Experimental investigation on hard turning of AISI 4340 steel using cemented coated carbide insert

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Abstract. Hard turning is a developing technology that offers many potential advantages compared to grinding, which remains the standard finishing process for critical hardened surfaces. In this work, an attempt has been made to experimentally investigate hard turning of AISI 4340 steel under wet and dry condition using cemented coated carbide insert. Hardness of the workpiece material is tested using Brinell and Rockwell hardness testers. CNC LATHE and cemented coated carbide inserts of designation CNMG 120408 are used for conducting experimental trials. Significant cutting parameters like cutting speed, feed rate and depth of cut are considered as controllable input parameters and surface roughness (Ra), tool wear are considered as output response parameters. Design of experiments is carried out with the help of Taguchi’s L9 orthogonal array. Results of response parameters like surface roughness and tool wear under wet and dry condition are analysed. It is found that surface roughness and tool wear are higher under dry machining condition when compared to wet machining condition. Feed rate significantly influences the surface roughness followed by cutting speed. Depth of cut significantly influences the tool wear followed by cutting speed.

1. Introduction

Manufacturers around the world constantly strive for lower cost solutions in order to maintain their competitiveness, on machined components and manufactured goods. Globally, part quality has been found to be at acceptable levels and it continues to improve, while the pressure for part piece cost is enormous and is constantly being influenced downward by competition and buyer strategies. The trend is toward higher quality, lower cost and smaller batch sizes. In current industrial scenario CNC machine tools, which operate with mature technology and provide both consistency and reliability, have now become the biggest contributor to part quality and cost. A rapid adoption of these newer and more cost effective manufacturing techniques will be constantly required if manufacturing operations are to remain competitive. The technology evolution for addressing machining of hard materials results in a newer solution called hard turning.

Hard turning is the process of machining hardened ferrous material with a hardness value more than 45HRC in order to obtain finished work pieces directly from hardened parts. The cutting tools

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of choice are typically Cubic Boron Nitride (CBN), ceramic, carbide and sometimes cement. Hard turning does provide an alternative for those applications that do not require the high end processing capability of a grinder, or for pregrind roughing operations. Clearly, for many applications involving very close tolerance work, grinding will still remain the process of choice. More specifically, hard turning does not eliminate the need for grinding but can relieve the production burden on the more expensive grinders for the properly chosen application. The tooling choice will need to be matched to the application, desired production rates and the operating cost goals. The current tooling technology allows the user to be able to choose between wet or dry operations. For parts, such as gears, that have interrupted cuts, dry condition is preferred. That is because the insert would experience thermal shock while entering and exiting cuts would likely cause tool or part breakage. Cutting without coolant provides obvious cost benefits as well. Wet operations refer to processes under flood or high-pressure with a water-soluble coolant. Coolant can be helpful for continuous cutting applications in terms of providing longer tool life and better surface finishes. Machine requirements for hard turning include machine rigidity, part rigidity, rigid tools, solid work holding and vibration dampening. The range of hard turned applications will vary based upon the part requirements, tolerance levels, surface finish and very importantly the machine tool. On a daily basis, parts are being hard turned in the following industry segments: automotive, bearing, marine, punch and die, mold, hydraulics and pneumatics, machine tool and aerospace. Commonly processed hard turned materials would include steel alloys such as bearing steels, hot and cold-work tool steels, high speed steels, die steels, case hardened steels. Advantages of hard turning are process flexibility, higher metal removal rates, improved surface finish, reduced time consumption, easier chip control. Limitations of hard turning include white layer formation, tooling and machine process capability.

2. Literature survey
Hamza Bensouilah et al. (2016) concluded that surface roughness is minimal at higher cutting speed and lower feed rate. Coated ceramic inserts performed significantly better than uncoated ceramic inserts. According to ANOVA it was observed that feed rate significantly influenced surface roughness. The optimum process parameters for better surface finish were found to be cutting speed = 150 m/min, feed rate = 0.04 mm/rev and depth of cut = 0.1 mm. D’Addona D M et al. (2016) investigated the analysis of surface roughness in hard turning using wiper insert geometry and observed that wiper insert geometry gives superior surface finish as compared to conventional inserts and it can give comparable surface finish with grinding operation. Feed is found to be most significant parameter for surface roughness. After feed, depth of cut and type of insert are found to have statistically significant effect on surface roughness. The cutting conditions to achieve good surface roughness are wiper geometry with 1.2 mm nose radius, 1200 RPM, 0.08 mm/rev feed rate and 0.1 mm depth of cut. Dipti Kanta Das et al. (2014) investigated on Investigations on hard turning using coated carbide insert and reported the good surface quality of roughness about 0.42 microns during hard machining of EN 24 steel with the help of coated carbide insert. Using grey-based Taguchi approach, the optimal parametric combination for surface quality characteristics (Ra and Rz) have been obtained to be depth of cut: 0.4 mm, feed: 0.04 mm/rev and cutting speed: 130 m/min respectively. Feed was considered to be the most dominant parameter for both surface roughness parameters Ra and Rz. Sathish Chinchanikar et al. (2014) studied on comparative evaluations on surface roughness during dry and wet condition and concluded that hard turning with cutting fluids has not significantly improved the surface finish in comparison to dry cutting. However coconut based cutting fluid produced lower values of surface roughness especially at higher values of cutting parameters in comparison to hard turning with dry and with water based cutting fluid. Surface roughness decreased initially with increase in speed but when it exceeded 150-160 m/min, Ra value increased. Ra values of about 0.5 – 0.6 µm was obtained. However it has been observed that by limiting cutting parameters hard turning under dry condition was the better option in comparison to wet condition. Varaprasad.Bh et al. (2014) investigated the effect of machining parameters on tool
wear in hard turning of AISI D3 steel. The authors observed that significant parameter for tool flank wear was depth of cut. The speed and feed have little influence on the total variation The RSM based DOE was found to be an effective way in determining the optimal cutting parameters to be speed of 165m/min, feed rate of 0.05mm/rev and depth of cut of 0.3mm to achieve a low tool wear of 0.148mm. A.Srithar [6] et al. (2014) reported on experimental investigation and surface roughness analysis on hard turning of AISI D2 steel using coated carbide insert. Investigations were carried out on conventional lathe using the prefixed cutting conditions. The results specify that the increase of cutting speed decreases the surface roughness. The results shows that feed rate is highly control the parameter, which influence the surface roughness parameters in machining of AISI D2 steel. Gaurav Bartarya [7] et al. (2012) reported on state of art in hard turning and observed that radial force seem to be dominant in hard turning. White layer formation was due to phase transformation to martensite. Coolant may help in reducing white layer thickness and tensile residual stress. For finish hard turning depth of cut was less than the nose radius of the tool. Guddat J [8] et al. (2011) reported on hard turning of AISI 52100 using PCBN wiper geometry inserts and the resulting surface integrity. The assessment of surface and subsurface integrity reveals that, when compared to conventional geometry inserts, the application of PCBN wiper inserts leads to significantly improved surface roughness and higher compressive residual stresses. The author summarized that using wiper inserts leads to superior surface integrity compared to conventional inserts. At the same time, higher productivity can be achieved. Vikram Kumar R [9] et al. (2007) investigated on performance of coated tools during hard turning under minimal fluid application and reported that overall performance of cutting tools during minimal cutting fluid application was found to be superior to that of dry turning. Cutting performance mainly depends on fluid application parameters such as cutting force, number of pulses and amount of cutting fluid. Grzesik W [10] et al. (2006) studied on the hard turning of quenched alloy parts using conventional and wiper inserts and concluded that hard turning with wiper provide higher surface finish.

From the extensive literature survey, it was found that hard machining has the advantages of cost, time and coolant savings compared to grinding. The biggest challenge for hard machining was the surface quality whether that was close to grinding or not. Therefore optimized process parameters are highly essential for its successful implementation in the industry. Therefore, the experimental investigation on hard turning was becoming increasingly important. As seen from the literature review, the hard machining operation was usually done by costly ceramic and CBN insert. The attempt has been made in the present work utilizing low cost coated carbide insert in hard turning under dry and wet condition to justify its usability compared to costlier CBN and ceramic insert. Thus the objective is to investigate surface quality characteristics (Ra), tool wear in hard turning of AISI 4340 steel using cemented coated carbide insert. The methodology adopted in the present work is shown in ‘figure 1’.
3. Experimental details

3.1. Workpiece material
The work material is AISI 4340 steel. It is a general-purpose steel having a wide range of application in automobile and allied industries by virtue of its good hardenability enabling it to be used in fairly large sections. Bars of 36 mm diameter and 100 mm length are used in the present investigation. The composition of the work material is shown in table 1.
Table 1. Chemical composition of AISI 4340 steel.

| %C   | %Mn | %Ni | %Cr | %Mo |
|------|-----|-----|-----|-----|
| 0.40 | 0.70| 1.80| 0.80| 0.25|

3.2. Machine tool
The CNC LATHE (Galaxy Midas 6) used for machining is shown in ‘figure 2’.

![Figure 2. CNC LATHE.](image)

3.3. Cutting tool
Cemented carbide inserts (commercially available) comprising of thick TiCN and thick Al₂O₃ coatings are selected for the present work. The selected insert with a general specification of CNMG 120408 and chip breaker of type DM is shown in ‘figure 3’. The tool holder of hole type clamping with a general specification of PCLNR 2525M12 is selected for the present investigation.

![Figure 3. CNMG 120408 insert.](image)

3.4. Brinell hardness testing
The hardness of the material is measured by applying load of 3000kg in different locations on the surface of the material. Ball indenter of 10 mm diameter is used to measure the hardness. The indentation time is 15 seconds. Three trials are conducted as shown in table 2, for evaluation of work material Brinell hardness. The Brinell hardness is calculated using equation (1).
Brinell hardness = \( \frac{2P}{\pi (D - \sqrt{D^2 - d^2})} \) BHN
(1)

where, P is the load (kg) applied, D is the diameter of indenter (mm) and d is the diameter of indentation (mm).

### Table 2. Hardness (BHN) of AISI 4340 steel.

| S.No | Diameter of indenter ‘D’ (mm) | Load ‘P’ (Kg) | Diameter of indentation ‘d’ (mm) | BHN     |
|------|------------------------------|--------------|--------------------------------|---------|
| 1.   | 10                           | 3000         | 2.85                           | 461.512 |
| 2.   | 10                           | 3000         | 2.84                           | 464.503 |
| 3.   | 10                           | 3000         | 2.83                           | 467.816 |

### 3.5. Rockwell hardness testing

The hardness of the material is also measured by applying load of 150kg in different locations on the surface of the material. Diamond indenter of 120° is used to measure the hardness. The indentation time is 15 seconds. Three trials are conducted as shown in table 3, for evaluation of work material Rockwell hardness.

### Table 3. Hardness (HRC) of AISI 4340 steel.

| S.No | Load ‘P’ (Kg) | HRC |
|------|--------------|-----|
| 1.   | 150          | 48  |
| 2.   | 150          | 51  |
| 3.   | 150          | 49  |

### 3.6. Selection of parameters

Taguchi method is used for execution of the plan of experiments, L9 orthogonal array is used for experimentation. The three dominant process parameters such as cutting speed, feed rate and depth of cut each varying at three levels are selected as controllable parameters for carrying out experimental trials. The range of these parameters are obtained based on initial experimental trials, literature survey, insert catalogue and machine specifications is shown in table 4.

### Table 4. Design factors along with levels.

|             | Cutting Speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|-------------|-----------------------|--------------------|-------------------|
|             | 150                   | 0.04               | 0.2               |
|             | 250                   | 0.08               | 0.4               |
|             | 350                   | 0.12               | 0.6               |
The experimental treatments of combination of these parameters are shown in table 5.

**Table 5.** L9 orthogonal array with design factors.

| Trial No | Speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|----------|---------------|---------------------|-------------------|
| 1        | 150           | 0.04                | 0.2               |
| 2        | 150           | 0.08                | 0.4               |
| 3        | 150           | 0.12                | 0.6               |
| 4        | 250           | 0.04                | 0.4               |
| 5        | 250           | 0.08                | 0.6               |
| 6        | 250           | 0.12                | 0.2               |
| 7        | 350           | 0.04                | 0.6               |
| 8        | 350           | 0.08                | 0.2               |
| 9        | 350           | 0.12                | 0.4               |

### 3.7. Experimental trials

Each experimental trial is conducted twice based on Taguchi L9 orthogonal array and the average values are taken for the response variables such as surface roughness value (Ra) and tool wear. Taguchi method is an experimental design technique, which is useful in reducing the number of experiments, decrease experimental time, reduce the cost and find out significant factors in a shorter time period. Taguchi’s smaller the better criteria is used for evaluation of surface roughness value and tool wear. For smaller the better, the S/N ratio is calculated using equation (2).

\[
\frac{S}{N} = -10 \log \frac{1}{n} \left( \sum_{i=1}^{n} y_i^2 \right)
\]

where, n is the number of trials and \(y_i\) is the response value. In order to establish the statistical significance of the cutting parameters on the output parameters analysis of variance (ANOVA) is used. The statistical significances of linear model are evaluated by P – values of ANOVA. When P – values are less than 0.05 (95% confidence) the obtained models are considered to be statistically significant. Analysis of the experimental data obtained through Taguchi experimental design is carried out using MINITAB 17 software. The response variables such as surface roughness and tool wear are measured during dry turning and wet turning. The specimen after hard turning is shown in ‘figure 4’.
3.8. Surface roughness measurement test
The surface roughness of hard turned AISI 4340 steel under dry and wet conditions is measured using a Mitutoyo surface roughness tester SJ 201 with cut-off length of 0.8 mm. The apparatus used for surface roughness measurement is shown in ‘figure 5’.

![Surface roughness tester](image)

**Figure 5.** Surface roughness tester.

3.9. Tool wear measurement
During the course of experimentation under dry and wet conditions, the tool wear of worn out inserts are measured with the help of a Tool maker’s microscope and digital weighing machine The apparatus used for tool wear measurement is shown in ‘figure 6’.

![Tool maker’s microscope](image)

**Figure 6.** Tool maker’s microscope.
4. Results and Discussion

4.1. Surface roughness test
The surface roughness values thus obtained as an average of two experimental trials for each combination of process parameters based on L9 orthogonal array in wet condition and dry condition is shown in table 6.

Table 6. \( R_a \) under dry and wet condition.

| Trial No. | Wet condition \( R_a \) (\( \mu \text{m} \)) | Dry condition \( R_a \) (\( \mu \text{m} \)) |
|-----------|-------------------------------------------|-------------------------------------------|
| 1         | 0.44                                      | 0.84                                      |
| 2         | 0.52                                      | 0.92                                      |
| 3         | 0.59                                      | 0.98                                      |
| 4         | 0.39                                      | 0.79                                      |
| 5         | 0.45                                      | 0.85                                      |
| 6         | 0.50                                      | 0.90                                      |
| 7         | 0.37                                      | 0.77                                      |
| 8         | 0.40                                      | 0.80                                      |
| 9         | 0.51                                      | 0.91                                      |
| Average   | 0.46                                      | 0.86                                      |

The ‘figure 7’, depicts the comparison of surface roughness values during hard turning under wet condition and dry condition. Heat is carried away from tool and work by means of cutting fluid which at same time reduce friction between tool and chip and between tool and work and also facilitates chip formation. So, surface roughness (\( R_a \)) is minimum in wet machining when compared to dry machining.

![Figure 7. Comparison of \( R_a \) values.](image)

4.2. Influence of process parameters on \( R_a \) – wet condition
From the table 7, it can be inferred that the response variable \( R_a \) is influenced more by feed rate followed by cutting speed and depth of cut respectively under wet condition.
Table 7. Response table for S/N ratio of $R_a$ – wet condition.

| Level | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|-------|-----------------------|-------------------|------------------|
|       | A                     | B                 | C                |
| 1     | 5.798                 | 7.982             | 7.037            |
| 2     | 7.045                 | 6.858             | 6.569            |
| 3     | 7.481                 | 5.484             | 6.718            |
| Delta | 1.683                 | 2.498             | 0.468            |
| Rank  | 2                     | 1                 | 3                |

Table 8. ANOVA for S/N ratio of $R_a$ – wet condition.

| Source               | DF | SS          | MS           | F      | P       | Contribution(%) | Remarks     |
|----------------------|----|-------------|--------------|--------|---------|----------------|-------------|
| Cutting speed (m/min)| 2  | 4.5785      | 2.28923      | 42.34  | 0.023   | 31.75          | Significant |
| Feed rate (mm/rev)  | 2  | 9.390       | 4.69501      | 86.84  | 0.011   | 65.121         | Most Significant |
| Depth of cut (mm)   | 2  | 0.3425      | 0.1712       | 3.17   | 0.240   | 2.37           | Insignificant |
| Error               | 2  | 0.1081      | 0.05406      | -      | -       | -              |             |
| Total               | 8  | 14.4191     | -            | -      | -       | -              |             |

4.3. Optimum combination of process parameters for $R_a$ – wet condition

It can be inferred from ‘figure 8’, that cutting speed at high level (350m/min), feed rate at low level (0.04mm/rev) and depth of cut at low level (0.2mm) provides optimum combination i.e. A3B1C1 for achieving the surface roughness value under wet condition.

![Main Effects Plot for SN ratios](image)

Figure 8. Main effects plot for S/N ratio of $R_a$ - wet condition.
4.4. Influence of process parameters on $R_a$ – dry condition

From the table 9, it can be inferred that the response variable $R_a$ is influenced more by feed rate followed by cutting speed and depth of cut respectively under dry condition.

| Level | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|-------|-----------------------|-------------------|------------------|
|       | A                     | B                 | C                |
| 1     | 0.8047                | 1.9440            | 1.4559           |
| 2     | 1.4581                | 1.3580            | 1.1970           |
| 3     | 1.6759                | 0.6366            | 1.2858           |
| Delta | 0.8711                | 1.3074            | 0.2590           |
| Rank  | 2                     | 1                 | 3                |

Table 10, shows ANOVA results for S/N ratio of $R_a$ under dry condition. It can be seen that contribution of feed rate is 65.31%, cutting speed is 31.30% and depth of cut is 2.63% in influencing the surface roughness under dry condition.

| Source                  | DF | SS   | MS  | F   | P    | Contribution (%) | Remarks       |
|-------------------------|----|------|-----|-----|------|------------------|---------------|
| Cutting speed (m/min)   | 2  | 1.2332 | 0.61660 | 42.15 | 0.023 | 31.30           | Significant   |
| Feed rate (mm/rev)      | 2  | 2.5731 | 1.2865  | 87.96 | 0.011 | 65.31           | Most significant |
| Depth of cut (mm)       | 2  | 0.10390 | 0.05195 | 3.55 | 0.220 | 2.63            | Insignificant |
| Error                   | 2  | 0.02926 | 0.01463 | -    | -     | -               |               |
| Total                   | 8  | 3.93954 | -     | -   | -    | -               |               |

4.5. Optimum combination of process parameters for $R_a$ – dry condition

It can be inferred from ‘figure 9’, that cutting speed at high level (350m/min), feed rate at low level (0.04mm/rev) and depth of cut at low level (0.2mm) provides optimum combination i.e. A3B1C1 for achieving the surface roughness value under dry condition.

![Main Effects Plot for SN ratios](image-url)

**Figure 9.** Main effects plot for S/N ratio of $R_a$ – dry condition.
4.6. Tool wear test

Table 11, shows the results of tool wear of inserts under dry and wet condition for various combinations of cutting conditions (cutting speed, feed rate and depth of cut) as per the design matrix.

| Trial No. | Wet condition Tool wear (mg) | Dry condition Tool wear (mg) |
|-----------|------------------------------|------------------------------|
| 1         | 0.44                         | 1.0                          |
| 2         | 0.55                         | 1.2                          |
| 3         | 0.64                         | 1.5                          |
| 4         | 0.56                         | 1.4                          |
| 5         | 0.5                          | 1.7                          |
| 6         | 0.47                         | 1.2                          |
| 7         | 0.71                         | 1.8                          |
| 8         | 0.59                         | 1.3                          |
| 9         | 0.68                         | 1.6                          |
| Average   | 0.58                         | 1.41                         |

The ‘figure 10’, depicts the comparison of tool wear during hard turning under wet condition and dry condition.

![Comparison of tool wear](image)

**Figure 10.** Comparison of tool wear.

4.7. Influence of process parameters on tool wear – wet condition

From the table 12, it can be inferred that the response variable tool wear is influenced more by depth of cut followed by cutting speed and feed rate respectively under wet condition.
Table 12. Response table for S/N ratio of tool wear – wet condition.

| Level | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|-------|-----------------------|--------------------|------------------|
|       | A                     | B                  | C                |
| 1     | 5.40                  | 5.04               | 6.09             |
| 2     | 5.11                  | 4.50               | 4.53             |
| 3     | 3.63                  | 4.59               | 3.53             |
| Delta | 1.76                  | 0.54               | 2.56             |
| Rank  | 2                     | 3                  | 1                |

Table 13. ANOVA for S/N ratio of tool wear – wet condition.

| Source                     | DF | SS   | MS   | F    | P     | Contribution (%) | Remarks          |
|----------------------------|----|------|------|------|-------|------------------|------------------|
| Cutting speed (m/min)      | 2  | 5.374| 2.6871| 21.08| 0.045 | 33.32            | Significant      |
| Feed rate (mm/rev)        | 2  | 0.5060| 0.2530| 1.98 | 0.335 | 3.13             | Insignificant    |
| Depth of cut (mm)         | 2  | 9.9897| 4.9949| 39.18| 0.025 | 61.95            | Most significant |
| Error                     | 2  | 0.2549| 0.1275| -     | -     | -                |                  |
| Total                     | 8  | 16.1249| 4.9949| 39.18| 0.025 | -                |                  |

4.8. Optimum combination of process parameters for tool wear – wet condition

It can be inferred from ‘figure 11’, that cutting speed at low level (150m/min), feed rate at low level (0.04mm/rev) and depth of cut at low level (0.2mm) provides optimum combination i.e. A1B1C1 for minimizing the tool wear under wet condition.

Figure 11. Main effects plot for S/N ratio of tool wear – wet condition.
4.9. **Influence of process parameters on tool wear – dry condition**

From the table 14, it can be inferred that the response variable tool wear is influenced more by depth of cut followed by cutting speed and feed rate respectively under dry condition.

**Table 14.** Response table for S/N ratio of tool wear – dry condition.

| Level | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|-------|-----------------------|--------------------|-------------------|
| A     | -1.702                | -2.676             | -1.287            |
| B     | -3.038                | -2.824             | -2.863            |
| C     | -3.822                | -3.063             | -4.412            |
| Delta | 2.12                  | 0.39               | 3.12              |

Table 15, shows ANOVA results for S/N ratio of tool wear under dry condition. It can be seen that contribution of depth of cut is 67.14%, cutting speed is 31.61% and feed rate is 0.010% in influencing the tool wear under dry condition.

**Table 15.** ANOVA for S/N ratio of tool wear – dry condition.

| Source         | DF | SS       | MS       | F     | P      | Contribution (%) | Remarks           |
|----------------|----|----------|----------|-------|--------|------------------|-------------------|
| Cutting speed  | 2  | 6.8970   | 3.44852  | 163.65| 0.006  | 31.61           | Significant       |
| Feed rate (mm/rev) | 2  | 0.2283   | 0.11417  | 5.42  | 0.156  | 0.010            | Insignificant     |
| Depth of cut (mm) | 2  | 14.6449  | 7.32245  | 347.41| 0.003  | 67.14            | Most Significant  |
| Error          | 2  | 0.0421   | 0.02107  | -     | -      | -                | -                 |
| Total          | 8  | 21.8124  | -        | -     | -      | -                | -                 |

4.10. **Optimum combination of process parameters for tool wear – dry condition**

It can be inferred from ‘figure 12’, that cutting speed at low level (150m/min), feed rate at low level (0.04mm/rev) and depth of cut at low level (0.2mm) provides optimum combination i.e. A1B1C1 for minimizing the tool wear under dry condition.

**Figure 12.** Main effects plot for S/N ratio of tool wear – dry condition.
4.11. Estimating the mean
Once an experiment is conducted and the optimum treatment condition within the experiment is
determined, the most direct way to estimate the mean for that treatment condition is to average all the
results for the trials which are set at those particular levels.

4.11.1. Estimating the mean for $R_a$ - wet condition. The estimated mean for surface roughness ($R_a$) is
obtained using the equation (3).

$$\mu = T + (A_3 - T) + (B_1 - T) + (C_1 - T) \cdots \cdots \cdots (3)$$

where, $T$ is the overall grand mean of the experimental results and has the value of 0.463 microns.
Table 16, shows the means of surface roughness ($R_a$) under wet condition. The mean for a selected
trial condition for parameters at $(A_3; B_1; C_1)$ is 0.348 microns.

| Level | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|-------|-----------------------|--------------------|-------------------|
| 1     | 0.5167                | 0.4000             | 0.4467            |
| 2     | 0.4467                | 0.4567             | 0.4733            |
| 3     | 0.4267                | 0.5333             | 0.4700            |
| Delta | 0.0900                | 0.1333             | 0.0267            |
| Rank  | 2                     | 1                  | 3                 |

Table 17, shows ANOVA results for means of surface roughness ($R_a$) under wet condition.

| Source               | DF | SS      | MS       | F       | P |
|----------------------|----|---------|----------|---------|---|
| Cutting speed (m/min)| 2  | 0.013400| 0.006700 | 201.00  | 0.005 |
| Feed rate (mm/rev)   | 2  | 0.026867| 0.013433 | 403.00  | 0.002 |
| Depth of cut (mm)    | 2  | 0.001267| 0.000633 | 19.00   | 0.050 |
| Error                | 2  | 0.000067| 0.000033 | -       | -   |
| Total                | 8  | 0.041600| -        | -       | -   |

4.11.2. Estimating the mean for $R_a$ - dry condition. The estimated mean for surface roughness ($R_a$) is
obtained using the equation (4).

$$\mu = T + (A_3 - T) + (B_1 - T) + (C_1 - T) \cdots \cdots \cdots (4)$$

where, $T$ is the overall grand mean of the experimental results and has the value of 0.862 microns.
Table 18, shows the means of surface roughness ($R_a$) under dry condition. The mean for a selected
trial condition for parameters at $(A_3; B_1; C_1)$ is 0.75 microns.
Table 18. Response table for means of $R_a$ – dry condition.

| Level | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|-------|-----------------------|--------------------|------------------|
|       | A                     | B                  | C                |
| 1     | 0.9133                | 0.8000             | 0.8467           |
| 2     | 0.8467                | 0.8567             | 0.8733           |
| 3     | 0.8267                | 0.9300             | 0.8667           |
| Delta | 0.0867                | 0.1300             | 0.0267           |
| Rank  | 2                     | 1                  | 3                |

Table 19, shows ANOVA results for means of surface roughness ($R_a$) under dry condition.

**Table 19. ANOVA for means of $R_a$ – dry condition.**

| Source                  | DF | SS       | MS       | F     | P     |
|-------------------------|----|----------|----------|-------|-------|
| Cutting speed (m/min)   | 2  | 0.012356 | 0.006178 | 79.43 | 0.012 |
| Feed rate (mm/rev)      | 2  | 0.025489 | 0.012744 | 163.86| 0.006 |
| Depth of cut (mm)       | 2  | 0.001156 | 0.000578 | 7.43  | 0.119 |
| Error                   | 2  | 0.000156 | 0.000078 | -     | -     |
| Total                   | 8  | 0.039156 | -        | -     | -     |

4.11.3. Estimating the mean for tool wear - wet condition. The estimated mean for tool wear is obtained using the equation (5).

$$\mu = T + (A_1 - T) + (B_1 - T) + (C_1 - T)$$

where, T is the overall grand mean of the experimental results and has the value of 0.58 milligram. Table 20, shows the means of tool wear under wet condition. The mean for a selected trial condition for parameters at $(A_1B_1C_1)$ is 0.45 milligram.

**Table 20. Response table for means of tool wear – wet condition.**

| Level | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|-------|-----------------------|--------------------|------------------|
|       | A                     | B                  | C                |
| 1     | 0.543                 | 0.570              | 0.500            |
| 2     | 0.560                 | 0.597              | 0.597            |
| 3     | 0.660                 | 0.597              | 0.667            |
| Delta | 0.117                 | 0.27               | 0.167            |
| Rank  | 2                     | 3                  | 1                |
Table 21, shows ANOVA results for means of tool wear under wet condition.

**Table 21. ANOVA for means of tool wear – wet condition.**

| Source                  | DF | SS    | MS    | F     | P      |
|-------------------------|----|-------|-------|-------|--------|
| Cutting speed (m/min)   | 2  | 0.0238| 0.0119| 38.39 | 0.025  |
| Feed rate (mm/rev)     | 2  | 0.0014| 0.0007| 2.29  | 0.304  |
| Depth of cut (mm)      | 2  | 0.0420| 0.0210| 67.54 | 0.015  |
| Error                  | 2  | 0.0006| 0.00031| -    | -      |
| Total                  | 8  | 0.0679| -     | -     | -      |

4.11.4. *Estimating the mean for tool wear - dry condition.* The estimated mean for tool wear is obtained using the equation (6).

$$\mu = T + (A_1 - T) + (B_1 - T) + (C_1 - T)$$

where, T is the overall grand mean of the experimental results and has the value of 1.4 milligram.

Table 22, shows the means of tool wear under dry condition. The mean for a selected trial condition for parameters at (A1:B1:C1) is 1 milligram.

**Table 22. Response table for means of tool wear – dry condition.**

| Level | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|-------|-----------------------|--------------------|-------------------|
|       | A                     | B                  | C                 |
| 1     | 1.23                  | 1.40               | 1.16              |
| 2     | 1.43                  | 1.40               | 1.40              |
| 3     | 1.56                  | 1.43               | 1.66              |
| Delta | 0.033                 | 0.03               | 0.5               |
| Rank  | 2                     | 3                  | 1                 |

Table 23, shows ANOVA results for means of tool wear under dry condition.

**Table 23. ANOVA for means of tool wear – dry condition.**

| Source                  | DF | SS    | MS    | F     | P      |
|-------------------------|----|-------|-------|-------|--------|
| Cutting speed (m/min)   | 2  | 0.1688| 0.0844| 76.0  | 0.013  |
| Feed rate (mm/rev)     | 2  | 0.0022| 0.0011| 1.0   | 0.5    |
| Depth of cut (mm)      | 2  | 0.3755| 0.1877| 169.0 | 0.006  |
| Error                  | 2  | 0.0022| 0.0011| -     | -      |
| Total                  | 8  | 0.5488| -     | -     | -      |
4.12. Confidence interval around the mean

The estimate of the mean obtained is only a point estimate based on average results of the experiment. This means there is a 50% chance of actual mean being greater than estimated mean and another 50% chance that the actual mean is less than the estimated mean. Thus a confidence interval is to be established within which actual mean lies at some stated level of confidence. There are three different types of confidence intervals proposed by Taguchi depending on purpose of the estimate. For the present work, the formula for calculating the confidence interval (CI) around the estimated mean in the confirmation experiment is given in equation (7).

\[ CI = [F (\alpha, 1, v_e) V_e [1/ \eta_{eff} + 1/r]]^{1/2} \]  

where, \( F (\alpha, 1, v_e) \) is the value of ‘F’ from F – tables for confidence level of \((1-\alpha)\), \( \alpha \) is the level of risk, \( V_e \) is the error variance, \( v_e \) is the degrees of freedom for the error, \( \eta_{eff} \) is the effective number of replications and \( r \) is the number of trials.

4.12.1. Confidence interval around the mean for \( R_a \) – wet condition. The confidence interval (CI) is calculated as follows. \( \eta_{eff} \) is calculated using equation (8).

\[ \eta_{eff} = \frac{N}{1 + U \text{ items in the estimate}} \]  

\( N = \) Total number of experiments conducted = 18
\( U \) items in the estimate = 4

Substituting in the above formula, \( \eta_{eff} = 3.6 \)
\( \alpha = 1 – \) confidence limits (95%) = 0.05.
\( F_{ratio} (0.05, 1, 2) = 18.51 \) (from F tables)
\( CI = +/-[18.51 \times 0.000033[1/3.6 + 1/5]]^{1/2} \)
\( CI = +/- 0.017 \)

The 95% confidence level of the predicted optimum of the surface roughness (\( R_a \)) under wet condition is given by:
\( [\mu - CI] < \mu < [\mu - CI] \), 0.331 < 0.348 < 0.365

4.12.2. Confidence interval around the mean for \( R_a \) – dry condition. The confidence interval (CI) is calculated as follows. \( \eta_{eff} \) is calculated using equation (8).

\( N = \) Total number of experiments conducted = 18
\( U \) items in the estimate = 4

Substituting in the equation (8), \( \eta_{eff} = 3.6 \)
\( \alpha = 1 – \) confidence limits (95%) = 0.05.
\( F_{ratio} (0.05, 1, 2) = 18.51 \) (from F tables)
\( CI = +/-[18.51 \times 0.000078[1/3.6 + 1/5]]^{1/2} \)
\( CI = +/- 0.026 \)

The 95% confidence level of the predicted optimum of the surface roughness (\( R_a \)) under dry condition is given by:
\( [\mu - CI] < \mu < [\mu - CI] \), 0.724 < 0.75 < 0.776

4.12.3. Confidence interval around the mean for tool wear – wet condition. The confidence interval (CI) is calculated as follows. \( \eta_{eff} \) is calculated using equation (8).

\( N = \) Total number of experiments conducted = 18
\( U \) items in the estimate = 4

Substituting in the equation (8), \( \eta_{eff} = 3.6 \)
\( \alpha = 1 – \) confidence limits (95%) = 0.05.
\( F_{ratio} (0.05, 1, 2) = 18.51 \) (from F tables)
\( CI = +/-[18.51 \times 0.000311[1/3.6 + 1/5]]^{1/2} \)
CI = +/- 0.052
The 95% confidence level of the predicted optimum of the tool wear under wet condition is given by:
\[ [\mu - CI] < \mu < [\mu + CI], 0.398 < 0.45 < 0.502 \]

4.12.4. Confidence interval around the mean for tool wear – dry condition. The confidence interval (CI) is calculated as follows. \( \eta_{\text{eff}} \) is calculated using equation (8).

\[ \alpha = 1 - \text{confidence limits (95%)} = 0.05. \]
\[ F_{\text{ratio}} (0.05, 1, 2) = 18.51 \text{ (from F tables)} \]
\[ CI = +/- [18.51 \times 0.00111111\{1/3.6 + 1/5\}]^{1/2} \]
\[ CI = +/- 0.099 \]

The 95% confidence level of the predicted optimum of the tool wear under dry condition is given by:
\[ [\mu - CI] < \mu < [\mu + CI], 0.901 < 1.0 < 1.099 \]

4.13. Confirmation experiments
A successful confirmation experiment is defined as one where the average of the samples falls within the predicted confidence interval of the true mean. When the average of the results from the confirmation experiment falls within the confidence interval, it providence evidence that the significant factors as well as their levels are properly chosen. If the average of the results of the confirmation experiment does not fall within the confidence interval, then there has been some form of misinterpretation of the significant factors. Also, the repeatability and reproducibility of the measurement system should be verified.

Five confirmation experiments have been conducted at the optimum settings of the process parameters obtained from the experiment. The results of the confirmation run are given in table 24. The average of the response variables such as surface roughness (\( R_a \)) and tool wear are found to be within the confidence interval around the mean. Therefore, the selected factors and their levels are properly chosen and are significant.

Table 24. Results of the confirmation test.

| Trial No. | Wet condition \( R_a \) (\( \mu m \)) | Dry condition \( R_a \) (\( \mu m \)) | Wet condition Tool wear (mg) | Dry condition Tool wear (mg) |
|-----------|----------------------------------|----------------------------------|-----------------------------|-----------------------------|
| 1         | 0.352                            | 0.742                            | 0.48                        | 1.04                        |
| 2         | 0.334                            | 0.764                            | 0.40                        | 0.98                        |
| 3         | 0.342                            | 0.727                            | 0.5                         | 1.07                        |
| 4         | 0.361                            | 0.770                            | 0.44                        | 0.97                        |
| 5         | 0.337                            | 0.754                            | 0.41                        | 1.02                        |
| Average   | 0.345                            | 0.751                            | 0.44                        | 1.01                        |
4.14. Microscopic images of tool wear

From the above microscopic images ‘figure 13 – figure 16’, it is observed that the tool wear during hard turning under dry condition is comparatively higher to tool wear under wet condition.

Figure 13. Before machining – wet.

Figure 14. After machining – wet.

Figure 15. Before machining – dry.

Figure 16. After machining – dry.
4.15. **Study on chips**

‘Figure 17’ and ‘figure 18’, shows comparison of chip forms during hard turning of AISI 4340 steel under dry and wet condition respectively. It is observed that tightly coiled chips are formed during wet turning that could be handled easily whereas as long snarled chips are prevalent during dry turning.

![Figure 17. Snarled chips - dry.](image1)

![Figure 18. Coiled chips – wet.](image2)

5. **Conclusion**

Analysis of surface roughness, tool wear and chip forms in hard turning of AISI 4340 steel using insert CNMG 120408 - DM under wet and dry conditions are presented. Within the range of the parameters under investigation following conclusions can be drawn.

- Surface roughness of AISI 4340 steel during hard turning under dry condition is found to be 46.51% higher to surface roughness generated during wet machining.
- Feed rate is found to be most significant parameter influencing surface roughness with 65.121% contribution under wet condition and 65.31% contribution under dry condition.
- Tool wear of insert during hard turning under dry condition is found to be 58.37% higher to tool wear under wet condition.
- Depth of cut is found to be most significant parameter influencing tool wear with 61.95% contribution under wet condition and 67.14% contribution under dry condition.
- Optimal parameters combination for better surface finish under wet and dry conditions are determined as A3B1C1 i.e. cutting speed at 350 m/min, feed rate at 0.04 mm/rev and depth of cut at 0.2mm.
- Optimal cutting parameters for minimizing tool wear under wet and dry machining are found to be A1B1C1 i.e. cutting speed at 150 m/min, feed rate at 0.04 mm/rev and depth of cut at 0.2 mm.
- Basic study on comparison of chips under wet and dry conditions are carried out. It is clear that snarled chips formed during dry condition may damage the tool or workpiece.

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