Multi-Response Optimization Of Machining Parameters In CNC Turning Of AISI 316L Stainless Steel Using MQL Nano fluids

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Abstract. In this research work, optimization of machining parameters in plain turning operation to minimize surface roughness and cutting temperature by applying Taguchi based Desirability function analysis and ANOVA method under Nano cutting fluid environment is performed. Experiments have been performed by plain turning of AISI 316L stainless steel on CNC lathe under MQL setup with Multi-walled carbon Nanotube (MWCNT) inclusions using carbide inserts. Carbon Nano tubes are mixed in a specific ratio (0.20% by wt.) with the cutting fluid. The impact of input parameters on the response variables such as surface roughness and cutting temperature are analysed by using desirability function based approach. Experimental results reveal that feed rate is said to have more effect on the response variables followed by depth of cut, type of cutting fluid and spindle speed.

Keywords: CNC lathe, AISI 316L stainless steel, Surface roughness, Cutting temperature, Nano fluids, Taguchi, Optimization.

1. Introduction
Sharma et al. [1] made an experimental work to optimize cutting variables to reduce surface roughness and to maximize material removal rate in plain turning of EN-31 alloy steel by using coated carbide tool. They have developed a mathematical model using regression technique and optimized the cutting conditions by using Box-Behnken of response surface methodology. The experimental results reveal that the spindle speed is the most significant factor affecting the responses followed by depth of cut and feed rate. Liew et al. [2] made an experimental investigation to optimize cutting variables such as cutting speed, feed rate and type of coolant to minimize surface roughness and flank wear in plain turning of AISI D2 steel. They have selected Carbon Nano fiber Nano fluid and Deionized water as their coolants. The experimental results reveal that cutting speed is influencing more for tool wear and feed rate is influencing more for surface roughness. They have found that 100m/min cutting speed, 0.2mm/rev feed rate and CNF coolant as optimal parameters for flank wear by using Taguchi method. They have found that 200m/min cutting speed, 0.1mm/rev feed rate and CNF coolant as optimal conditions for surface roughness by Taguchi method. They have found that 144.58m/min cutting speed, 0.14mm/rev feed rate and CNF coolant as optimum parameters for minimizing tool wear and
surface roughness according to RSM. Ramana et al. [3] made a research work to optimize machining parameters to minimize flank wear in plain turning of Titanium alloy by using Taguchi Design methodology. The ANOVA results indicate that cutting speed is contributing more to minimize tool wear followed by tool material, depth of cut, feed rate and coolant condition. Sonu Ram and Raj Kumar Yadav [4] made an experimental work to find optimum machining conditions in CNC turning of EN-31 alloy steel. The experimental results reveal that spindle speed is influencing more for surface roughness and depth of cut is influencing more for material removal rate. Shamnad and Thulaseedharan Raman [5] made an experimental investigation to study the effect of process parameters in plain turning of AISI 304 steel under different machining conditions. They have used Taguchi’s L18 orthogonal array to design the experiment. They have made a comparison between machining environment like mineral oil MQL, vegetable and mineral oil flooded and dry cutting. The experimental results reveal that flow rate is the most significant parameter for cutting temperature and frequency of pulse is the most significant parameter for surface roughness. They have found that MQL provides good performance than other conventional fluid application while measuring cutting temperature and surface finish. Katle et al. [6] made an experimental investigation to study the effects of different cutting parameters on material removal rate in straight turning operation of EN31 steel under different environmental conditions. They have used Taguchi L9 orthogonal array to analyse the effect of cutting parameters on material removal rate. The experimental results reveal that depth of cut is most significant factor for material removal rate in the turning operation. Shrikant Borade and Kadam [7] made an experimental work to study the effect of Minimum Quantity Lubrication and Al₂O₃ Nano fluids on the machinability characteristics of EN353 steel in CNC turning operation by using CBN cutting tool inserts. The experimental results reveal that Nano cutting fluids reduced surface roughness and temperature significantly as compared to MQL vegetable oil. They have concluded that depth of cut has significant effect on responses under MQL Nano fluids conditions. Ramana et al. [8] made an experimental work to investigate the effects of process parameters in plain turning of Titanium alloy under different lubricant conditions by using Taguchi’s robust design methodology. The ANOVA results indicate that feed rate has major effect in optimizing the surface roughness. They have found that MQL exhibits better performance and improvement to reduce surface roughness as compared to dry and flooded lubricant conditions. Mamundi azaath et al. [9] in their research work, Taguchi’s L9 orthogonal array to optimize the process parameters in plain turning of EN24 steel under different cutting environment. They have concluded that Nano MQL machining gives the better results as compared to dry and MQL machining. They have found that Nano MQL machining gives 70% betterment in surface finish of the work piece. Vishnu et al. [10] have employed Taguchi’s L9 orthogonal array to optimize the machining parameters in plain turning of EN353 steel under different cutting environment. They have found that 1500rpm spindle speed, 0.8mm/min feed rate, 2.5mm depth of cut and Gold coated carbide tip as tool type are the optimum parameters for maximizing material removal rate under MQL conditions. They have concluded that MQL is a better alternate cooling technique than flood cooling. Patole and Kulkarni [11] made an experimental investigation to study the impact of process parameters in CNC turning of AISI 4340 alloy steel under MQL mode with Nano fluid. The ANOVA results reveal that feed rate is influencing more for surface roughness and depth of cut is influencing more for cutting force in the turning operation. They have found that 0.04mm/rev feed rate, 75m/min cutting speed, 1mm depth of cut, 0.8mm tool nose radius are the optimal conditions for lowering the surface roughness. They have found that 0.04mm/rev feed rate, 90m/min cutting speed, 0.5mm depth of cut, 0.4mm tool nose radius are the optimum conditions for lowering the cutting force. From the literature survey, the machinability characteristics of hard materials can be improved by introducing minimum quantity lubrication Nano cutting fluids. Therefore, the present work deals with the process of improving the machining characteristics of AISI 316L stainless steel by using MQL Nano cutting fluids.
2. Materials and methods

2.1. Materials used
The stainless steel type AISI 316L of 60mm diameter and 150mm length was used for all the experiments. The chemical analysis has been carried out using the spark emission spectrometer. The chemical composition of AISI 316L stainless steel is given in Table 1. In this investigation, coated carbide insert was chosen as the tool material and Multi-walled carbon Nano tube (MWCNT) dispersed in SAE20W40 engine oil as lubricant for conducting turning trials. The Nano fluids were prepared by dispersing 10g of MWCNTs into the SAE20W40 oil base fluid (4000ml) using Esterification process. The properties of Nano fluids are tested in Delta lab, Chennai, India and presented in Table 2.

| Table 1. Chemical composition of AISI 316L Stainless steel |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Element         | C   | Si  | Mn  | S   | P   | Ni  | Cr  | Mo  | N   | Fe  |
| Wt. %           | 0.018 | 0.350 | 1.664 | 0.014 | 0.043 | 10.176 | 16.115 | 2.197 | 0.10 | Rest |

| Table 2. Properties of Nano fluids |
|-----------------------------------|----------------|----------------|
| Thermal property                  | Without MWCNTs | With MWCNTs    |
| Flash Point (°C)                  | 242            | 251            |
| Fire Point (°C)                   | 262            | 255            |
| Pour Point (Deg. C)              | -17            | -15            |
| Viscosity index (cST)            | 117.54         | 120.37         |
| Kinematic Viscosity @ 40°C (cST) | 13.7           | 15.1           |
| Thermal Conductivity (W/mK)      | 0.137          | 0.176          |

2.2 Experimental design
The experiments for this work were planned using Taguchi’s design of experiments (DoE). For the experimental plan, the Taguchi’s mixed level design was selected as it was decided to keep two levels of cutting fluid type. The rest three parameters were kept at three levels. The machining parameters used in this work and their levels are shown in Table 3.

| Table 3. Machining parameter and levels |
|----------------------------------------|----------------|----------------|
| Control parameters                     | Symbol         | Level          |
|                                       |                | 1              | 2              | 3              |
| Type of cutting fluid                  | A              | SAE20W40       | SAE20W40 + 0.2% MWCNT | -              |
| Spindle speed rpm                      | B              | 500            | 750            | 1000           |
| Feed rate mm/rev                       | C              | 0.1            | 0.15           | 0.2            |
| Depth of cut mm                        | D              | 0.4            | 0.7            | 1.0            |

2.3 Experimental Procedure
The experimental study was carried out on DX160 JYOTI CNC Lathe machine with the following specifications: spindle power 5.5/7kw, working temperature 10°C to 50°C, spindle speed range 50 to 4000rpm, swing over bed 500mm and maximum turning length 500mm. The experiment is conducted for MQL (with cutting fluid) of using AISI 316L stainless steel as work material and coated carbide as tool material on CNC Lathe machine. The output responses to be measured are surface roughness and
The surface roughness of the turned surface was measured using a Mitutoyo Surfest SJ-201 contact profile meter as shown in Figure 1. The instrument was set to a cut off length of 0.8mm with a transverse length of 5mm. The cutting temperature at the tool chip interface was measured using a non-contact infrared thermometer. Turning operation is carried out on work piece with 85mm length. The experimental set up is presented in Figure 2. Based on the Taguchi’s L18 Orthogonal array design, eighteen turning experiments are conducted as shown in Table 4.

![Figure 1. Surface roughness measurement setup](image1)

![Figure 2. Experimental set up](image2)
Table 4. Experimental results

| Order | Run | Type of cutting fluid | Spindle speed rpm | Feed rate mm/rev | Depth of cut mm | Surface Roughness µm | Cutting Temperature °C |
|-------|-----|------------------------|-------------------|-----------------|-----------------|----------------------|-----------------------|
| 1     | 6   | SAE20W40               | 500               | 0.10            | 0.40            | 0.28                 | 39.9                  |
| 2     | 4   | SAE20W40               | 500               | 0.15            | 0.7             | 0.705                | 39.8                  |
| 3     | 5   | SAE20W40               | 500               | 0.20            | 1.0             | 1.1                  | 39.7                  |
| 4     | 7   | SAE20W40               | 750               | 0.10            | 0.40            | 0.575                | 36.2                  |
| 5     | 16  | SAE20W40               | 750               | 0.15            | 0.7             | 0.78                 | 42.4                  |
| 6     | 2   | SAE20W40               | 750               | 0.20            | 1.0             | 1.065                | 46.8                  |
| 7     | 10  | SAE20W40               | 1000              | 0.10            | 0.7             | 0.615                | 41.7                  |
| 8     | 9   | SAE20W40               | 1000              | 0.15            | 1.0             | 0.775                | 42.7                  |
| 9     | 17  | SAE20W40               | 1000              | 0.20            | 0.40            | 1.07                 | 47.7                  |
| 10    | 18  | SAE20W40+MWCNT         | 500               | 0.10            | 1.0             | 0.635                | 43.4                  |
| 11    | 12  | SAE20W40+MWCNT         | 500               | 0.15            | 0.40            | 1.07                 | 42.7                  |
| 12    | 1   | SAE20W40+MWCNT         | 500               | 0.20            | 0.7             | 1.54                 | 45.2                  |
| 13    | 8   | SAE20W40+MWCNT         | 750               | 0.10            | 0.7             | 0.50                 | 43.5                  |
| 14    | 11  | SAE20W40+MWCNT         | 750               | 0.15            | 1.0             | 0.88                 | 42.2                  |
| 15    | 15  | SAE20W40+MWCNT         | 750               | 0.20            | 0.40            | 1.34                 | 40.9                  |
| 16    | 13  | SAE20W40+MWCNT         | 1000              | 0.10            | 1.0             | 0.535                | 41.6                  |
| 17    | 14  | SAE20W40+MWCNT         | 1000              | 0.15            | 0.40            | 0.87                 | 40.5                  |
| 18    | 3   | SAE20W40+MWCNT         | 1000              | 0.20            | 0.7             | 1.32                 | 41.5                  |

2.4 Desirability Function Analysis

Desirability function analysis is used to convert the multi response parameters into single response parameters. By using DFA, multi-response optimization of machining parameters can be converted into single-response optimization called composite desirability. The responses such as surface roughness and cutting temperature are combined as composite desirability.

The individual desirability \( D_i \) is calculated for surface roughness and cutting temperature by using the formula given in equation 1.

\[
D_i = \frac{y - y_{\text{max}}}{y_{\text{min}} - y_{\text{max}}} \tag{1}
\]

Where \( y_{\text{min}} \) represents the minimum value of the response variable and \( y_{\text{max}} \) represents the maximum value of the response variable.

In this research work, the smaller-the-better desirability function is used to find the individual desirability for the response variables.

To compute the composite desirability \( D_G \), the following equation 2 is employed.

\[
D_G = \left( D_1^{W_1} \times D_2^{W_2} \times \ldots \times D_i^{W_i} \right)^{1/W} \tag{2}
\]

Where, \( D_i \) is the individual desirability of the response variable \( Y_i \), \( W_i \) is the weight of the response variable “\( Y_i \)” in the composite desirability. \( W \) is the sum of the individual weights of the response variables.
3. Results and Discussions

3.1 Results from Desirability Function Analysis (DFA)

The multiple performances characteristics of the experimental results are evaluated using Desirability Function Analysis (DFA). After finding the individual desirability values of the response variables, then the composite desirability is calculated by using the formula given in equation 2. The resulting values are tabulated as shown in Table 5.

| Order | Run | Type of cutting fluid | Spindle speed rpm | Feed rate mm/rev | Depth of cut mm | Individual Desirability (D_i) | Composite Desirability (D_G) |
|-------|-----|-----------------------|-------------------|------------------|-----------------|-------------------------------|----------------------------|
| 1     | 6   | SAE20W40              | 500               | 0.10             | 0.40            | 1                             | 0.6509434                  | 0.77196541                |
| 2     | 4   | SAE20W40              | 500               | 0.15             | 0.7             | 0.662698413                 | 0.66037736                  | 0.67877339                |
| 3     | 5   | SAE20W40              | 500               | 0.20             | 1.0             | 0.349206349                 | 0.66981132                  | 0.55286888                |
| 4     | 7   | SAE20W40              | 750               | 0.10             | 0.40            | 0.765873016                 | 1                           | 0.9149252                 |
| 5     | 16  | SAE20W40              | 750               | 0.15             | 0.7             | 0.603174603                 | 0.41509434                  | 0.50411896                |
| 6     | 2   | SAE20W40              | 750               | 0.20             | 1.0             | 0.376984127                 | 0                           | 0.13217139                |
| 7     | 10  | SAE20W40              | 1000              | 0.10             | 0.7             | 0.734126984                 | 0.48113208                  | 0.58464558                |
| 8     | 9   | SAE20W40              | 1000              | 0.15             | 1.0             | 0.607142857                 | 0.38679245                  | 0.48597255                |
| 9     | 17  | SAE20W40              | 1000              | 0.20             | 0.40            | 0.373015873                 | -0.08490566                 | 0                          |
| 10    | 18  | SAE20W40+MWCNT        | 500               | 0.10             | 1.0             | 0.718253968                 | 0.32075472                  | 0.46480746                |
| 11    | 12  | SAE20W40+MWCNT        | 500               | 0.15             | 0.40            | 0.373015873                 | 0.38679245                  | 0.41313363                |
| 12    | 1   | SAE20W40+MWCNT        | 500               | 0.20             | 0.7             | 0                           | 0.1509434                  | 0                          |
| 13    | 8   | SAE20W40+MWCNT        | 750               | 0.10             | 0.7             | 0.825396825                 | 0.31132075                  | 0.47927918                |
| 14    | 11  | SAE20W40+MWCNT        | 750               | 0.15             | 1.0             | 0.523809524                 | 0.43396226                  | 0.49298575                |
| 15    | 15  | SAE20W40+MWCNT        | 750               | 0.20             | 0.40            | 0.158730159                 | 0.55660377                  | 0.38144085                |
| 16    | 13  | SAE20W40+MWCNT        | 1000              | 0.10             | 1.0             | 0.797619048                 | 0.49056604                  | 0.60769617                |
| 17    | 14  | SAE20W40+MWCNT        | 1000              | 0.15             | 0.40            | 0.531746032                 | 0.59433962                  | 0.5929133                 |
| 18    | 3   | SAE20W40+MWCNT        | 1000              | 0.20             | 0.7             | 0.174603175                 | 0.5                         | 0.37023711                |

3.2 Effect of input parameters on Composite Desirability (D_G):

Table 6 shows the mean response values for each level of machining parameters on composite desirability. Figure 3 shows the response graph of means for composite desirability.
Table 6. Response table for the composite desirability

| Control factors | Average composite desirability | Max-Min | Rank |
|-----------------|-------------------------------|---------|------|
| Type of cutting fluid, A | 0.51393 | 0.42249 | 0.09144 | 3 |
| Spindle speed, B | 0.48025 | 0.48415 | 0.44024 | 0.04391 | 4 |
| Feed rate, C | 0.63721 | 0.52798 | 0.23945 | 0.39776 | 1 |
| Depth of cut, D | 0.53098 | 0.43475 | 0.43749 | 0.09623 | 2 |

Total mean of the composite desirability = 0.46808

Figure 3. Response graph of means for Composite Desirability ($D_c$)

Basically, when the composite desirability is higher, the better is the output response variables. The optimal machining parameters for the surface roughness and cutting temperature are obtained as A1B2C1D1 as shown in table 7.

Table 7. Optimal machining parameters

| Exp. No. | Type of cutting fluid | Spindle speed | Feed rate | Depth of cut |
|----------|-----------------------|---------------|-----------|-------------|
| 1        | SAE20W40              | 750rpm        | 0.10mm/rev | 0.40mm     |

3.3 ANOVA for composite desirability
The main objective of the statistical ANOVA is to find the significant machining parameters which affect the performance characteristics. From the ANOVA Table 8, it is observed that the feed rate is the most influencing cutting parameter for affecting the output responses. Simultaneously, the interaction between the type of cutting fluid and spindle speed affects the surface roughness and cutting temperature.
Figure 4. Residual plot for Composite desirability

Table 8. Analysis of Variance for the composite desirability ($D_G$)

| Source | DOF | Seq SS  | Adj SS  | Adj MS  | F-test  | P (%)  |
|--------|-----|---------|---------|---------|---------|--------|
| A      | 1   | 0.04233 | 0.024190| 0.024190| 1.21    | 8.92   |
| B      | 2   | 0.01935 | 0.003699| 0.001850| 0.09    | 4.09   |
| C      | 2   | 0.17378 | 0.220139| 0.110070| 5.49    | 36.77  |
| D      | 2   | 0.05937 | 0.013807| 0.006904| 0.34    | 12.56  |
| A×B    | 2   | 0.07725 | 0.086746| 0.043373| 2.16    | 16.37  |
| A×C    | 2   | 0.02024 | 0.020236| 0.010118| 0.50    | 4.32   |
| Residual| 4   | 0.08020 | 0.080197| 0.020049| 16.97   |        |
| Total  | 15  | 0.47250 |         |         |         | 100    |

From the figure 4, it is found that all the points fall close to the straight line in the normal probability plot. This indicates that the developed models are significant.

3.4 Confirmation Experiments

The composite desirability value is predicted for the optimal combination of parameters ($A1B2C1D1$) and its value is 0.76203. Finally, Confirmation test was conducted using the optimum combination of parameters ($A1B2C1D1$). Table 9 shows the comparison of predicted composite desirability value with the actual one.

Table 9. Results of Confirmation Experiment

| Optimal machining parameters | Experimental | Prediction |
|------------------------------|--------------|------------|
| Setting level                | $A1B2C1D1$   | $A1B2C1D1$ |
| Surface roughness            | 0.575        |            |
| Cutting temperature          | 36.2         |            |
| Composite desirability value | 0.91495      | 0.76203    |

4. Conclusions

In this study, the $L_{18}$ taguchi orthogonal array design is used for conducting the experimental runs. The desirability function analysis method is applied to optimize the responses for the machining parameters during CNC turning of AISI 316L stainless steel with carbide tool inserts. It is shown that the multiple performance characteristics during machining of AISI 316L stainless steel are improved by using the desirability function analysis method in this study. The optimal parametric setting
obtained using DFA is A1B2C1D1. From the ANOVA and response tables, it is concluded that feed rate is the most influencing cutting variable on the response variables.

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