Experimental investigation and optimization of cutting parameters with multi response characteristics in MQL turning of AISI 4340 using nano fluid

P.B. Patole* and V.V. Kulkarni

Abstract: To increase the productivity in machining industries demand for better surface finish and accuracy has been increasing rapidly in recent years. Therefore, this paper focus on an effective approach for the optimization of process parameters in Minimum Quantity Lubrication (MQL) turning of AISI 4340 with nano fluid by using Grey Relational Analysis (GRA). Sixty experimental trials based on full factorial design matrix were carried on CNC turning lathe machine to optimize best level. Analysis of experimental results for response variable such as surface roughness and cutting force was performed using Grey Relational Grade (GRG). From GRA the optimal conditions are obtained as cutting speed (75 m/min), Feed (0.04 mm/rev), Depth of cut (0.5 mm) and Tool nose radius (0.8 mm) for optimal response variable surface roughness (1.26 μm) and cutting force (7.69 kgf). The Signal to Noise ratio plot for GRA shows similar optimum condition therefore the results obtained from ANOVA are closely matching to the results of GRA. Improvement in GRG is near about 4.32%. By analysing the GRG, it is observed that the cutting performance in MQL turning of AISI 4340 under MQL mode can be improved.

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PUBLIC INTEREST STATEMENT
Industries are looking for ways to reduce the amount of lubricants in metal removing operations due to ecological, economical and environmental impact. During turning operation high temperature is produced such high temperature leads to several problems like large heat affected zone, high tool wear, change in hardness and microstructure of the work piece, burning and micro crack etc. To reduce above problem minimum quantity lubrication is convenient method in order to achieve good surface roughness and reduce tool wears. Also the advanced heat transfer and tribological properties of nano fluids can provide better cooling and lubricating in the MQL machining process, and make it production-feasible. With proper selection of the MQL system and the cutting parameters, it is possible for MQL machining with minimum cost and less quantity of coolant to obtain better conditions, in terms of lubricity, tool life, cutting temperature and surface finish and optimization of cutting parameters.
1. Introduction
Nowadays, modern machining industries are trying to achieve high quality, dimensional accuracy, surface finish, high production rate and cost saving along with reduced environmental impact (Narana Rao & Satyanarayana, 2011). Turning is the commonly carried out operation in the machining process. It can be carried out on different machines like conventional lathe, CNC machine and special purpose lathe machine (Shaw, 2005). The quality of turning is measured in terms of tolerances and roughness of surface. Surface finish is a quality specified by customer for machined parts (Suhil & Ismail, 2010). In turning operation, parameters such as cutting speed, depth of cut, feed rate and tool nose radius have great impact on the surface finish. The turning operation seems very simple; through high speed turning of steel inherently generates high cutting zone temperature. Such high temperature causes dimensional deviation and premature failure of cutting tools. It also impairs the surface integrity of the product by inducing tensile residual stresses and surface and subsurface micro cracks in addition to rapid oxidation and corrosion (Dhar, Islam, & Kamruzzaman, 2007). However, in high speed machining the conventional cutting fluid application fails to carry away the heat effectively (Lohar & Nanavte, 2013). Therefore, the recent development of nano fluids provides alternative cutting fluids which can be used in MQL machining (Tasdelen, Thordenberg, & Olofsson, 2008). The tribological and advanced heat transfer properties of nano fluids can provide better lubricating and cooling in the MQL machining process, and make it production-feasible. With proper selection of the cutting parameters and the MQL system, it is possible for MQL machining with minimum cost and less quantity of coolant to obtain better conditions, in terms of lubricity, tool life, cutting temperature, surface finish and optimisation of cutting parameters (Shen, 2008). To improve the surface characteristics from micro level to nano level, nano fluids are useful in the machining process (Prabhu & Vinayagam, 2011). Taguchi and Analysis of Variance (ANOVA) can conveniently optimize the cutting parameters with designed experimental trials. Taguchi design optimizes the parameters and reduces the sensitivity of the system performance (Berger & Maurer, 2002). This study describes how to select process parameters which can minimize the effect of nuisance factor. Also this paper deals with the experimental investigation on effect of cutting parameters and optimization of cutting parameters in MQL turning of AISI 4340 with nano fluid for surface roughness and cutting force using Grey Relational Analysis (GRA).

2. Experimental set up and procedure

2.1. Preparation of nano fluid
Nano fluid is a new class of fluids engineered by dispersing nano meter-size solid particles into base fluids such as water, ethylene glycol, lubrication oils, and synthetic oil etc. (Shen, 2008). The Multi Walled Carbon Nano Tube (MWCNT 15 nm in diameter and 30 μm in length) particle is mixed with cutting fluid. The cutting fluid is a base fluid such as ethylene glycol in the proportion of the MWCNT is mixed in the concentration of 0.2%. The nano cutting fluid is prepared for 2 litres. The mass of the MWCNT nano particle required for the preparation of nano fluid is calculated as follows

\[
\text{Density of MWCNT} = 2100 \text{ kg/m}^3, \quad \text{One litre} = (1/1000) \text{ m}^3, \\
\text{Therefore, Mass} = \text{Density} \times \text{Volume}
\]

For 1 litre the mass of MWCNT required is, Mass = \((2100 \times 1)/1000\) = 2.1 kg

At 0.1% concentration \(\text{mass} = (2.1 \times 0.1 \times 1000)/100 = 2.1\ GM\).

At 0.2% concentration \(\text{mass} = (2.1 \times 0.2 \times 1000)/100 = 4.2\ GM\).

For 2 litres the mass of MWCNT is \(\text{mass} = 4.2 \times 2 = 8.4\ GM\).
The mass of the MWCNT required for the preparation of nano fluid is 8.4 gm. This nano particle is mixed with the cutting fluid using “Ultrasonic Vibrator” and “Magnetic Stirrer” in the Nano Science Laboratory. The alloy steel AISI 4340 is widely used for gears, shafts, couplings and other parts. Therefore the nano cutting fluid having better heat carrying capacity it results in better surface finish, maintain degree of cutting temperature and cutting force hence tool life increases so that it is used as the coolant for the turning operation of AISI 4340 under MQL mode.

2.2. Experimental procedure

To verify the grade of particular material chemical composition test is carried out. The chemical composition of work piece material in percentage is shown in Table 1.

According to design of experiment principles the factors and levels are selected for experimentation. The design matrix is \( (3^1 \times 5^1 \times 2^2) \) (Montgomery, 2001). Such as, three values of depth of cut, five values of feed rate, two values of cutting speed and tool nose radius respectively. Therefore, No. of sets of experiment \( = 3^1 \times 5^1 \times 2^2 = 60 \) sets. Whereas the air pressure 5 bar and fluid flow rate, 140 ml/h. are optimized value selected for experimental work. The input parameters and their levels are shown in Table 2.

The experimental trials were conducted on the high speed precision MAXTURN++ (MTAB) CNC lathe machine (Speed 50–4,000 rpm, motor 7 KW). The alloy steel AISI 4340 used as a work piece material having diameter 24 mm, 100 mm length and BHN 217. Tungsten Carbide coated inserts with specification CCMT 090308 are used in MQL turning of AISI 4340 with nano fluid and different cutting parameters with their levels are shown in Table 2. For experimental work MWCNT is mixed in the cutting fluid used as a coolant because it is having better heat carrying capacity. In this research work, the surface roughness of the turned work piece was measured with Mitutoyo make surface roughness tester (SJ-201P). All measurements were repeated three times and the average value was taken as the final value. The cutting forces measured with the help of Kistler Dynamometer, a charge amplifier and PC software. Therefore surface roughness and cutting force are selected as response parameters whereas cutting force is a nuisance factor it affects by controlled as well as uncontrolled parameters so it is need to study the effect of cutting parameters on cutting force to improve the cutting performance under MQL condition with nano fluid. Figures 1–3 shows Experimental set up, MQL set up and Machined work piece respectively.

### Table 1. Chemical composition

| Element | Fe  | Ni  | Cr  | Mn  | C   | Mo  | Si  | S   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| %       | 95.8| 1.3 | 1.15| 0.596| 0.42| 0.22| 0.21| 0.027|

### Table 2. Input parameters and their levels

| S. no | Factor                | Level |
|-------|-----------------------|-------|
| 1     | Cutting speed (m/min) | 75    | 90    |
| 2     | Feed (mm/rev)         | 0.04  | 0.06  | 0.08  | 0.1   | 0.12 |
| 3     | Depth of cut (mm)     | 0.5   | 1     | 1.5   |
| 4     | Nose radius (mm)      | 0.4   |       | 0.8   |
| 5     | Air pressure (bar)    |       | 5     |
| 6     | Fluid flow (ml/h)     |       | 140   |
3. Results and discussion

The sixty experimental trials were carried out under MQL mode with nano fluid to optimize process parameters (cutting speed, depth of cut, feed rate and tool nose radius) on the output response variable such as cutting force and surface roughness. Full factorial orthogonal array was used for designing the experiments. The measured values of cutting force and surface roughness for the machined surfaces corresponding to all the experimental trials are shown in Table 3.

3.1. Analysis of variance

ANOVA is a computational technique that enables the estimation of the contribution of the control factors to the overall measured response. Therefore, the statistical analysis of the experimental
### Table 3. Experimental results

| S. no | CS (m/min) | NR (mm) | FR (mm/rev) | DOC (mm) | Avg. Ra (μm) | Avg. force (kgf) |
|-------|------------|---------|-------------|----------|--------------|------------------|
| 1     | 75         | 0.8     | 0.04        | 1.5      | 1.01         | 22.45            |
| 2     | 75         | 0.8     | 0.04        | 1        | 1.06         | 15.52            |
| 3     | 75         | 0.8     | 0.04        | 0.5      | 1.26         | 7.67             |
| 4     | 75         | 0.8     | 0.06        | 1.5      | 1.24         | 33.21            |
| 5     | 75         | 0.8     | 0.06        | 1        | 1.32         | 23.15            |
| 6     | 75         | 0.8     | 0.06        | 0.5      | 1.35         | 11.7             |
| 7     | 75         | 0.8     | 0.08        | 1.5      | 1.62         | 39.85            |
| 8     | 75         | 0.8     | 0.08        | 1        | 1.5          | 28.07            |
| 9     | 75         | 0.8     | 0.08        | 0.5      | 1.61         | 13.58            |
| 10    | 75         | 0.8     | 0.1         | 1.5      | 1.6          | 45.42            |
| 11    | 75         | 0.8     | 0.1         | 1        | 1.64         | 32.82            |
| 12    | 75         | 0.8     | 0.1         | 0.5      | 1.75         | 16.94            |
| 13    | 75         | 0.8     | 0.12        | 1.5      | 1.7          | 52.26            |
| 14    | 75         | 0.8     | 0.12        | 1        | 1.78         | 37.25            |
| 15    | 75         | 0.8     | 0.12        | 0.5      | 1.88         | 19.15            |
| 16    | 90         | 0.8     | 0.04        | 1.5      | 1.29         | 20.72            |
| 17    | 90         | 0.8     | 0.04        | 1        | 1.37         | 14.14            |
| 18    | 90         | 0.8     | 0.04        | 0.5      | 1.4          | 7.81             |
| 19    | 90         | 0.8     | 0.06        | 1.5      | 1.41         | 31.38            |
| 20    | 90         | 0.8     | 0.06        | 1        | 1.5          | 21.45            |
| 21    | 90         | 0.8     | 0.06        | 0.5      | 1.56         | 10.66            |
| 22    | 90         | 0.8     | 0.08        | 1.5      | 1.67         | 39.14            |
| 23    | 90         | 0.8     | 0.08        | 1        | 1.72         | 28.21            |
| 24    | 90         | 0.8     | 0.08        | 0.5      | 1.8          | 14.74            |
| 25    | 90         | 0.8     | 0.1         | 1.5      | 1.78         | 44.22            |
| 26    | 90         | 0.8     | 0.1         | 1        | 1.82         | 31.56            |
| 27    | 90         | 0.8     | 0.1         | 0.5      | 1.93         | 16.52            |
| 28    | 90         | 0.8     | 0.12        | 1.5      | 1.93         | 50.61            |
| 29    | 90         | 0.8     | 0.12        | 1        | 2.02         | 36.72            |
| 30    | 90         | 0.8     | 0.12        | 0.5      | 2.16         | 19.46            |
| 31    | 75         | 0.4     | 0.04        | 1.5      | 1.09         | 22.56            |
| 32    | 75         | 0.4     | 0.04        | 1        | 1.21         | 15.16            |
| 33    | 75         | 0.4     | 0.04        | 0.5      | 1.5          | 6.62             |
| 34    | 75         | 0.4     | 0.06        | 1.5      | 1.12         | 31.44            |
| 35    | 75         | 0.4     | 0.06        | 1        | 1.32         | 21.19            |
| 36    | 75         | 0.4     | 0.06        | 0.5      | 1.64         | 9.71             |
| 37    | 75         | 0.4     | 0.08        | 1.5      | 1.15         | 38.82            |
| 38    | 75         | 0.4     | 0.08        | 1        | 1.4          | 27.5             |
| 39    | 75         | 0.4     | 0.08        | 0.5      | 1.93         | 12.64            |
| 40    | 75         | 0.4     | 0.1         | 1.5      | 1.28         | 45.55            |
| 41    | 75         | 0.4     | 0.1         | 1        | 1.56         | 31.73            |
| 42    | 75         | 0.4     | 0.1         | 0.5      | 2.08         | 15.48            |
| 43    | 75         | 0.4     | 0.12        | 1.5      | 1.47         | 52.8             |

(Continued)
results can be processed by using Analysis of Variance (ANOVA) (Singh & Rao, 2007). The design of matrix has a major effect on the number of experiments needed. Therefore it is essential to have a proper design of experiments. In present work, the experimental results were analysed with Analysis of Variance which is used for identifying the factors affecting on the surface roughness and cutting force shown in Tables 4 and 5. In this research work, by using full factorial matrix design sixty experimental trials were carried out in MQL turning of AISI 4340 with nano fluid. The results were analysed by using MINITAB statistical software. The response variable surface roughness and cutting force whose lower value is desirable related to machining performance. From Table 4 and Figure 4 it is seen that feed rate and cutting speed having maximum percentage contribution i.e. 38.94 and 22.87 respectively. Also it is observed that from Table 4 feed rate and cutting speed had strongest influence on surface roughness followed by nose radius and depth of cut. Similarly from Table 5 depth of cut had strongest influence on cutting force followed by feed rate and last by nose radius whereas cutting speed is a non significant factor. From Table 4 it can be concluded that depth of cut and feed rate had maximum percentage contribution i.e. 65.27 and 34.12% respectively.

Analysis of influence of each control factor speed, feed, depth of cut and tool nose radius on the surface roughness and cutting force has been performed with signal to noise ratio response table. The influence of each parameter can be clearly shown by response graphs. The response graphs of mentioned control parameters are shown in Figures 4 and 5 for surface roughness and cutting force respectively. The slope of the line clearly shows the power of influence of each control factor. From

| S. no | CS (m/min) | NR (mm) | FR (mm/rev) | DOC (mm) | Avg. Ra (μm) | Avg. force (kgf) |
|-------|------------|---------|-------------|----------|--------------|-----------------|
| 44    | 75         | 0.4     | 0.12        | 1        | 1.82         | 37.14           |
| 45    | 75         | 0.4     | 0.12        | 0.5      | 2.32         | 17.57           |
| 46    | 90         | 0.4     | 0.04        | 1.5      | 2.07         | 22.78           |
| 47    | 90         | 0.4     | 0.04        | 1        | 1.42         | 14.56           |
| 48    | 90         | 0.4     | 0.04        | 0.5      | 1.75         | 6.87            |
| 49    | 90         | 0.4     | 0.06        | 1.5      | 2.22         | 30.81           |
| 50    | 90         | 0.4     | 0.06        | 1        | 1.5          | 20.5            |
| 51    | 90         | 0.4     | 0.06        | 0.5      | 1.88         | 10.2            |
| 52    | 90         | 0.4     | 0.08        | 1.5      | 2.31         | 39.8            |
| 53    | 90         | 0.4     | 0.08        | 1        | 1.67         | 27.48           |
| 54    | 90         | 0.4     | 0.08        | 0.5      | 2.15         | 13.44           |
| 55    | 90         | 0.4     | 0.1         | 1.5      | 2.52         | 46.15           |
| 56    | 90         | 0.4     | 0.1         | 1        | 1.82         | 31.88           |
| 57    | 90         | 0.4     | 0.1         | 0.5      | 2.28         | 16.25           |
| 58    | 90         | 0.4     | 0.12        | 1.5      | 2.9          | 51.12           |
| 59    | 90         | 0.4     | 0.12        | 1        | 2.07         | 36.57           |
| 60    | 90         | 0.4     | 0.12        | 0.5      | 2.52         | 18.7            |

Table 4. ANOVA results for surface roughness

| Source | DF  | F    | P    | % Contr. |
|--------|-----|------|------|----------|
| CS     | 1   | 45.48| 0.000| 22.87    |
| NR     | 1   | 11.17| 0.002| 5.61     |
| FR     | 4   | 19.36| 0.000| 38.94    |
| DOC    | 2   | 6.89 | 0.002| 6.92     |
| Error  | 51  |      |      | 25.64    |
| Total  | 59  |      |      | 100      |
Figure 4 it is seen that the optimum conditions for surface roughness are cutting speed 75 m/min, Feed rate 0.04 mm/rev, Depth of cut 1 mm and Tool nose radius 0.8 mm. From Figure 5 it is observed that the optimum conditions for cutting force are cutting speed 90 m/min, Feed rate 0.04 mm/rev, Depth of cut 0.5 mm and Tool nose radius 0.4 mm.

3.2. Grey Relational Analysis

This analysis can be used to represent the grade of correlation between two sequences so that the distance of two factors can be measured discretely (Ulas & Ahmet, 2008). When the experimental method cannot be carried out exactly, grey analysis helps to compensate for the shortcoming in statistical regression (Lin & Ho, 2003). GRA can analyse many factors that can overcome the disadvantages of statistical method (Chang, Tsai, & Chen, 2003). Grey relational coefficients, grade and order of the measured values of surface roughness and cutting force for the machined surfaces corresponding to all the experimental trials are shown in Table 6. Table 6 shows that experiment No. 3 has the highest Grey Relational Grade (GRG) (Appendix A). The response variables in this experiment are surface roughness (1.26 μm) and cutting force (7.69 kgf).

| Source | DF | F   | P   | % Contr. |
|--------|----|-----|-----|----------|
| CS     | 1  | 0.61| 0.439| 0.006    |
| NR     | 1  | 10.21| 0.002| 0.1      |
| FR     | 4  | 874.16| 0.000| 34.12    |
| DOC    | 2  | 3,344.71| 0.000| 65.27    |

Figure 4. S/N ratio for surface roughness.

Figure 5. S/N ratio for cutting force.
| Exp. no | GRC | Grade | Order |
|--------|-----|-------|-------|
| Ra     | Force |       |       |
| Ra     | Force |       |       |

(Continued)
To calculate Average GRG for each factor level Taguchi method was employed. In orthogonal array average the GRG by factor level for each column (Fung, 2003). The mean of GRGs of all parameters at different levels and the difference between the maximum and minimum value of GRG for cutting parameters are shown in Table 7. The (Max-Min) the value of GRG shows the importance of individual parameter in MQL turning of AISI 4340 with nano fluid. From Table 7, it is observed that the difference between maximum and minimum value of GRG for parameter feed rate is higher than that of spindle speed, depth of cut and tool nose radius parameters. It indicates that feed rate has stronger effect on the multi performance characteristics than other parameters. Table 7 indicates that the highest GRG of each parameter shows optimal level of parameter. The optimised parameters are as Feed rate 1, Depth of cut 1, Cutting speed 1 and Tool nose radius 2. Therefore the optimized parameters are as cutting speed (75 m/min), Feed rate (0.04 mm/rev), Depth of cut (0.5 mm) and Tool nose radius (0.8 mm).

From Table 8 it is seen that, feed rate is a most significant factor and also observed that the obtained results are statistically significant as probability of significance (p-value) is less than 0.05. The Signal to Noise ratio (S/N) is calculated by using MINITAB software. Signal represents desirable value whereas noise represents undesirable value for the output characteristics (Rao, Ramji, & Satyanaraya, 2010). The S/N ratio plot for GRA (Figure 6) shows similar optimum condition i.e.

| Exp. no | Ra  | Force | Grade | Order |
|--------|-----|-------|-------|-------|
| 43     | 0.6726 | 0.3333   | 0.503 | 47    |
| 44     | 0.5384 | 0.4118   | 0.4851 | 51    |
| 45     | 0.4191 | 0.6753   | 0.5472 | 40    |
| 46     | 0.4713 | 0.5864   | 0.5289 | 43    |
| 47     | 0.6974 | 0.7449   | 0.7212 | 13    |
| 48     | 0.5609 | 0.981    | 0.7709 | 8     |
| 49     | 0.4385 | 0.4894   | 0.464  | 53    |
| 50     | 0.6585 | 0.6222   | 0.6404 | 22    |
| 51     | 0.5207 | 0.8663   | 0.6935 | 15    |
| 52     | 0.4209 | 0.4099   | 0.4154 | 58    |
| 53     | 0.5888 | 0.5241   | 0.5564 | 36    |
| 54     | 0.4532 | 0.7728   | 0.613  | 28    |
| 55     | 0.3649 | 0.3697   | 0.3773 | 59    |
| 56     | 0.5384 | 0.4767   | 0.5076 | 46    |
| 57     | 0.4266 | 0.7066   | 0.5666 | 35    |
| 58     | 0.3333 | 0.3421   | 0.3377 | 60    |
| 59     | 0.4713 | 0.4347   | 0.453  | 56    |
| 60     | 0.3849 | 0.6538   | 0.5194 | 44    |

**Table 7. Response table for grey relational grade**

| Factor | L1   | L2   | L3   | L4   | L5   | Max-Min |
|--------|------|------|------|------|------|---------|
| FR     | 0.7628* | 0.6632 | 0.5846 | 0.5342 | 0.483 | 0.2789 |
| DOC    | 0.6717* | 0.6   | 0.3456 | 0.5342 | 0.483 | 0.1261 |
| CS     | 0.6416* | 0.5698 | 0.3421 | 0.3377 | 0.563 | 0.096  |
| NR     | 0.5939 | 0.6176* | 0.6538 | 0.5194 | 0.2237 | 0.453  |

*Optimized level.
cutting speed (75 m/min), feed rate (0.04 mm/rev), depth of cut (0.5 mm) and tool nose radius (0.8 mm). It means that the results obtained from ANOVA are closely matching to the results of GRA.

The validation of optimal level of cutting parameters is evaluated by using GRG. Table 9 shows GRG improvement with optimised parameters. A good improvement with optimised parameters is 4.32%.

Figure 7 shows GRG vs. experimental trial. According to conducted full factorial experimental design, it is clearly seen that from Table 6 and Figure 7 that the process parameters setting of
experiment No. 3 has the highest GRG. Thus, the third experiment gives the best multi performance characteristics among the sixty experiments.

3.3. Comparative analysis

The experimental runs were carried out on CNC turning lathe machine at different levels of process parameters to evaluate the effect of cutting parameters such as depth of cut and feed rate on surface roughness at different conditions such as—MQL1 (MWCNT nano particles mixed with ethylene as a base fluid), MQL2 (MWCNT nano particles mixed with water as a base fluid), Flooded and Dry. Figure 8 shows surface roughness vs feed rate at 0.5 mm depth of cut for MQL1, MQL2, Flooded and Dry lubrication systems. From Figure 8, it is observed that among the four lubrication systems, MQL1 with nano fluid gives better values of surface roughness. It is observed from Figures 8, as feed rate increases surface roughness value increases. Hence, it can be seen that from the lower surface roughness values that nano fluid has better heat carrying capacity with MQL1 as compared to other lubrication conditions.

3.4. Regression analysis

The regression model is mostly used to predict the responses is an algebraic representation of the regression line and is used to built up the relationship between the response and predictor parameters (Montgomery (2001), Patel et al.,(2015)).

Response = constant + coefficient (predictor) + … + coefficient (predictor)  

(1)

Regression analysis was implemented to develop prediction model using the predictors such as feed, speed, depth of cut and tool nose radius in CNC turning of AISI 4340 under MQL mode with nano fluid. The Minitab software was used for the analysis of experimental work and to develop the predictive model for the GRG of surface roughness and cutting force. Therefore the regression equation obtained is

\[
\text{Grey Relational Grade} = -6.76 + 0.00544 \text{ SS} - 0.901 \text{ NR} + 49.0 \text{ FR} + 1.92 \text{ DOC}
\]

(2)

The quantity $R^2$ called as coefficient of determination is used to judge the adequacy of regression model developed. The higher of $R^2$ indicates the better fitting of the model with the data (Mandal, Doloi, & Mondal, 2011). In this model the adjusted $R^2$ value is nearly closer to the predicted $R^2$. To test the statistical significance of model, analysis of variance table is constructed and shown in Table 10 for GRG. $F$-ratio is also the important factor to check the adequacy of model where $F$-table value should be smaller than the $F$-calculated value (Hwang & Lee, 2010). From Table 11 it is seen that model is to be statistically significant as probability of significance (p-value) is less than 0.05 and $F$-calculated value is greater than $F$-table value (5.14). It is observed that the parameters mentioned

| Table 10. Summary of the model |
|--------------------------------|
| Cooling system | Response variable | $S$ | $R^2$ (%) | $R^2$ (adj) (%) | PRESS | $R^2$ (pred) (%) |
|-----------------|-------------------|-----|------------|----------------|--------|----------------|
| MQL             | GRG               | 0.6303 | 88.7      | 87.9          | 26.29  | 86.43          |
in the model have significant effect on the response. Also, at optimum condition actual value (0.87) and predicted value (0.85) for response are very close to each other showing the significance of model developed.

4. Conclusion
By using GRA, the process parameters in MQL turning of AISI 4340 with nano fluid are optimized such as cutting speed (75 m/min), feed rate (0.04 mm/rev), depth of cut (0.5 mm) and tool nose radius (0.8 mm). From result analysis it is observed that, feed rate is a most significant factor. The optimum response variable obtained as surface roughness 1.26 μm and cutting force 7.69 kgf. From Figure 7 it is also seen that the experiment No. 3 has highest GRG. Improvement in GRG is near about 4.32%. Table 12 shows optimised parameter value. From comparative analysis it is observed that, MQL1 gives better surface roughness value as compared to other lubrication systems.

To achieve the desire quality more focus should be on right selection of machining parameters. Therefore, the regression model would be helpful in selecting cutting conditions for required response characteristics. It may be helpful in optimising machining parameters to obtain desired value of GRG of surface roughness and cutting force under Minimum Quantity Lubrication turning of alloy steel with nano fluid.

Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| MQL          | Minimum Quantity Lubrication |
| MWCNT        | Multi Walled Carbon Nano Tube |
| FR           | Feed rate   |
| CS           | Cutting speed |
| DOC          | Depth of cut |
| NR           | Nose radius  |
| Ra           | Surface roughness |

Table 11. Analysis of variance for GRG model

| Source              | DF | CS   | MS  | F    | P   | Remark |
|---------------------|----|------|-----|------|-----|--------|
| Regression          | 4  | 171.87 | 42.96 | 108.15 | 0.00 | Significant |
| Residual error      | 55 | 21.85 | 0.39 |      |     |         |
| Total               | 59 | 193.72 |      |      |     |         |

Table 12. Optimised parameters

| S. no. | Optimisation                                      | Parameters                      |
|--------|---------------------------------------------------|---------------------------------|
|        |                                                  | Cutting speed | Feed rate | Depth of cut | Tool nose radius |
| 1      | Optimisation based on surface roughness           | 75             | 0.04      | 1            | 0.8              |
| 2      | Optimisation based on cutting force               | 90             | 0.04      | 0.5          | 0.4              |
| 3      | Optimisation based on surface roughness and cutting force (GRA) | 75             | 0.04      | 0.5          | 0.8              |
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Appendix A

For experimental No. 3

| Surface roughness (μm) | Normalisation (Ra) | Deviation sequence = Normalisation (Ra) | GRC (Ra) | GRG |
|------------------------|--------------------|----------------------------------------|---------|----|
| 1.26                   | 0.867              | 0.133                                  | 0.7908  | 0.871 |

(1) Normalisation of Ra

\[
\frac{(2.9 - 1.26)}{(2.9 - 1.01)} = 0.867
\]

(2) Deviation sequence of Ra

\[(1 - 0.867) = 0.133\]

(3) Grey Relational Coefficient (GRC) of Ra

\[
\frac{(0.00 + 0.5 \times 1)}{(0.1323 + 0.5 \times 1)} = 0.7908
\]

(4) Grey Relational Grade of Ra

\[
\frac{(0.7908 + 0.952)}{2} = 0.871
\]