Performance investigations and comparisons of green machining between CNC-turning of EN24 & EN9 steels

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Abstract. In metal machining process, use of cutting fluids have several disadvantages such as increase in machining cost, poor operator health, environmental impacts etc.. Green machining is a metal machining process in which cutting fluids are not used. Therefore it is a cost effective and environment-friendly approach and it is being adopted fast by the metal-machining industries. This article focuses on the investigations and comparisons into the effects of green machining (dry machining) on the surface roughness in CNC-turning of EN24 and EN9 steels. This article also focuses on the investigation of optimum machining parameters for the surface-roughness and material removal rate (MRR) in CNC-turning of EN24 and EN9 steels using Taguchi method. For the experiments, L9 Taguchi orthogonal array design was selected, and all experiments were carried out under dry machining conditions. The statistical analysis methods such as S/N ratio of Taguchi method and ANOVA were employed to investigate the influence of machining parameters on the average surface-roughness (Ra) and MRR. All experimental data of Ra and MRR were used to develop second-order regression models. In last, machining performance comparison between EN24 and EN9 steels under dry/green cutting condition on the basis of surface-roughness obtained were carried out.

1. Introduction
A manufacturing engineer always want to produced high quality of product with less investment and want to get more profit for the organization. A large amount of cost is always associated with machining and its maintenance, power consumption, optimization of machining parameter and lubrication system. Cutting fluids act as both lubrication as well as coolant for the machining operation but the use of cutting fluids surrounds many issues such as maintenance of fluid system, worker health, fluid pretreatment, fluid disposal, safety concerns, environmental concerns etc.. Nowadays manufacturing industries are moving toward acquiring green manufacturing which leads to produce cost effective product under the healthy shop floor environment and ensure. In green manufacturing, the word “green” indicates the various aspects, such as environment friendly, hazard-free properties, quality, ecological, time saving and production costs. Green machining refers to describe the products that are machined using minimum resources, at lower costs and in a healthy environment. On considering the above cases, machining can be done either in dry condition (i.e. machining without cutting fluids) or with coolant as Minimum Quantity of Lubrication (MQL) to control the harmful
effect to the environment [1-4]. Dry machining (or green machining) is ecologically desirable and it is expected that in coming days all machining industries will be enforced to adopt dry machining for obeying laws of environmental protection, health regulations, and occupational safety [5]. Galanis et al. in 2008 observed that, in case of AISI 422 stainless steel turning, performance of dry machining was better than wet machining [6]. Applications of dry machining are broadly dependent on the selection of workpiece material, machining parameters and appropriate cutting tools. Performance of dry machining can be improved by developing the coating of the coated cutting tool. Coated cutting tools offers better performance in case of dry machining of alloyed steel, cast iron, aluminium having 10% Si etc. [7-8]. Several years ago, leading coating materials for cutting tool was aluminium oxide. Today titanium aluminium nitride (TiAlN), titanium carbon nitride (TiCN) and titanium nitride (TiN) based coating was developed to tolerate more severe cutting conditions. Canter in 2009 reported that, TiAlN coated cutting tool exhibits up to 900°C thermal stability [9]. Lin et al. in 2008 showed that AlCrN coated cutting tools are suitable to machine under dry conditions at high cutting speed [10].

![Figure 1. Experimental setup: (a) CNC-lathe machine-tool of model: LT-16 LM of ACE-designer (b) contact-type surface profiler of model SJ-210 of MITUTOYO.](image)

EN24-steel is most suitable material for manufacturing shaft, heavy-duty axel, gears, studs, bolts etc.. This material is also used in ship borne mechanical handling equipment, tensionless hydraulic bolt [11]. EN9 steel is a suitable material for heat-treated components where high impact and tensile strength are required. This material is broadly used in compound gear-box of the rolling mill, moulding dies, blanking tools etc. [12]. In present study depth of cut (mm), feed rate (mm/rev), and spindle speed (rpm) are chosen as cutting parameters in order to investigate their influence on Ra and MRR under dry (green) cutting condition in CNC-turning of EN8 and EN24 steel, and the relationship between these parameters are developed with Ra and MRR (machinability performances). The experiments were designed by using Taguchi technique, and ANOVA (Analysis of variance) is employed to determine the dominant cutting parameters on Ra and MRR. In last, machining performance comparison between EN24 steel and EN9 steel under dry/green cutting condition on the basis of surface roughness obtained were carried out.

2. Experimental

A CNC-lathe machine-tool of model LT-16 LM of ACE-designer as illustrated in Fig. 1(a) is used to perform the turning experiments. This machine-tool have (a) distance between centers 400mm, (b) swing over bed Ø500, (c) swing over cross slide Ø225mm, and (d) accuracy X-0.01mm. Coated cemented carbide cutting tool-insert is employed for the turning of both materials EN24 steel and EN9 steel, during the experiments. Experiments are conducted on cylindrical work-pieces of diameter 32mm and length 45mm clamped into the three jaw chuck of machine-tool as shown in Fig. 1(a). Both the materials are tested before the experiments on the material testing machine Ark/Spark Optical Emission Spectrometer. Obtained chemical composition of EN24 steel and EN9 steel are shown in Tables 1. Cutting parameters and their values used in the experiments for both the materials EN24 steel as well as EN9 steel are same as shown in Table 2. Taguchi orthogonal array (OA) with L9 was
selected for conducting the experiments. Nine experiments were performed with different combination of parameters (as shown in Table 3) by turning 20mm length on cylindrical work pieces for both types of materials. All the experiments are carried out in dry/green cutting conditions to make the experiments environment-friendly and cost effective. The average surface roughness (Ra) and material removal rate (MRR) are selected as response factors for the experimentation. For the measurement of surface roughness, a contact-type surface profiler of model SJ-210 of MITUTOYO as shown in Fig. 1(b) was used. The average surface roughness (Ra) for each individual turned surface was predicted by taking the average of surface-roughness values of five sampling length of each turned-surface. MRR is calculated as (weight before turning – weight after turning)/ time taken of turning.

Table 1. chemical composition of EN24 steel and EN9 steel

| Chemical composition | EN24 Steel |  | EN9 Steel |  |
|----------------------|------------|--------|-----------|--------|
|                     | % Obtained value | % Required range | % Obtained value | % Required range |
| Carbon               | 0.430   | 0.35 – 0.45 | 0.512   | 0.50 – 0.60 |
| Manganese            | 0.579   | 0.45 – 0.70 | 0.743   | 0.50 – 0.80 |
| Silicon              | 0.246   | 0.10 – 0.35 | 0.322   | 0.05 – 0.35 |
| Phosphorous          | 0.032   | 0.05 Max    | 0.057   | 0.06 Max   |
| Sulphur              | 0.032   | 0.05 Max    | 0.048   | 0.06 Max   |
| Chromium             | 1.082   | 0.90 – 1.40 | 0.110   |            |
| Nickel               | 1.381   | 1.3 – 1.8   | 0.074   |            |
| Molybdenum           | 0.215   | 0.20 – 0.35 | 0.019   |            |

Table 2. Cutting parameters with their values used in the experiment.

| Cutting Parameters | Code | Levels |
|--------------------|------|--------|
| Spindle speed, SS (rpm) | A | 1000 | 1500 | 2000 |
| Feed rate, FR (mm/rev) | B | 0.025  | 0.075  | 0.125  |
| Depth of Cut, DOC (mm) | C | 0.5  | 1.0  | 1.5  |

Table 3. Taguchi’s L9(3^4) OA-design & result of experiments and their S/N-ratio.

| Exp. parameters & levels A B C | Designation | MRR1 (g/sec) | Ra1 (µm) | S/N-ratio (ƞ) | MRR2 (g/sec) | Ra2 (µm) | S/N-ratio (ƞ) |
|-------------------------------|-------------|--------------|----------|---------------|--------------|----------|---------------|
|                             |             | η(MRR1) | η(Ra1) | η(MRR2) | η(Ra2) | η(MRR1) | η(Ra1) | η(MRR2) | η(Ra2) |
| 1 1 1 A1B1C1                 | 0.24 3.50 | -12.39 | -10.89 | 0.30 3.73 | -10.45 | -11.49 |
| 2 1 2 A1B2C2                 | 0.77 3.54 | -2.27  | -11.00 | 0.72 4.26 | -2.85  | -12.63 |
| 3 1 3 A1B3C3                 | 1.10 2.66 | 0.82  | -8.52  | 1.07 3.10 | -0.89  | -9.86 |
| 4 2 1 A2B1C2                 | 0.33 0.51 | -9.62  | 5.76   | 0.31 0.55 | -10.17 | -5.09 |
| 5 2 2 A2B2C3                 | 1.11 0.62 | 0.90  | 4.07   | 0.97 0.70 | 0.26  | 3.02 |
| 6 2 3 A2B3C1                 | 1.89 0.50 | 5.52  | 6.01   | 1.52 0.51 | 3.63  | 5.76 |
| 7 3 1 A3B1C3                 | 0.52 0.49 | -5.67  | 6.17   | 0.48 0.48 | -6.73 | 6.36 |
| 8 3 2 A3B2C2                 | 1.27 0.54 | 2.07  | 5.30   | 1.19 0.60 | 1.51  | 4.43 |
| 9 3 3 A3B3C2                 | 2.01 0.45 | 6.06  | 6.79   | 1.76 0.44 | 4.91  | 6.96 |

3. Results and its discussion

In this section, various results of experiments are presented and analysed through S/N-ratio and ANOVA. S/N ratios and level values are calculated by MINITAB software using “larger is better” condition for MRR, and “smaller is better” condition for Ra. Table 3 depict the results of experiments and corresponding S/N-ratio of MRR and Ra both. The level of a control factor with the greatest S/N-ratio gives an optimal level, regardless of the type of performance characteristics (such as MRR, Ra,
etc.). For analyzing the influence of control factors (cutting parameters) on MRR, main effects plot for S/N ratios for both the materials are generated as shown in Fig. 2(a) and 2(b). Similarly for analyzing the effect of control factors on Ra, main effects plot for S/N ratios for both the materials are generated as depicted in Fig.2(c) and 2(d).

![Figure 2](image)

**Figure 2.** Main effects plot for S/N ratios of (a) MRR for EN24 steel (b) MRR for EN9 steel (c) Ra for EN24 steel (d) Ra for EN9 steel.

### 3.1. Material removal rate (MRR)

Fig. 2(a), reveal that the material MRR obtained for EN24 steel is the maximum (optimal) at the third level spindle speed (A3), the third level feed rate (B3), and the third level depth of cut (C3). As a result, optimal parameter for MRR of EN24 steel is A3B3C3, i.e. spindle speed 2000rpm, feed rate 0.125mm/revolution, and depth of cut 1.5mm. And Fig. 2(b), reveal that MRR obtained for EN9 steel is the maximum (optimal) at the third level spindle speed (A3), the third level feed rate (B3), and the first level depth of cut (C1). As a result, optimal parameter for MRR of EN9 steel is A3B3C1, i.e. spindle speed 2000rpm, feed rate 0.125mm/revolution, and depth of cut 0.5mm. According to the S/N ratio table, it is observed that feed rate (mm/rev) has more influence, spindle speed (rpm) has moderate influence and depth of cut (mm) has less influence on MRR for CNC turning of both the materials EN24 and EN9 steel. According to main effects plot for mean, it is observed that MRR increases with increase of feed rate and spindle speed, and decreases with increase of depth of cut for both the materials EN24 and EN9 steel.

MRR for both the materials EN24 and EN9 steel are analyzed with ANOVA to identify the factors influencing the performance output. Analysis is done for significance level $\alpha = 0.05$ i.e. 95% confidence level. The control factors with P-value less than 0.05 are considered as statistical significant contribution to the performance output. ANOVA results depict that the feed rate is more significant (79.43% for EN24 steel and 82.51% for EN9 steel) on the MRR which is statistically significant, while spindle speed has moderate significance (15.79% for EN24 steel and 13.91% for EN9 steel) on the MRR which is statistically not significant in CNC turning of both EN24 and EN9 steel. Depth of cut (DOC) has least effect (2.41% for EN24 steel and 1.86% for EN9 steel) on the MRR which is also statistically not significant. The error contributions are 2.37% and 1.72% for EN24 steel and EN9 steel respectively.
3.2. Surface roughness (Ra)
Fig. 2(c) and 2(d), reveal that the Ra obtained for both EN24 steel and EN9 steel are the minimum (optimal) at the third level spindle speed (A3), the third level feed rate (B3), and the third level depth of cut (C3). As a result, optimal parameter for Ra of both the materials EN24 steel and EN9 steel is A3B3C3, i.e. spindle speed 2000rpm, feed rate 0.125mm/revolution, and depth of cut 1.5mm. According to the S/N ratio table, it is observed that spindle speed (rpm) has more influence, feed rate (mm/rev) has moderate influence and depth of cut (mm) has less influence on Ra for CNC turning of both the materials EN24 steel as well as EN9 steel. According to main effects plot for mean, it is observed that Ra decreases rapidly when spindle speed increases from 1000rpm to 1500rpm and it decreases very slowly when spindle speed increases from 1500rpm to 2000rpm. Ra increases slow when feed rate increases from 0.025mm/rev to 0.075mm/rev, and it decreases fast when feed rate increases from 0.075mm/rev to 0.125mm/rev. And Ra decreases slowly with increase of depth of cut from 1.0mm to 1.5mm in CNC turning of both the materials EN24 and EN9 steel.

Surface roughness for both the materials EN24 and EN9 steel are analyzed with ANOVA to identify the factors influencing the performance output. Analysis is done for significance level $\alpha = 0.05$ i.e. 95% confidence level. The control factors with P-value less than 0.05 are considered as statistical significant contribution to the performance output. ANOVA results depict that the spindle speed is more significant (96.64% for EN24 steel and 96.56% for EN9 steel) on the Ra which is statistically significant, while feed rate has moderate significance (1.48% for EN24 steel and 1.83% for EN9 steel) on the Ra which is statistically not significant in CNC turning of both EN24 and EN9 steel. Depth of cut (DOC) has least effect (0.83% for EN24 steel and 0.78% for EN9 steel) on the Ra which is also statistically not significant. The error contributions are 1.05% and 0.83% for EN24 steel and EN9 steel respectively.

4. Regression Analysis
Regression analysis was used to determine the relationship between response factors (such as MRR and Ra) and the cutting parameters. The standard statistical software MINITAB 17 was used to generate the regression models between these cutting parameters and various response factors. The final second-order regression models were established by neglecting insignificant coefficient and are presented as follows:

(i) Regression model for MRR obtained for EN24 steel;
$$\text{MRR}_1 = 0.1475 + 0.000257A + 2.93B + 0.256C + 4B^2 + 0.56C^2 + 0.0124AB + 0.00036AC + 10BC$$  \(3\)
$$R^2 = 99.49\%$$

(ii) Regression model for MRR obtained for EN9 steel;
$$\text{MRR}_2 = 0.226 + 0.000063A + 8.267B + 0.5467C + 26B^2 + 0.2267C^2 + 0.0052AB + 0.000093AC + 1.067BC$$  \(4\)
$$R^2 = 99.57\%$$

(iii) Regression model for surface roughness obtained for EN24 steel;
$$\text{Ra}_1 = 8.666 + 0.00387A + 178.5B + 16.86C - 668.7B^2 - 5.713C^2 - 0.1051AB + 0.01165AC + 105.6BC$$  \(5\)
$$R^2 = 99.13\%$$

(iv) Regression model for surface roughness obtained for EN9 steel;
$$\text{Ra}_2 = 8.6 - 0.004141A + 223.5B - 18.15C - 826.7B^2 - 7.233C^2 - 0.1263AB + 0.01345AC + 121.2BC$$  \(6\)
$$R^2 = 99.51\%$$

For justifying the validation of established regression model, $R^2$ value is generally used. $R^2$ value reports the variation amount in observed responses explained by the predicted model. In present research, regression models [Eq. (3), Eq.(4), Eq.(5), and Eq.(6)] were found to be consistent ($R^2 > 90\%$) with experimental values. The experimental results were compared with predicted values obtained from regression models for MRR and Ra as depicted in Fig.3. From these figures it was found that the variation amount between predicted values and experimental values are minimal. As a
result, the developed regression second-order models are statistically significant for MRR and Ra and hence these models can be utilized for further analysis.

Figure 3. Comparison between predicted and experimental values of (a) MRR$_1$ (b) MRR$_2$ (c) Ra$_1$ (d) Ra$_2$

5. Comparative Study between EN24 and EN9 steel

The comparison of MRR obtained for EN24 and EN9 steel at each experimental run reveal that MRR obtained for EN24 steel is more as compare to MRR obtained for EN9 steel (Table 3) almost at all experimental run, due to material property. The comparison of Ra for EN24 and EN9 steel at each experimental run reveal that surface roughness obtained for EN24 is less as compare to surface roughness obtained for EN9 steel (Table 3) at most of the experimental run, due to comparatively less carbon percentage in EN24 steel.

6. Conclusions

This study focused on application of the Taguchi design method to investigate the influences of cutting parameters on material removal rate and surface roughness, and comparison in CNC turning of EN24 and EN9 steel under dry/green cutting condition. On the basis of experimental results and analysis the following conclusions are made:

- A3B3C3 (spindle speed=2000rpm, feed rate=0.125mm/rev, and depth of cut=1.5mm), and A3B3C1 (spindle speed=2000rpm, feed rate=0.125mm/rev, and depth of cut=0.5mm) are predicted optimal parameters of MRR for EN24 and EN9 steel respectively.
- A3B3C3 (spindle speed=2000rpm, feed rate=0.125mm/rev, and depth of cut=1.5mm) is predicted optimal parameters of Ra for both EN24 and EN9 steel.
- Feed rate has statistical more significance (79.43% for EN24 steel and 82.51% for EN9 steel) on the MRR, while spindle speed has moderate significance (15.79% for EN24 steel and 13.91% for EN9 steel) on the MRR. Depth of cut (DOC) has least effect (2.41% for EN24 steel and 1.86% for EN9 steel) on the MRR in CNC turning of both EN24 and EN9 steel.
- Spindle speed has statistical more significance (96.64% for EN24 steel and 96.56% for EN9 steel) on the Ra, while feed rate has moderate significance (1.48% for EN24 steel and 1.83% for EN9 steel) on the Ra. Depth of cut (DOC) has least effect (0.83% for EN24 steel and 0.78% for EN9 steel) on the Ra in CNC turning of both EN24 and EN9 steel.

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