Multi Objective Optimization on Machinability Aspects of Dry Hard Turning of EN31 Alloy Steel using Coated Inserts

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Abstract

Objective: In this work, the design parameters that significantly affect the machinability of EN31 alloy steel using coated carbides were analysed and optimized using multi response methodology. Methods/Statistical Analysis: The EN31 steel is machined in the dry cutting environment using the coated carbide insert and their evaluation is studied. The experiments were conducted with three significant parameters namely cutting speed, feed rate and depth of cut. These parameters are optimized using Taguchi based grey relational analysis and their effects of parameters on surface roughness, interface temperature and flank wear were examined. Findings: The result reveals that all three input variables have influence over surface roughness, interface temperature and flank wear. ANOVA indicates that the output response is greatly influenced by cutting speed followed by feed and depth of cut. The results at optimum condition were predicted and it is found to be closer to the experimental results. From the analysis, it has been found that the coated carbide exceeds the performance compared to the uncoated carbides. Application/Improvements: The optimum parameters obtained from this experiment are effective in improving the machinability of EN31 alloy steel in the industry that minimizes cost and time.

Keywords: Alloy Steel, ANOVA, Grey Relational Analysis, Hard Turning, Machinability

1. Introduction

In recent days, various manufacturing industries works in the machining of hardened steel toward the improvement of product quality. To obtain desired outputs the manufacturers are focusing continuously to obtain the finished products with good quality reduced cost and less time by optimizing the machining parameters.

The conventional grinding operations have been replaced by an evolving technology called hard turning that should be implemented to achieve the good surface finish. Hard turning is the machining of the hardened materials in which the hardness lies between 45 and 65 HRC\cite{5}. In\cite{6} investigated the machinability of hardened steel during both hard and soft turning using ceramic tools mixed with TiC and alumina. He observed the cutting force and the interfacial temperature to be high and surface roughness to be low for harder work piece. Further the surface roughness gets influenced by the feed rate whereas the interface temperature is influenced with cutting speed and depth of cut. The depth of cut followed by the feed value affects the tangential and feed cutting forces. In\cite{7} conducted an experiment in multi-layer coating on cemented carbide using the chemical vapour deposition and observed abrasive wear mechanism in all conditions for AISI 4340. The surface roughness is minimized with the low feed rate and high cutting speed. In\cite{6} concluded from his experiment that both chipping and

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The objective of our research is based on analysing the machining parameters while hard turning of EN31 steel with multilayer coated carbide in the dry cutting environment. The hard turning operations were carried out as per the design of experiments using Taguchi’s L9 orthogonal array. Analysis of variance is also conducted to identify the influencing input parameters for the output response. The interactions between these parameters were fitted with the regression model. Also, the various output responses were optimized using multi-response methodology like Grey Relational Analysis.

2. Experimental Details

2.1 Workpiece Material

EN-31 equivalent to AISI 52100 (high strength) steel test samples of dimensions $63 \times 2000$ mm is used for the experiment. EN-31 steel has a greater hardness for which it is quite difficult to machine it. This material has wider applicability in the industry because of its greater wear resistance and hardness.
Figure 1 shows the EN31 alloy steel used for the experiment and Table 1 shows the chemical composition of EN31 alloy steel.

![Figure 1. Workpiece](image1)

**2.2 Cutting Tools**

In the present work, the carbide used is Tungsten, Cobalt based, designated by TNMG 120408. The insert is triangular in shape with the chip breaker geometry that is mounted on the tool holder. The tool holder has the clearance angle of 0°, entering angle of 75°, back and side rake angle of -6°, point angle of 90° and nose radius of 0.8 mm.

The ceramic particles with metallic binders of TiN/TiCN/TiN were used as coating material for carbide insert by Physical Vapour Deposition technique as shown in Figure 2. The inner and the outer most layers is given with the Titanium nitride coatings and the intermediate layer with the Titanium carbonitride.

![Figure 2. Thermal evaporation setup and coated insert.](image2)

**2.3 Machine Tool and Measuring Instruments**

Figure 3 shows the turning operation of EN31 steel. The surface roughness tester is used to measure the roughness of the surface and the infrared thermometer measures the interface temperature. By analysing the SEM image the insert flank wear is found.

**2.4 Experimental Layout**

During hard turning the three input parameters such as cutting speed, feed rate and depth of cut were varied and the output response like surface roughness, interfacial temperature and flank wear were analyzed. The experiments were planned as per the design of experiments using Taguchi’s L9 orthogonal array. The input factors and levels for the experiment is tabulated in Table 2.

| Element | Si    | C      | S    | Mn    | P      | Ni   | Cr    | Mo    |
|---------|-------|--------|------|-------|--------|------|-------|-------|
| Chemical composition | 0.25% | 1.08%  | 0.015% | 0.53% | 0.022% | 0.33% | 1.46% | 0.06% |

![Table 1. Chemical composition of EN31 alloy steel](table1)
Table 2. Input factors and levels

| Factors | Process parameters | Level 1 | Level 2 | Level 3 |
|---------|-------------------|---------|---------|---------|
| A       | Cutting Speed (m/min) | 100     | 150     | 200     |
| B       | Feed (mm/rev) | 0.1     | 0.2     | 0.3     |
| C       | Depth of Cut (mm) | 0.1     | 0.5     | 1.0     |

Table 3. Experimental results for coated carbide

| Experimental run | Cutting Speed (m/min) | Feed (mm/rev) | Depth of Cut (mm) | Surface Roughness (µm) | Interface Temperature (°C) | Flank Wear (mm) |
|------------------|-----------------------|--------------|-------------------|------------------------|---------------------------|-----------------|
| 1                | 100                   | 0.1          | 0.1               | 0.56                   | 152                       | 0.21            |
| 2                | 100                   | 0.2          | 0.5               | 0.79                   | 155                       | 0.32            |
| 3                | 100                   | 0.3          | 1.0               | 0.81                   | 163                       | 0.25            |
| 4                | 150                   | 0.1          | 0.5               | 0.42                   | 170                       | 0.41            |
| 5                | 150                   | 0.2          | 1.0               | 0.53                   | 177                       | 0.39            |
| 6                | 150                   | 0.3          | 0.1               | 0.64                   | 165                       | 0.25            |
| 7                | 200                   | 0.1          | 1.0               | 0.36                   | 205                       | 0.49            |
| 8                | 200                   | 0.2          | 0.1               | 0.49                   | 191                       | 0.43            |
| 9                | 200                   | 0.3          | 0.5               | 0.68                   | 195                       | 0.36            |

Table 4. ANOVA of surface roughness for coated carbide

| Source                  | DF | SS        | MS        | F       | P      | Remarks     |
|-------------------------|----|-----------|-----------|---------|--------|-------------|
| Cutting speed           | 2  | 17.4204   | 8.7102    | 37.81   | 0.026  | Significant |
| Feed                    | 2  | 26.0751   | 13.0376   | 56.60   | 0.017  | Significant |
| Depth of cut            | 2  | 1.8633    | 0.9316    | 4.04    | 0.198  | Insignificant |
| Error                   | 2  | 0.4607    | 0.2304    |         |        |             |
| Total                   | 8  | 45.8196   |           |         |        |             |
| S = 0.479963            |    | R-sq = 98.99% | R-sq (adj) = 95.98% |        |        |             |

Table 5. ANOVA of interfacial temperature for coated carbide

| Source                  | DF | SS        | MS        | F       | P      | Remarks     |
|-------------------------|----|-----------|-----------|---------|--------|-------------|
| Cutting speed           | 2  | 6.06476   | 3.03238   | 4335.68 | 0.000  | Significant |
| Feed                    | 2  | 0.00183   | 0.00091   | 1.31    | 0.433  | Insignificant |
| Depth of cut            | 2  | 0.57968   | 0.28984   | 414.41  | 0.002  | Significant |
| Error                   | 2  | 0.00140   | 0.00070   |         |        |             |
| Total                   | 8  | 6.64766   |           |         |        |             |
| S = 0.0264462           |    | R-sq = 99.98% | R-sq (adj) = 99.92% |        |        |             |
Table 6. ANOVA of insert wear for coated carbide

| Source            | DF | SS      | MS     | F     | P     | Remarks     |
|-------------------|----|---------|--------|-------|-------|-------------|
| Cutting speed     | 2  | 28.787  | 14.393 | 13.39 | 0.070 | Insignificant |
| Feed              | 2  | 10.132  | 5.066  | 4.71  | 0.175 | Insignificant |
| Depth of cut      | 2  | 9.281   | 4.640  | 4.32  | 0.188 | Insignificant |
| Error             | 2  | 2.150   | 1.075  |       |       |              |
| Total             | 8  | 50.349  |        |       |       |              |
| $S =$             | 1  | 1.03688 |        |       |       |              |
| R-sq =            | 95.73% |       |       |       |       |              |
| R-sq (adj) =      | 82.92% |       |       |       |       |              |

Table 7. Normalized values of output responses and quality loss function

| Run | Normalized Values | Quality Loss Function |
|-----|-------------------|-----------------------|
|     | Ra    | T     | VbC   | Ra    | T     | VbC   |
| 1   | 0.555 | 1     | 1     | 0.444 | 0     | 0     |
| 2   | 0.044 | 0.943 | 0.607 | 0.955 | 0.057 | 0.393 |
| 3   | 0     | 0.792 | 0.857 | 1     | 0.207 | 0.143 |
| 4   | 0.867 | 0.660 | 0.286 | 0.133 | 0.340 | 0.714 |
| 5   | 0.622 | 0.528 | 0.357 | 0.378 |       |       |
| 6   | 0.378 | 0.755 | 0.857 | 0.622 | 0.245 | 0.143 |
| 7   | 1     | 0     | 0     | 0     | 1     | 1     |
| 8   | 0.711 | 0.264 | 0.214 | 0.289 | 0.735 | 0.786 |
| 9   | 0.289 | 0.189 | 0.464 | 0.711 | 0.811 | 0.536 |

Table 8. Individual grey relational coefficient and grey relational grade

| Run | Grey Relation Coefficient | Grey Relational Grade | Rank |
|-----|---------------------------|-----------------------|------|
|     | Ra    | T     | VbC   | Ra    | T     | VbC   |
| 1   | 0.529 | 1     | 1     | 0.843 | 1     |       |
| 2   | 0.343 | 0.898 | 0.56  | 0.601 | 4     |       |
| 3   | 0.333 | 0.707 | 0.778 | 0.606 | 3     |       |
| 4   | 0.789 | 0.595 | 0.412 | 0.599 | 5     |       |
| 5   | 0.570 | 0.514 | 0.437 | 0.507 | 7     |       |
| 6   | 0.445 | 0.671 | 0.778 | 0.631 | 2     |       |
| 7   | 1     | 0.333 | 0.333 | 0.555 | 6     |       |
| 8   | 0.634 | 0.404 | 0.389 | 0.476 | 8     |       |
| 9   | 0.413 | 0.381 | 0.483 | 0.426 | 9     |       |
3. Results and Discussion

The result for the coated carbide obtained from the experiment is shown in Table 3.

For every one of the nine test runs, the responses like surface roughness, interfacial temperature and flank wear of the insert are analyzed. For each test three input parameters namely cutting speed, feed and depth of cut were considered.

These outcomes are evaluated with the Analysis of Variance (ANOVA), multiple regression analysis and grey relational analysis. The ANOVA determines the dominant input variable that has great impact on output responses. The correlation between the input and the output parameters were established by the multiple regression analysis. The optimal setting of the input parameters is determined by the Grey Relational Analysis.

3.1 Analysis of Variance

From ANOVA it can be found that which independent variable dominates the other variable. The ANOVA is carried out for a confidence level of 95% t. The measures are considered to be significant if the p values are less than 0.05. The ANOVA results of the surface roughness, interfacial temperature and flank wear for the coated carbide is shown in Tables 4, 5 and 6.

From Table 4 it is found that for surface roughness the feed is the dominant variable followed by cutting speed and depth of cut. The value of R-sq for surface roughness is found to be 98.99%.

For the interfacial temperature the cutting speed has a great impact followed by the depth of cut and the feed. The R-sq value for the interfacial temperature is found to be 99.98% and is shown in Table 5.

In case of insert wear the three factors are considered to be insignificant where the cutting speed is the most influencing parameter followed by the feed and the depth of cut. The R-sq value for the insert wear is found to be 95.73% and is shown in Table 6.

3.2 Mathematical Modelling

Surface Roughness = 0.639 - 0.002100 Cutting Speed + 1.317 Feed - 0.0016 D.O.C;
(R-Sq = 87.18%)

Interfacial Temperature = 108.24 + 0.4033 Cutting Speed - 6.7 Feed + 13.83 D.O.C;
(R-Sq = 97.04%)

Insert Wear = 0.1328 + 0.001667 Cutting Speed - 0.417 Feed + 0.0863 D.O.C;
(R-Sq = 85.42%)

The value of R-Sq is found to be 87.18% for surface roughness, 97.04% for interfacial temperature and 85.42%
for insert wear. The response predictions are better and a good relation is found between these variables.

**Figure 3.** Dry machining of EN31 steel.

**Figure 4.** S/N Ratio graph for each parameter at different levels.

**Figure 5.** GRG for minimum surface roughness, minimum interfacial temperature and minimum insert wear.

### 3.3 Multi-response Optimization with Grey Relational Grade

The Grey relational coefficients and Grey relational grades for the coated carbide have been represented in Tables 7 and 8. The ANOVA of GRG with coated carbide is tabulated in Table 9.

From the ANOVA table it has been concluded that cutting speed is the most dominant parameter on Grey Relational Grade followed by feed and depth of cut. Figure 4 represents the main effect plot for S/N ratios of GRG that shows the optimal settings of input parameters.

The optimal conditions according to Grey relational Taguchi approach has been found 100 m/min cutting speed, 0.1 mm/rev feed and 0.1 mm depth of cut. Figure 5 shows the Grey relational grades for minimum Surface Roughness, minimum Interface Temperature and minimum Insert Wear.

The confirmation tests were carried out for the optimal parameters with its levels and its characteristics were evaluated. Table 10 indicates the comparison between the experimental and the predicted values and a good agreement is found.

### 4. Conclusions

From this work the conclusions are summarized as follows:

- Coated carbides experience a lower surface roughness, lower interface temperature and lower flank wear.
- From the regression equation it is found that the R-Sq value is close to unity that indicates the good relation between the variables.
- Cutting speed is the most dominant parameter followed by feed rate and depth of cut.
- The optimal parametric combination is cutting speed = 100 m/min, feed = 0.1 mm/rev, depth of cut = 0.1 mm.
- The performance of coated carbides is improved with the help of multilayer coating. As a result the surface roughness, interface temperature and flank wear are less when coated carbides are used instead of uncoated carbides.

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Multi Objective Optimization on Machinability Aspects of Dry Hard Turning of EN31 Alloy Steel using Coated Inserts

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