Investigations on high speed machining of EN-353 steel alloy under different machining environments

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Abstract. The addition of Nano Particles into conventional cutting fluids enhances its cooling capabilities; in the present paper an attempt is made by adding nano sized particles into conventional cutting fluids. Taguchi Robust Design Methodology is employed in order to study the performance characteristics of different turning parameters i.e. cutting speed, feed rate, depth of cut and type of tool under different machining environments i.e. dry machining, machining with lubricant - SAE 40 and machining with mixture of nano sized particles of Boric acid and base fluid SAE 40. A series of turning operations were performed using L27 (3)13 orthogonal array, considering high cutting speeds and the other machining parameters to measure hardness. The results are compared among the different machining environments, and it is concluded that there is considerable improvement in the machining performance using lubricant SAE 40 and mixture of SAE 40 + boric acid compared with dry machining. The ANOVA suggests that the selected parameters and the interactions are significant and cutting speed has most significant effect on hardness.

1. Introduction
In machining, higher order friction develops between tool, work piece and chips which lead to high temperatures in the machining zone. In order to reduce high temperatures in the machining zone; cutting fluids are employed in machining. Cutting fluid improves the surface conditions of the work piece, tool life and the process [1, 4]. Nano-fluids refer to cutting fluids obtained by dispersing the certain amount of nano-particles (average sizes < 100 nm) in base fluids. When little amount of nano sized particles are consistently suspended and dispersed in base fluids, can give overstated upgrades in the thermal characteristics of base fluids [1]. Alloy steels - which contain mixture of steel and other chemical elements like Ni, Mn, Cr, W, Mo, V etc. The chemical elements are added to plain carbon steels for enhancement of one or more of their properties. Due to the presence of the above chemical elements, alloy steels are superior to plain carbon steels with respect to the strength, hardness, toughness, etc. In addition Alloy steels have fewer tendencies of wrapping and cracking during heat treatment, high hardenability and more uniform properties throughout the cross section. En 353 Alloy steel provides material properties that are acceptable for many automobile applications such as heavy duty gear, shaft, pinion, cam shafts, gudgeon pins etc [2, 11]. The objective of the present work is to find out the set of optimum conditions for the selected control parameters, in order to measure hardness under Different Machining environments. Taguchi Robust Design methodology is used to determine the optimum parameters for the selected control factors viz. Type of Machining Environment, cutting speed, feed rate, depth of cut and type of tool at three different levels where the experiments are carried out using L27 (313) orthogonal array.

2. Method and Material
The Literature survey helped in proper selection of method and material. Taguchi Methodology is used to determine the optimum conditions for the selected cutting parameters. Orthogonal Array, Signal to Noise Ratio and Analysis of Variance are employed to study the cutting performance characteristics for the selected process parameters under different machining conditions in order to measure hardness for the
Table 1. Selected Control Factors with Levels

| Factors/Levels | Type of machining conditions (A) | Cutting Speed (B) (rpm) | Feed Rate (C) (mm/rev) | Depth of Cut (D) (mm) | Type of Tool (E) |
|----------------|---------------------------------|------------------------|------------------------|----------------------|-----------------|
| 1              | DRY                             | 849                    | 0.05                   | 0.2                  | UNCOATED        |
| 2              | SAE 40                          | 1379                   | 1.25                   | 0.35                 | CVD             |
| 3              | BORIC ACID + SAE 40             | 1910                   | 0.2                    | 0.5                  | PVD             |

Table 2. Standard L_{27}(3^{13}) Orthogonal Array Considering Control Factors and Interactions

| Type of Coolent | Cutting Speed (Rpm) | Feed (mm/rev) | Depth of Cut (Mm) | Type of Tool |
|-----------------|---------------------|---------------|-------------------|--------------|
|                 | A B A*B A*B C A*C A*C D A*D A*D E A*D A*D E | | | |
| 1 DRY           | 1                   | 1             | 0.05              | 1            | 1              | Un-Coated       | 1 | 1 |
| 2 DRY           | 2                   | 1             | 0.125             | 2            | 2              | CVD             | 2 | 2 |
| 3 DRY           | 2                   | 1             | 0.2               | 3            | 3              | PVD             | 3 | 3 |
| 4 DRY           | 2                   | 2             | 0.05              | 1            | 1              | PVD             | 2 | 2 |
| 5 DRY           | 2                   | 2             | 0.125             | 2            | 2              | Un-Coated       | 1 | 1 |
| 6 DRY           | 2                   | 2             | 0.2               | 3            | 3              | CVD             | 2 | 2 |
| 7 DRY           | 3                   | 3             | 0.05              | 1            | 1              | CVD             | 3 | 3 |
| 8 DRY           | 3                   | 3             | 0.125             | 2            | 2              | PVD             | 3 | 3 |
| 9 DRY           | 3                   | 3             | 0.2               | 3            | 3              | Un-Coated       | 2 | 2 |
| 10 SAE-40       | 2                   | 3             | 0.05              | 2            | 3              | Un-Coated       | 2 | 2 |
| 11 SAE-40       | 2                   | 3             | 0.125             | 3            | 1              | CVD             | 3 | 3 |
| 12 SAE-40       | 2                   | 3             | 0.2               | 1            | 2              | PVD             | 1 | 2 |
| 13 SAE-40       | 2                   | 3             | 0.125             | 3            | 1              | PVD             | 1 | 2 |
| 14 SAE-40       | 2                   | 3             | 0.05              | 2            | 3              | Un-Coated       | 2 | 3 |
| 15 SAE-40       | 2                   | 3             | 0.125             | 3            | 1              | Un-Coated       | 2 | 3 |
| 16 SAE-40       | 1                   | 2             | 0.05              | 2            | 3              | CVD             | 3 | 1 |
| 17 SAE-40       | 1                   | 2             | 0.125             | 3            | 1              | PVD             | 1 | 2 |
| 18 SAE-40       | 1                   | 2             | 0.2               | 1            | 2              | CVD             | 3 | 3 |
| 19 BORIC + SAE-40 | 3           | 2             | 0.05              | 3            | 2              | Un-Coated       | 3 | 2 |
| 20 BORIC + SAE-40 | 3           | 2             | 0.125             | 1            | 3              | CVD             | 1 | 3 |
| 21 BORIC + SAE-40 | 3           | 2             | 0.2               | 2            | 1              | PVD             | 2 | 1 |
| 22 BORIC + SAE-40 | 3           | 2             | 0.125             | 1            | 3              | PVD             | 2 | 1 |
| 23 BORIC + SAE-40 | 3           | 2             | 0.2               | 2            | 1              | Un-Coated       | 3 | 2 |
| 24 BORIC + SAE-40 | 3           | 2             | 0.125             | 1            | 3              | CVD             | 1 | 3 |
| 25 BORIC + SAE-40 | 2           | 1             | 0.05              | 3            | 2              | CVD             | 2 | 1 |
| 26 BORIC + SAE-40 | 2           | 1             | 0.125             | 1            | 3              | PVD             | 2 | 1 |
| 27 BORIC + SAE-40 | 2           | 1             | 0.2               | 2            | 1              | Un-Coated       | 3 | 2 |
work material EN 353 alloy steel. The Selection of orthogonal array depends on the number of factors, levels of each factor, Interactions between them and the total degrees of freedom [3-8, 10]. Based on these factors, the required minimum number of experiments to be conducted are 27, the nearest orthogonal array fulfilling this condition is L\(_{27}(3^{13})\) and the factors assigned to L\(_{27}(3^{13})\) orthogonal array is shown in table 1. The standard orthogonal array considering the control factors and interactions are tabulated in table 2, with respect to which the corresponding experiments were carried out.

2.1 Experimentation

In the present work, the experiments are carried out using proper selection of orthogonal array considering the control parameters i.e. different machining environments, cutting speed, feed rate, depth of cut and type of tool at three different levels. Turning operations are carried out using CNC Lathe shown in figure 1. The cutting tools used for machining are CNMG carbide tools of Uncoated, PVD and CVD inserts shown in figure 3, 4 and 5.

The machining is carried out under different machining environments i.e.

- Dry condition as shown in figure 6,
- Machining with lubricant - SAE 40 and water at a ratio of 1:20 and the coolant flow is maintained at around 3 lit/min as shown in figure 7
- Machining with nano sized particles Boric acid mixed with base fluid SAE 40 + water at a ratio of 1:20, where the coolant flow is maintained at around 3 lit/min as shown in figure 8

A total of 27 experiments are performed as per the orthogonal array and the hardness is measured and the corresponding results are tabulated in table 3.
3. Results & Discussions

The experiment results observed from the Rockwell Hardness Tester and are tabulated in Table 3, the performance characteristic is the hardness which is to be improved and hence the S/N ratio associated with the response is “Larger-the-better”. The Minitab statistical tool is used to analyze the data.

3.1 Optimization and Effect of Process Parameters on output parameter

Taguchi’s methodology has been successfully implemented to identify the optimum process parameters for the selected cutting parameters in order to improve the hardness for the selected EN 353 Alloy Steel. The optimum process parameters found are tabulated in Table 4. The main effect plots for hardness are shown in Figure 13. The level of parameter with the highest S/N ratio is the optimal level. It is also observed that, machining with lubricant SAE 40 is found to be optimum compared to SAE 40 + Nano Fluids and Dry conditions and uncoated tool is found to be optimum compared to CVD and PVD coated tools. The mean response refers to the average value of the performance characteristic for each parameter at different levels. Thus, the optimal process parameters are A2, B2, C3, D2 and E1. The two factor interaction effects of selected parameters on S/N ratio are analyzed to determine the relative importance of the process parameters on hardness under different coolant/machining environments.

3.1.1 Effect of cutting speed and type of coolant on hardness

Figure 9 shows the interaction plots between cutting speed and type of coolant condition. Under dry condition, the effect of cutting speed on hardness from 849 to 1379 rpm is minimum and 1379 to 1910 rpm is maximum. Similarly under SAE 40 condition the effect of cutting speed hardness from 849 to 1379 rpm and 1379 to 1910 rpm is maximum and under SAE 40 with boric acid condition the effect of cutting speed on hardness from 849 to 1379 rpm is maximum and from 1379 to 1910 rpm is minimum. Hence, SAE 40 and SAE40+Boric Acid shows almost nearer improvement in hardness compared to dry machining.
Table 3. Hardness Results with corresponding S/N Ratios

| Experiment number | TRAIL 1 | TRAIL 2 | MEAN  | S/N Ratio |
|-------------------|---------|---------|-------|-----------|
| 1                 | 100     | 103     | 101.5 | 40.13     |
| 2                 | 107     | 109     | 108   | 40.67     |
| 3                 | 103     | 101     | 102   | 40.17     |
| 4                 | 109     | 110     | 109.5 | 40.79     |
| 5                 | 102     | 101     | 101.5 | 40.13     |
| 6                 | 101     | 104     | 102.5 | 40.21     |
| 7                 | 103     | 100     | 101.5 | 40.13     |
| 8                 | 113     | 110     | 111.5 | 40.95     |
| 9                 | 108     | 109     | 108.5 | 40.71     |
| 10                | 103     | 104     | 103.5 | 40.30     |
| 11                | 109     | 110     | 109.5 | 40.79     |
| 12                | 104     | 101     | 102.5 | 40.21     |
| 13                | 114     | 113     | 113.5 | 41.10     |
| 14                | 112     | 113     | 112.5 | 41.02     |
| 15                | 111     | 115     | 113   | 41.06     |
| 16                | 112     | 115     | 113.5 | 41.10     |
| 17                | 100.5   | 101     | 100.75| 40.06     |
| 18                | 115     | 116     | 115.5 | 41.25     |
| 19                | 104     | 102     | 103   | 40.26     |
| 20                | 102     | 103     | 102.5 | 40.21     |
| 21                | 103     | 105     | 104   | 40.34     |
| 22                | 110     | 112     | 111   | 40.91     |
| 23                | 111     | 113     | 112   | 40.98     |
| 24                | 115     | 113     | 114   | 41.14     |
| 25                | 112     | 110     | 111   | 40.91     |
| 26                | 104     | 103     | 103.5 | 40.30     |
| 27                | 114     | 116     | 115   | 41.21     |

Table 4. Optimum process parameters from Taguchi method

| Factors | Type of machining conditions (A) | Cutting Speed (B) (rpm) | Feed Rate (C) (mm/rev) | Depth of Cut (D) (mm) | Type of Tool (E) |
|---------|---------------------------------|-------------------------|------------------------|-----------------------|-----------------|
| Optimum value | SAE 40                      | 1379                    | 0.2                    | 0.35                  | Uncoated        |

3.1.2 Effect of Feed rate and type of coolant on hardness

Figure 10 shows the interaction plots between feed rate and type of coolant condition. Under dry and SAE 40 conditions, the effect of feed rate on hardness from 0.05 to 0.125mm/rev and 0.125 to 0.2 mm/rev
is maximum. Similarly under SAE 40 with boric acid conditions, the effect of feed rate on hardness from 0.05 to 0.125mm/rev and 0.125 to 0.2mm/rev is maximum is minimum. Under Dry and SAE 40 Condition the effect of feed rate from 0.05mm/rev to 0.2mm/rev is minimum. It indicates that, considerable interaction effect exists when the feed rate changes from one level to another level. Hence, SAE 40 shows improvement in hardness compared to dry and SAE 40 + Boric acid except feed rate at 0.2mm/rev where SAE40 + Boric acid show improvement in hardness.

3.1.3 Effect of Depth of Cut and type of coolant on hardness

Figure 11 shows the interaction plots between depth of cut and type of coolant condition. Under dry condition, the effect of depth of cut on hardness from 0.2 to 0.35 mm is minimum and 0.35 to 0.5 mm is maximum. Similarly under SAE 40 condition the effect of depth of cut on hardness from 0.2 to 0.35 mm is maximum and 0.35 to 0.5 mm is minimum and under SAE 40 with boric acid condition, the effect of depth of cut on hardness from 0.2 to 0.35 mm is maximum and 0.35 to 0.5 mm is minimum. Hence, SAE 40 shows improvement in hardness compared to dry and SAE 40 + boric acid except depth of cut at 0.2mm where SAE40+ boric acid shows improvement.
3.1.4 Effect of Depth of Cut and type of coolant on hardness

Figure 12 shows the interaction plots between type of tool material and coolant condition. Under dry condition, the effect of change of tool material on hardness from CVD to PVD is minimum and PVD to Uncoated is maximum. Similarly under SAE 40 condition, the effect and change of tool material on hardness from CVD to PVD and PVD to Uncoated is maximum, where the effect between CVD and uncoated is minimum and under SAE 40 with boric acid condition effect and change of tool material on hardness from CVD to PVD is minimum and PVD to Uncoated is maximum. Hence, SAE 40 shows improvement in hardness compared to dry and SAE 40 + Boric acid except PVD where SAE40 with boric acid shows improvement in Hardness.
It also indicates that, considerable mutual interaction effect exists when the process parameters changes from one level to another level with respect to the type of coolant/ machining environments. As the machining environment changes, S/N ratios increases from dry to SAE 40 with boric acid and SAE 40.

3.2 Influence of Process Parameters
Analysis of Variance (ANOVA) is performed to find out the influence and performance of each process parameter in machining. Table 5 and 6 shows the results of ANOVA on performance characteristic. The F-Ratio in Table No.5 indicates the significant condition of each factor and its interactions, where all the factors selected are significant and the corresponding interactions indicated are significant. To improve the hardness, the cutting speed has major percent contribution (23.02%) in optimizing the performance characteristics followed by type of coolant, depth of cut, feed rate and type of tool. It is also observed that ANOVA has resulted in 0.09% of error contribution. Further the interaction between type of coolant condition with cutting speed, feed rate, depth of cut and type of tool are significant. The S/N ratios of optimum conditions are used to develop predictive or additive model to predict the S/N ratio of the optimum condition using the below equation 1.

$$\eta_{predicted} = Y + (A2 - Y) + (B2 - Y) + (C3 - Y) + (D2 - Y) + (E1 - Y) \quad \text{---(1)}$$

$$\eta_{predicted} = 40.6314 + (40.77 - 40.6314) + (40.81 - 40.6314) + (40.7 - 40.6314) + (40.85 - 40.6314) + (40.67 - 40.6314) = 41.27439$$

Where Y is the average of S/N ratios. Conducting a verification experiment is essential and final step of the Taguchi Robust Design methodology. Hence the verification test is conducted with the optimum parameters as shown in Table 4 and the corresponding results are tabulated in Table 7. It is found that the S/N ratio of the verification test is within the limits of the predicted value at 95% confidence level when compared as shown in Table 8 and the objective is fulfilled. Therefore, the suggested optimum conditions can be adopted.
Table 5. Summary of Basic ANOVA

| SOURCE                      | S.S  | DOF | M.S.S | F.RATIO | RESULT |
|-----------------------------|------|-----|-------|---------|--------|
| Type Of Coolent             | 287.931 | 2   | 143.965 | 66.87   | Significant |
| Cutting Speed (rpm)         | 390.924 | 2   | 195.462 | 90.80   | Significant |
| Feed (mm/Rev)               | 52.181  | 2   | 26.090  | 12.12   | Significant |
| Depth Of Cut (mm)           | 141.946 | 2   | 70.973  | 32.97   | Significant |
| Type Of Tool                | 38.620  | 2   | 19.310  | 8.97    | Significant |
| Type Of Coolent*Cutting Speed (rpm) | 254.181 | 4   | 63.545  | 29.52   | Significant |
| Type Of Coolent*Feed (mm/rev) | 187.444 | 4   | 46.861  | 21.77   | Significant |
| Type Of Coolent*Depth Of Cut (mm) | 66.372  | 4   | 16.593  | 7.71    | Significant |
| Type Of Coolent*Type Of Tool | 201.685 | 4   | 50.421  | 23.42   | Significant |
| Error                       | 58.125  | 27  | 2.153   |         |        |
| Total                       | 1679.40 | 53  |         |         |        |

Table 6. Summary of ANOVA of Hardness

| SOURCE                      | S.S  | DOF | M.S.S | F. RATIO | $\eta^2$ | $\rho$ % |
|-----------------------------|------|-----|-------|----------|----------|----------|
| Type Of Coolent             | 287.931 | 2   | 143.965 | 66.87    | 283.6254 | 16.8841  |
| Cutting Speed (rpm)         | 390.924 | 2   | 195.462 | 90.80    | 386.6184 | 23.0211  |
| Feed (mm/Rev)               | 52.181  | 2   | 26.090  | 12.12    | 52.12389 | 3.103704 |
| Depth Of Cut (mm)           | 141.946 | 2   | 70.973  | 32.97    | 141.8889 | 8.448739 |
| Type Of Tool                | 38.620  | 2   | 19.310  | 8.97     | 38.56289 | 2.296218 |
| Type Of Coolent*Cutting Speed (rpm) | 254.181 | 4   | 63.545  | 29.52    | 245.5699 | 14.6224  |
| Type Of Coolent*Feed (mm/rev) | 187.444 | 4   | 46.861  | 21.77    | 187.3298 | 11.15451 |
| Type Of Coolent*Depth Of Cut (mm) | 66.372  | 4   | 16.593  | 7.71     | 66.25778 | 3.945303 |
| Type Of Coolent*Type Of Tool | 201.685 | 4   | 50.421  | 23.42    | 201.5708 | 12.00248 |
| Error                       | 58.125  | 27  | 2.153   |          | 1.513444 | 0.090118 |
| Total                       | 1679.40 | 53  |         |          | 1677.896 |          |

Table 7. Conformation test results

|          | Trail 1 | Trail 2 | Mean | S/N Ratio |
|----------|---------|---------|------|-----------|
|          | 116     | 117     | 116.5| 41.326    |

Table 8. Comparison of $\eta$ ratios

| Source     | Value   |
|------------|---------|
| $\eta_{predicted}$ | 41.274  |
| $\eta_{calculated}$ | 41.326  |
4. Conclusions
In the present work, an attempt has been made to evaluate the performance of lubricant SAE 40 and nano particle based lubricant, mixed with the base lubricant SAE 40 for turning of EN 353 steel alloy. Based on the results of the present experimental investigations, the following conclusions are drawn:
- It is found that the selected process parameters have considerable influence on hardness with respect to the machining environments/ type of coolants.
- Machining with lubricant SAE 40 is found to be better than dry and SAE40 with boric acid. But very small difference in the results is observed between SAE 40 and SAE 40 with boric acid.
- The optimal and best combination to improve hardness by using taguchi methodology obtained are lubricant SAE 40, cutting speed at 1379 rpm, feed rate at 0.2 mm/rev, depth of cut at 0.35 mm and UN coated tool.
- Using ANOVA, the individual factor effects are found to be significant factors and concluded that the effect of cutting speed is more followed by type of coolant, depth of cut, feed rate and type of tool for Hardness.
- The interaction between type of machining environment with cutting speed (rpm), feed rate (mm/rev), depth of cut (mm) and type of tool material are also found to be significant.
- The confirmation results are within the limits of the predicted value at 95% confidence level and the suggested optimum results can be adopted.

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