (mm) | 3 | 0.013160 | 0.004387 | 15.26 | 0.025 |
| $TiO_2$ concentration (wt.%) | 3 | 0.012809 | 0.004270 | 14.85 | 0.026 |
| Error | 3 | 0.000863 | 0.000288 | - | - |
| Total | 15 | 0.066163 | - | - | - |

**Table 5:** Results of ANOVA for the of surface roughness observations at the levels of different factors.

| Term | Coef | SE coef | T-value | p-value | VIF |
|---|---|---|---|---|---|
| Constant | 0.13975 | 0.00424 | 32.97 | 0.000 | - |
| **Spindle Speed (rpm)** | | | | | |
| 1200 | 0.02125 | 0.00734 | 2.89 | 0.063 | 1.50 |
| 1800 | 0.04525 | 0.00734 | 6.16 | 0.009 | 1.50 |
| 2400 | -0.03100 | 0.00734 | -4.22 | 0.024 | 1.50 |
| **Feed rate (mm/rev)** | | | | | |
| 0.05 | -0.04025 | 0.00734 | -5.48 | 0.012 | 1.50 |
| 0.10 | -0.01025 | 0.00734 | -1.40 | 0.257 | 1.50 |
| 0.15 | -0.00725 | 0.00734 | -0.99 | 0.396 | 1.50 |
| **Depth of cut (mm)** | | | | | |
| 0.01 | -0.01300 | 0.00734 | -1.77 | 0.175 | 1.50 |
| 0.02 | -0.03550 | 0.00734 | -4.84 | 0.017 | 1.50 |
| 0.03 | 0.04275 | 0.00734 | 5.82 | 0.010 | 1.50 |
| **$TiO_2$ concentration (wt.%)** | | | | | |
| 0.25 | -0.01575 | 0.00734 | -2.15 | 0.121 | 1.50 |
| 0.50 | 0.04250 | 0.00734 | 5.79 | 0.010 | 1.50 |
| 0.75 | -0.03325 | 0.00734 | -4.53 | 0.020 | 1.50 |

– 0.01575 $TiO_2$ Concentration (wt.%)_0.25 + 0.04250 $TiO_2$ Concentration (wt.%)_0.50 – 0.03325 $TiO_2$ Concentration (wt.%)_0.75 + 0.00650 $TiO_2$ Concentration (wt.%)_10.00 (1)

The observation and model validation can be ensured from figure 5. It shows the residuals of observations. From this graph shows that all observations are good no errors found. The model yielded $R^2$ value as 98.70% which is greater than 95% the model can be used in the solution space. The statistical model is reliable. The prediction model has good agreement with experiential results. And there is no confirmation validation required.

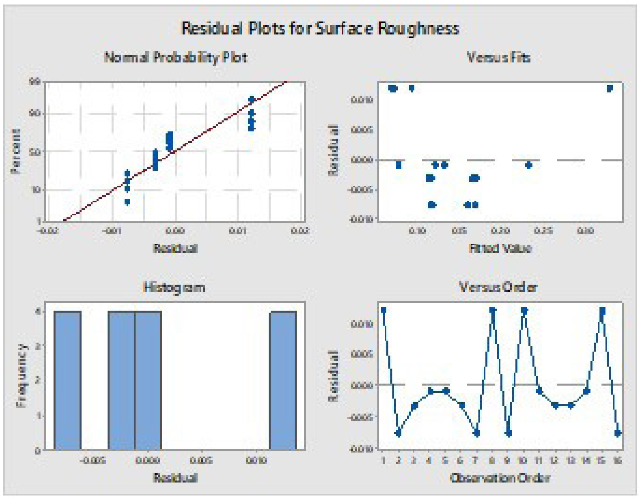

**Figure 5:** The residuals of surface roughness observations.

## Conclusions

This investigation prepared nanofluids for using as cutting fluid to machine the Inconel 718 work material in the CNC turning center. There were 16 samples machined with various input parameters combinations and measured the average surface roughness on machined surfaces. Taguchi analysis used for statistical optimization. The followings are conclusions.

- The possibilities of machining Inconel 718 with flood cooling environment are experimented.
- Considerably good surface finish observed in the machined surfaces.
- All the parameters considered in this investigation like spindle speed, feed rate, depth of cut, and $TiO_2$ concentration are significantly influencing on surface finish in which the feed rate and depth of cut were notably influenced as their p-value found less than 0.05.
- The observations were statistically sound and error free.
- The mathematical model developed for prediction and found good agreement with experimental results.

## Acknowledgements

None.

## Conflict of Interest

None.

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