Holes quality investigations and comparative analysis in CNC-drilling of AISI-4340 & AISI-1055 steels

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Abstract. This article focuses on the investigations of holes quality and comparative analysis in terms of surface roughness and diameter error in CNC-drilling of AISI-4340 and AISI-1055 steels under dry as well as wet cutting condition. All experiments were conducted with high speed steel (HSS) twist-drill of diameter 7.78mm via Taguchi method. For the experiments, L\textsuperscript{9} Taguchi orthogonal array design was selected. The statistical analysis methods such as S/N ratio of Taguchi method and ANOVA were employed to optimize the machining parameters and to investigate the influence of machining parameters on the average surface-roughness (Ra) and diameter error (DE). All experimental data of Ra and DE were used to develop second-order regression-models. These second-order regression-models could be utilized to predict the responses in CNC-drilling of both steels with a very small error. Finally, machining performance comparison between AISI-4340 and AISI-1055 steels on the basis of surface roughness and diameter error obtained were carried out. Results of this study show that the machinability of AISI-4340 steel is better than the machinability of AISI-1055 steel in terms of surface roughness and diameter error obtained in CNC-drilling. And the surface quality of holes was better with wet-cutting conditions in CNC-drilling of both the materials.

1. Introduction
Although various methods are available to generate holes in different types of workpiece material, still conventional drilling method is one of the most common methods. Conventional drilling method is usually most economical and efficient method to generate holes in various types of materials therefore it has a big importance in manufacturing industries. Quality of holes generated with conventional drilling method depends on various factors such as tool configuration, tool materials, cutting fluids, cutting parameters etc. [1]. In metal machining process, cutting fluids are generally used for smoother machining-performance, removal of heat generated, removal of chips formed, longer tool-life and a better machined-surface. Strategies for the application of cutting fluids are: mist application of cutting fluids, jet application of cutting fluids and flood application of cutting fluids. Flood coolant ensures good cooling and better chip removal from cutting zone to improve holes quality and machining precision. Industries generally use the flood coolant (or conventional cutting fluids) for lubricating and cooling the machining process [2]. Surface finish, diameter accuracy, tapers less and burr free holes
etc. are the some important aspect of the circular holes drilling which decide the quality of the holes produced. For functional behaviors of the parts, achievement of required quality of holes is very important. Many types of experiments were carried out to achieve the accuracy and surface quality of the drilled holes. Still there is need of more accuracy and surface quality of the drilled holes in various types of materials using conventional drilling method [3]. For this purpose the aim of this study is to investigate and comparison the surface quality and accuracy of the drilled holes in two greater strength and greater wear resistance materials AISI-4340 & AISI-1055 steels.

AISI-4340 steel is most suitable material for manufacturing machine tool parts and automobile parts such as shaft, heavy-duty axel, gears, studs, bolts etc.. This material is also used in ship borne mechanical handling equipment, tensionless hydraulic bolt [4]. AISI-1055 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, roller, moulding dies, forming andblanking tools etc. [5]. In present study feed rate (mm/min) and spindle speed (rpm) and depth of cut (mm) are chosen as cutting parameters in order to investigate their influence on the average surface roughness (Ra) and diameter error (DE) under dry cutting condition and wet cutting condition using conventional cutting fluids in CNC-drilling of AISI-4340 & AISI-1055 steels, and the relationship between these variable parameters are developed with Ra and DE. The experiments were designed by using Taguchi design technique, and ANOVA (Analysis of variance) is employed to determine the dominant cutting parameters on Ra and DE. In last, machining performance comparison between AISI-4340 and AISI-1055 steels on the basis of surface roughness and diameter error obtained were carried out.

![Figure 1](image.png)

**Figure 1.** Experimental setup: (a) CNC-milling machine-tool of model: chandra-plus of BFW-India (b) contact-type surface profiler of model SJ-210 of MITUTOYO (c) drilled holes.

2. Experimental

A 3-axis CNC-milling machine-tool of model chandra-plus of BFW-India as illustrated in Fig. 1(a) is used to perform the drilling experiments. This machine-tool has travel length in X- 800mm, Y-350mm, Z-380mm and accuracy 0.005mm. High speed steel (HSS) twist-drill of diameter 7.78mm and conventional flood coolant (in wet cutting condition) are employed for the drilling of both materials AISI-4340 and AISI-1055 steels, during the experiments. Experiments are conducted on a rectangular workpiece (180×26×20mm) of both materials clamped on the machine-table 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 compositions of AISI-4340 and AISI-1055 steels are shown in Tables 1. Cutting parameters and their values used in the experiments under dry as well as wet cutting condition for both the materials 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 drilling 9 holes (with 14mm depth) on the rectangular work pieces along the longitudinal axis of the workpiece for both types of materials. All the experiments are carried out in dry as well as wet cutting conditions. The average surface roughness (Ra) and diameter error (DE) are selected as response factors for the experimentation. For the measurement of surface roughness, work- pieces are cut along the diameters of the holes and a contact-type surface profiler of model SJ-210 of MITUTOYO as shown in Fig. 1(b) was used. The average surface roughness for each individual drilled-surface was predicted by taking the average of
surface-roughness values of four sampling length of each drilled-hole as shown in Fig. 1(b) and 1(c). Diameter error is calculated as (diameter of drilled hole – diameter of twist drill).

| Chemical composition | AISI-4340 Steel | AISI-1055 Steel |
|----------------------|-----------------|-----------------|
| Carbon               | % Obtained value | % Required range | % Obtained value | % Required range |
|                      | 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           |                  |

| Cutting Parameters   | Code | Levels       |
|----------------------|------|--------------|
| Spindle speed, SS (rpm) | A    | 800, 1200, 1600 |
| Feed rate, FR (mm/min) | B    | 20, 40, 60    |
| Depth of Cut, DOC(µm) | C    | 200, 225, 250 |

| Exp. Run | Designation | For AISI-4340 steel (1) | For AISI-1055 steels (2) |
|----------|-------------|-------------------------|--------------------------|
|          | DRY         | WET                     | DE1 (µm)                 | DRY           | WET           | DE2 (µm)     |
|          | Ra1(dry)    | Ra1(wet)                |                          | Ra2(dry)      | Ra2(wet)      |              |
| 1        | 3.806       | 3.255                   | 70                       | 3.899         | 3.922         | 129          |
| 2        | 4.432       | 3.684                   | 99                       | 4.263         | 4.148         | 151          |
| 3        | 4.648       | 3.926                   | 95                       | 4.581         | 4.392         | 149          |
| 4        | 3.815       | 3.227                   | 109                      | 4.013         | 3.893         | 160          |
| 5        | 3.911       | 3.638                   | 111                      | 4.201         | 4.095         | 164          |
| 6        | 4.109       | 3.716                   | 120                      | 4.483         | 4.281         | 171          |
| 7        | 3.783       | 3.115                   | 118                      | 3.892         | 3.801         | 170          |
| 8        | 3.892       | 3.454                   | 130                      | 4.195         | 4.002         | 167          |
| 9        | 3.998       | 3.562                   | 125                      | 4.300         | 4.209         | 173          |

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 “smaller is better” condition for both Ra and DE. Table 3 depict the results of experiments of Ra and DE both. Ra1 and DE1 are respectively surface roughness and diameter error for material AISI-4340 steel. Ra2 and DE2 are respectively surface roughness and diameter error for material AISI-1055 steel. 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, DE etc.). For analyzing the influence of control factors on Ra and DE, main effects plot of S/N ratios for both the materials are generated.

3.1. Optimization and influence of cutting parameters

Main effects plots of S/N ratios for both the materials AISI-4340 and AISI-1055 steel reveal that the obtained surface roughness Ra1(dry), Ra1(wet), Ra2(dry) and Ra2(wet) are the minimum (optimal) at the third level of spindle speed (A3), the first level of feed rate (B1), and first level of depth of cut.
(C1). As a result, optimal parameter for Ra1(dry), Ra1(wet), Ra2(dry) and Ra2(wet) of AISI-4340 and AISI-1055 steel under dry as well as wet cutting conditions is A3B1C1, i.e. spindle speed 1600rpm, feed rate 20mm/min, and depth of cut 200µm. According to the S/N ratio table, it is observed that feed rate (mm/min) has more influence, spindle speed (rpm) has moderate influence and depth of cut has least influence on Ra1(dry), Ra1(wet), Ra2(dry) and Ra2(wet) all for CNC drilling of both the materials under dry as well as wet cutting conditions. According to main effects plot as shown in Fig. 2, it is observed that Ra decreases with increase of spindle speed, and increases with increase of feed rate under dry as well as wet cutting condition for both the materials AISI-4340 and AISI-1055 steel.

Main effects plots of S/N ratios for diameter error (DE) reveal that the diameter error DE1 and DE2 respectively for AISI-4340 and AISI-1055 steel are the minimum (optimal) at the first level of spindle speed (A1), the first level of feed rate (B1), and first level of depth of cut (C1). As a result, optimal parameter for DE1 and DE2 of AISI-4340 and AISI-1055 steel respectively is A1B1C1, i.e. spindle speed 800rpm, feed rate 20mm/min, and depth of cut 200µm. According to the S/N ratio table, it is observed that spindle speed (rpm) has more influence, feed rate (mm/min) has moderate influence and depth of cut has least influence on DE1 and DE2 both for CNC drilling of both the materials AISI-4340 steel as well as AISI-1055 steel. According to main effects plot for mean, and interaction plot as shown in Fig. 3, it is observed that DE increases with increase of spindle speed and feed rate for both the materials.

![Figure 2. Interaction plot of surface roughness obtained for (a) AISI-4340 steel under dry condition (b) AISI-4340 steel under wet condition (c) AISI-1055 steel under dry condition (d) AISI-1055 steel under wet condition.](image)

3.2. ANOVA analysis
Surface roughness (Ra) and diameter error (DE) for both the materials AISI-4340 and AISI-1055 steel are analyzed with ANOVA to identify the factors influencing the performance output. Analysis is done for significance level α=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 for Ra depict that the feed rate is more significant (50.54% under dry cutting condition and 81.13% under wet cutting condition for AISI-4340 steel, and 86.95% under dry cutting condition and 88.15% under wet cutting condition for AISI-1055 steel) on the Ra which is statistically significant. While spindle speed
has moderate significance (43.90% under dry cutting condition and 16.04% under wet cutting condition for AISI-4340 steel, and 11.07% under dry cutting condition and 11.21% under wet cutting condition for AISI-1055 steel) on the Ra which is statistically significant in CNC drilling of both AISI-4340 as well as AISI-1055 steel. Depth of cut has least significant for both cutting conditions and both materials on Ra. The error contributions are 0.71% and 0.43% for AISI-4340 and AISI-1055 steel respectively under dry cutting conditions.

ANOVA results for DE depict that the spindle speed is more significant (69.23% for AISI-4340 steel, and 81.20% for AISI-1055 steel) on the DE which is statistically significant, while feed rate has moderate significance (29.30% for AISI-4340 steel, and 17.00% for AISI-1055 steel) on the DE which is statistically significant in CNC drilling of both AISI-4340 as well as AISI-1055 steel. Depth of cut has least significant for both the materials on DE. The error contributions are 0.03% and 0.51% for AISI-4340 and AISI-1055 steel respectively.

4. Regression Analysis

Regression analysis was used to determine the relationship between response factors (such as Ra and DE) 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 of surface roughness obtained for AISI-4340 steel under dry cutting;

\[
Ra_{1(dry)} = 10.19 - 0.004838A - 0.04160B - 0.01747C - 0.000465B^2 - 0.000107C^2 - 0.000043AB + 0.000028AC + 0.000665BC
\]

\[
R^2 = 99.2\%
\] (1)

(ii) Regression model of surface roughness obtained for AISI-4340 steel under wet cutting;

\[
Ra_{1(wet)} = 3.224 + 0.001383A + 0.04727B - 0.01453C - 0.000205B^2 + 0.000077C^2 + 0.000003AB - 0.000002AC - 0.000011BC
\]

\[
R^2 = 99.9\%
\] (2)

(iii) Regression model of surface roughness obtained for AISI-1055 steel under dry cutting;

\[
Ra_{2(dry)} = 7.684 + 0.000215A + 0.01426B - 0.03400C - 0.000013B^2 + 0.000077C^2 - 0.000003AB - 0.000002AC + 0.000011BC
\]

\[
R^2 = 99.9\%
\] (3)

(iv) Regression model of surface roughness obtained for AISI-1055 steel under wet cutting;

\[
Ra_{2(wet)} = 3.209 + 0.000593A + 0.01184B + 0.00114C + 0.000054B^2 + 0.000014C^2 + 0.000002AB - 0.000004AC - 0.000043BC
\]

\[
R^2 = 99.1\%
\] (4)

(v) Regression model of diameter error obtained for AISI-4340 steel;

\[
DE_{1} = -678.99 + 0.3075A + 5.975B + 4.053C - 0.00125B^2 - 0.002667C^2 + 0.0005AB - 0.001333AC - 0.02867BC
\]

\[
R^2 = 99.3\%
\] (5)
(vi) Regression model of diameter error obtained for AISI-1055 steel;
\[
DE2 = -381.2 + 0.2333A + 5.625B + 2.193C + 0.009583B^2 + 0.001867C^2 + 0.001042AB - 0.001167AC - 0.034*B*C
\]
\[R^2 = 99.4\%\]  

In present research, regression models [Eq. (1), Eq. (2), Eq. (3), Eq.(4), Eq.(5), and Eq.(6)] were found to be consistent (R² > 90%) with experimental values. The experimental results were compared with predicted values obtained from regression models for all Ra and DE. And this comparison shows 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 Ra and DE and hence these models can be utilized for further analysis.

![Figure 4. Machinability comparisons in terms of (a) surface roughness and (b) diameter error.](image)

5. Comparative analysis on machinability of AISI-4340 and AISI-1055 steel

Figure 4 shows the machinability comparisons in terms of (a) surface roughness and (b) diameter error obtained in CNC drilling of both the materials AISI-4340 and AISI-1055 steel. From figure 4(a) it clear that surface roughness [i.e., Ra1(dry) and Ra1(wet)] obtained for AISI-4340 steel is less than the surface roughness [i.e., Ra2(dry) and Ra2(wet)] obtained for AISI-1055 steel at most of the experimental run in dry as well as wet cutting conditions both. Figure 4(a) also shows that surface roughness obtained in wet cutting condition is less than dry cutting condition for both the materials. From figure 4(b), it is clear that diameter error (i.e., DE1) obtained for AISI-4340 steel is less than the diameter error (i.e., DE2) obtained for AISI-1055 steel.

6. Conclusions

This study focuses on the investigations of holes quality and comparative analysis in terms of surface roughness (Ra) and diameter error (DE) in CNC-drilling of AISI-4340 and AISI-1055 steels under dry as well as wet cutting condition. On the basis of experimental results and analysis the following conclusions are made:

- Feed rate has statistical more significance, while spindle speed has moderate significance and depth of cut has least effect on the Ra in CNC drilling of AISI-4340 and AISI-1055 steels.
- Spindle speed has statistical more significance, while feed rate has moderate significance and depth of cut has least effect on the DE in CNC drilling of AISI-4340 and AISI-1055 steels.
- The machinability of AISI-4340 steel is better than the machinability of AISI-4340 steel in terms of surface roughness and diameter error obtained in CNC-drilling.
- A better surface quality of holes can be achieved with wet-cutting conditions in CNC-drilling of both the materials AISI-4340 steel as well as AISI-4340 steel.

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