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RESEARCH ARTICLE - MECHANICAL ENGINEERING

# Multi-response Optimization of Cutting Parameters for Hole Quality in Drilling of AISI 1050 Steel

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**Abstract** In this study, the surface roughness, dimensional accuracy, and circular and cylindrical deviations characterizing the hole quality were investigated experimentally. AISI 1050 steel in experiments was chosen as reference material due to its extensive applications in many areas. Uncoated and TiAlN coated by physical vapor deposition (PVD) method HSS twist drills with different diameters were used. Experiments were conducted on a CNC vertical machining center under dry condition with different cutting speeds and feed rates. The hole depth was 17 mm to ensure $L < 3D$ condition. After each experiment, hole properties such as surface roughness, dimensional accuracy, circular deviation, and axial misalignment between inlet and outlet holes (cylindrical deviation), all of those that show the hole quality, were measured, and the results were evaluated. In addition to experimental analysis, a statistical analysis was carried out to indicate the effects of drilling parameters on test results. Process parameters such as tool type, drill diameter, feed rate, and cutting speed were optimized with consideration of multiple performance characteristics using desirability functional analysis. As a result, coated tools compared with uncoated tools gave positive results for each evaluation criterion. As the most important parameter on surface roughness (Ra) was drill diameter, the most effective parameter on dimensional accuracy, and circular and cylindrical deviations was cutting speed for both uncoated and coated tools except from cylindrical deviation occurring in uncoated drill.

**Keywords** Metallic material · Metal working · Drilling · Hole quality · Optimization · ANOVA

## 1 Introduction

Drilling process is one of the most important material removal processes, covering approximately 33 % of machining operations [1]. Since drilling application has an important place in machining processes, investigation of its process is very important for manufacturing industry. There are many problems in drilling applications. For example, with varying cutting forces and material removal rate during drilling process, the cutting tool can jam in the hole. Further, the use of unsuitable spindle and drill chuck can cause geometric errors, thereby resulting the circular deviation and axial misalignment between inlet and outlet holes (cylindrical deviation). Because of these reasons, the desired quality of hole will be out of the tolerance limits. Recently, high-precision demands in production have been increased in parallel to the technological developments. The most important parameters determining the quality of the hole are the dimensional accuracy (within tolerances), circularity, cylindrical deviation, and the quality of the drilled surfaces. As these indicators are important for obtaining high-quality holes, additional operations such as reaming are necessary. However, this second operation will require more machining

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time, thereby increasing the production cost. When the literature was reviewed, it was shown that various studies using different parameters such as cutting tool type, tool geometry, hole diameter, rigidity of machine tool, cutting fluids, and cutting parameters affecting machining performance during drilling processes were conducted. For instance, Dinc et al. [2] analyzed tool temperature with an infrared imaging method during orthogonal machining. It was seen that maximum temperature at tool–chip interface increased with increasing cutting speed and feed rate. Soylu [3] designed a dynamometer that measures the thrust force and torque to determine the optimum cutting conditions. Optimum cutting conditions were determined as 30° helix angle, 118° edge angle, 28 m/min cutting speed, and 0.2 mm/rev feed rate. Kelly and Cotterell [4] performed drilling experiments using different methods of cutting fluid applications and changing parameters of feed rate and cutting. They determined that because the use of cutting fluid decreases cutting temperature, its application makes drilling much easier than dry cutting. Strenkowski [5] drilled AISI 1020 material under varying parameters of drill diameter, cutting speed, and feed rate. It was seen that thrust force decreases with increasing chip angle and increases with increasing drill diameter [5]. Armerago and Cheng [6] theoretically investigated the forces and torque affecting different size conventional and modified drills and confirmed the estimates of force and torque with the experiments by making an analogy. They determined that in modified drills, forces decrease in the ratio of 40–42 % and torque decreases in the ratio of 15 %. In some studies, various mathematical models about cutting forces and torques were developed depending on the drill edge geometry. Kaynak [7] calculated numerically the temperature values obtained during drilling Al 2024 material using finite elements software. It was determined that cutting temperature and cutting force measured in dry drilling conditions were closer to the results obtained with numerical approach. Kucukturk evaluated the thrust forces and torques with varying process parameters in drilling of AISI 316L stainless steel by using finite element method [8]. Bono [9] calculated the distribution of temperature at the drill by examining the region of the maximum temperature on the cutting edge of drill using finite element methods. It was determined that the maximum temperature is on radial edge. In the studies about the tool wear, which determines the tool life, the effect of various factors such as tool geometry, cutting parameters have also been theoretically and experimentally examined. Kıvak et al. [10] optimized the process parameters by using the Taguchi method to achieve minimum surface roughness (Ra) and thrust force (Ff) in drilling of AISI 316 steel. Incal [11] eroded drill cutting edge by applying hole enlarging on C45 material with HSS drill bit. It was seen that the wear on TiAlN-coated drill bits is less than uncoated. Tosun [12] researched experimentally the effect of drill types, drill bit angles, and aging on drilling of A1 2124 alloy. It was observed that the area of subsurface damage region increases with increasing drill bit angles of uncoated HSS and TiAlN-coated HSS drills, and the area of subsurface damage region decreases with increasing drill bit angle in carbide drills. Cheung et al. [13] investigated the effect of cutting edge on tool life and tool wear in HSS drills. According to this study, the best result is observed for edge radius between 24–27 μm. The effects of microstructure and hardness of the workpiece material, and heat treatments to be applied on the workpiece materials were experimentally investigated by using different materials in drilling processes. Haggrty [14] drilled the A-131 and B-1112 steel materials with two different drills by using quick-stop technique and compared the relative edge height for both two drills. It was seen that edge height difference for both drills causes shear in drilling process, growth in size, and irregular material removal.

In light of the above information, this study can be summarized into three phases in the following manner:

The first phase included the effect of process parameters on test results such as surface roughness, dimensional accuracy, circular and cylindrical deviations by considering drill types (coated and uncoated), drill diameter, cutting speed, and feed rate. In the second phase, analysis of variance (ANOVA) was conducted to determine the effect of drilling parameters on experimental results. In the final phase, it was simultaneously optimized by considering the multi-response outputs via response surface methodology (RSM) based on desirability function.

## 2 Experimental Setup

Drilling experiments were conducted on a CNC vertical machining center (Johnford VMC-550 model) under dry condition with different cutting speeds and feed rates. The TiAlN coatings with PVD were applied on DIN 338 HSS RN 118° twist drills. DIN 338 HSS RN 118° ground drills were preferred for experimental study. Stationary workpiece—rotating tool application—was selected for drilling experiments. The standard helix angle and the point angle were, respectively, chosen as 30° and 118° for drilling of AISI 1050 because these angles were recommended in the literature [15]. The chemical composition of workpiece is given in Table 1. The cutting parameters were determined based on the pilot experiments by considering the recommended values of manufacturer. The pilot experiments showed that cutting speed and feed rate should not exceed 40 m/min and 0.15 mm/rev, respectively. The cutting parameters and tool specifications used in the drilling process are given in Table 2. In order to obtain optimal results throughout the drilling, the drilling depth was chosen as 17 mm to comply with the requirement of $L < 3D$ [16]. The experiments were carried

**Table 1** Chemical composition of material

| SAE/AISI | C | Mn | Si | P | S |
|---|---|---|---|---|---|
| 1050 | 0.45–0.54 | 0.60–0.90 | 0.10–0.30 | 0.040 max | 0.050 max |

**Table 2** Cutting tool specifications and cutting parameters

| Type of tool | HSS high-speed steel, N, diameter tolerance h8, right-hand side (uncoated and TiAlN coated) |
|---|---|
| Standard | DIN 338 |
| Toll geometry | Ø 6–8–10 mm, point angle 118°, helix angle 30° |
| Cutting speed | 20, 30, 40 m/min |
| Feeding rate | 0.05, 0.1, 0.15 mm/rev |

out by using new drills for each experiment, and experimental setup on the workpieces for Ø6, Ø8, and Ø10 mm holes is shown in Fig. 1.

After all tests were completed, coordinate measuring machine (CMM) was used for measuring the hole diameters, and circular and cylindrical deviations for the holes obtained from the drilling experiments. To determine the quality of drilled surfaces, the portable device (Mahr Perthometer M1) for measuring average surface roughness (Ra) was also used. Because of very small diameters of holes, the samples were cut along the hole axis by SODICK EX21 model wire EDM machine for surface roughness measurements, and mean values of the measurements executed in both half sides were calculated. In experiments, a full factorial experimental design was used because such an experimental design enables to researchers in order to work the effect of each control parameter on the test result, as well as the effects of interactions between parameters on the test result. For this reason, the experimental design for three parameters (drill diameter, feed rate, and cutting speed and) with three levels and one parameter (drill type) with two levels was organized, and according to the full factorial experimental design, a total of 54 experiments were performed.

## 3 Results and Discussion

The accuracy of hole diameter dimension (deviation from the diameter), the resulting roundness of the hole (circular deviation), axial misalignment (cylindrical deviation), and machined surface quality (average surface roughness, Ra), which are outputs of the experiments to determine the hole quality, were evaluated. Input parameters were the type of tools (coated, uncoated), drill diameter, and cutting parameters. The results obtained from experiments are shown in Figs. 2, 3, 4, 5, and 6 and are also evaluated in the following sections.

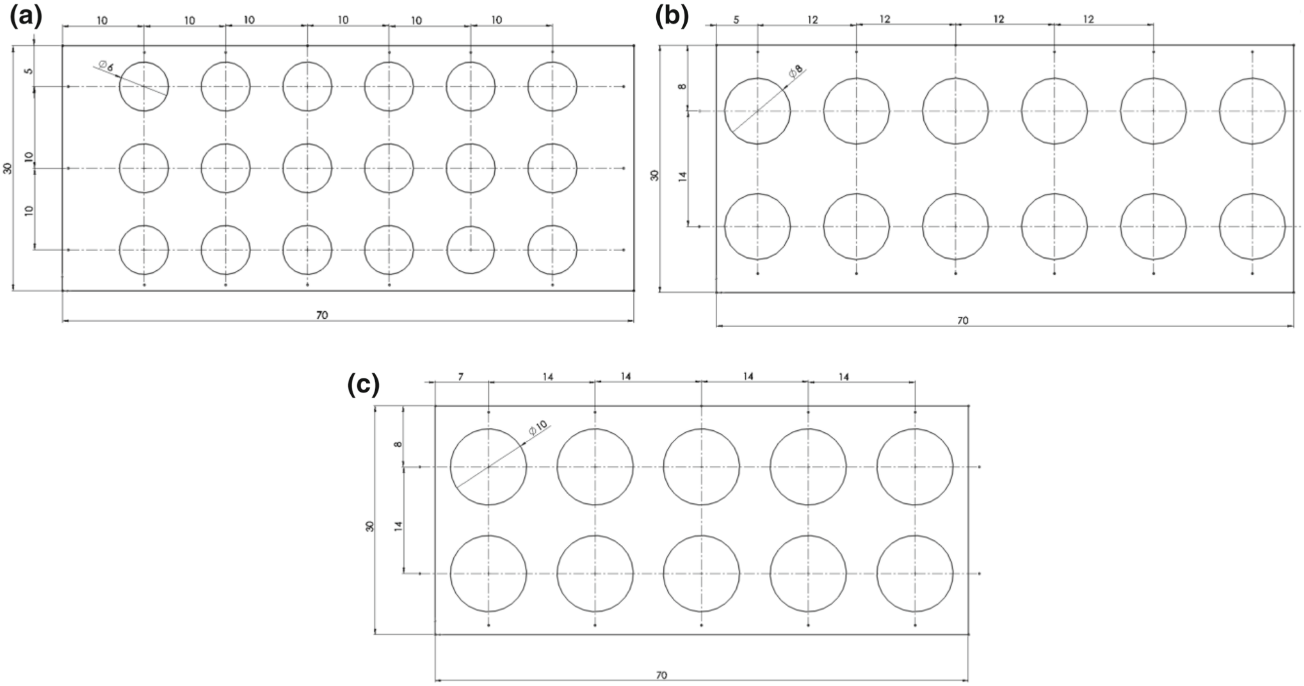

Fig. 1 Experimental setup for **a** Ø6 mm drill, **b** Ø8 mm drill, **c** Ø 10 mm drill

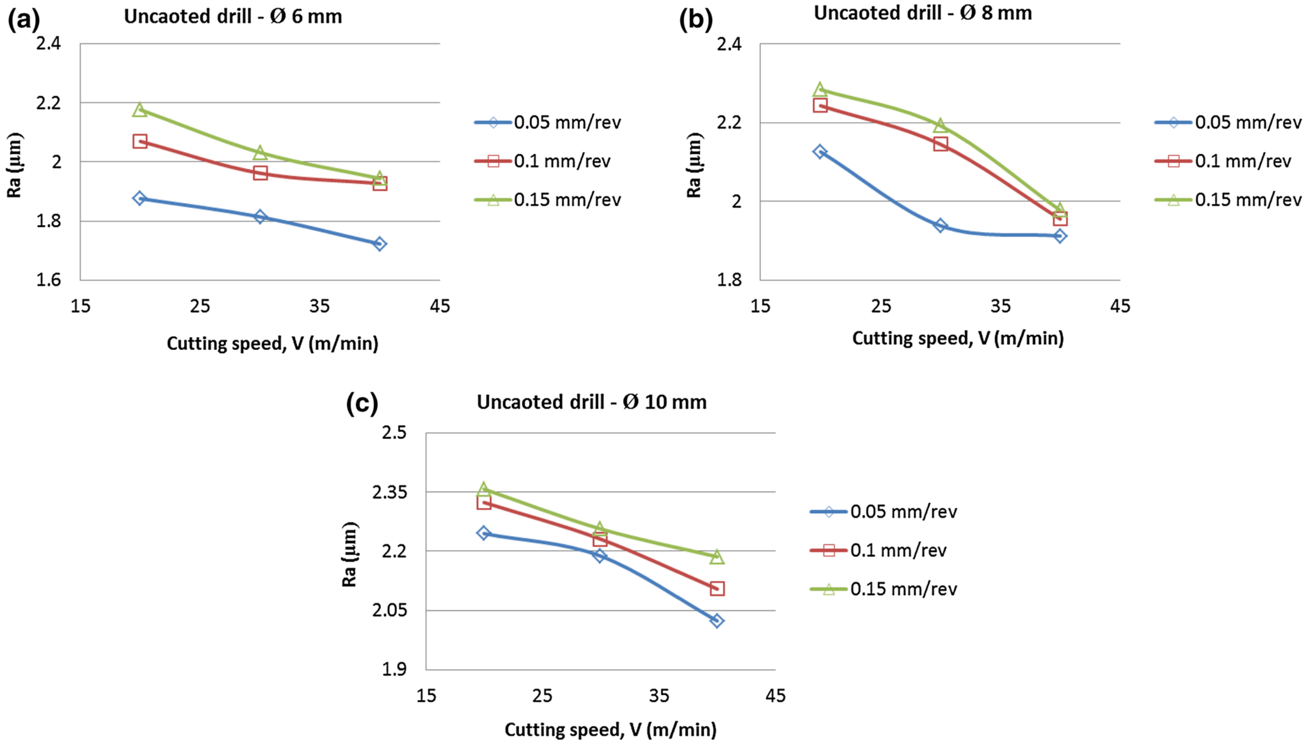

**Fig. 2** Surface roughness obtained by uncoated tools **a** Ø6 mm drill, **b** Ø8 mm drill, **c** Ø 10 mm drill

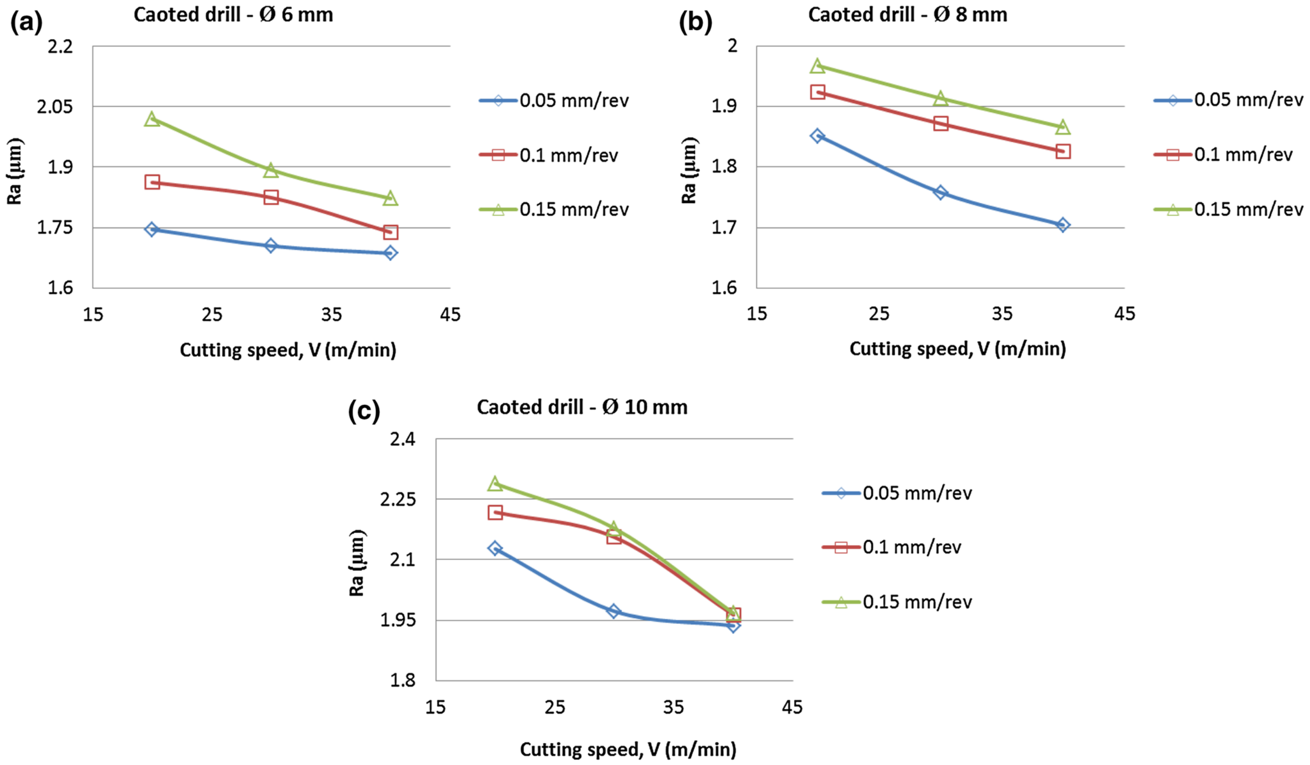

**Fig. 3** Surface roughness obtained by coated tools for **a** Ø6 mm drill, **b** Ø8 mm drill, **c** Ø 10 mm drill

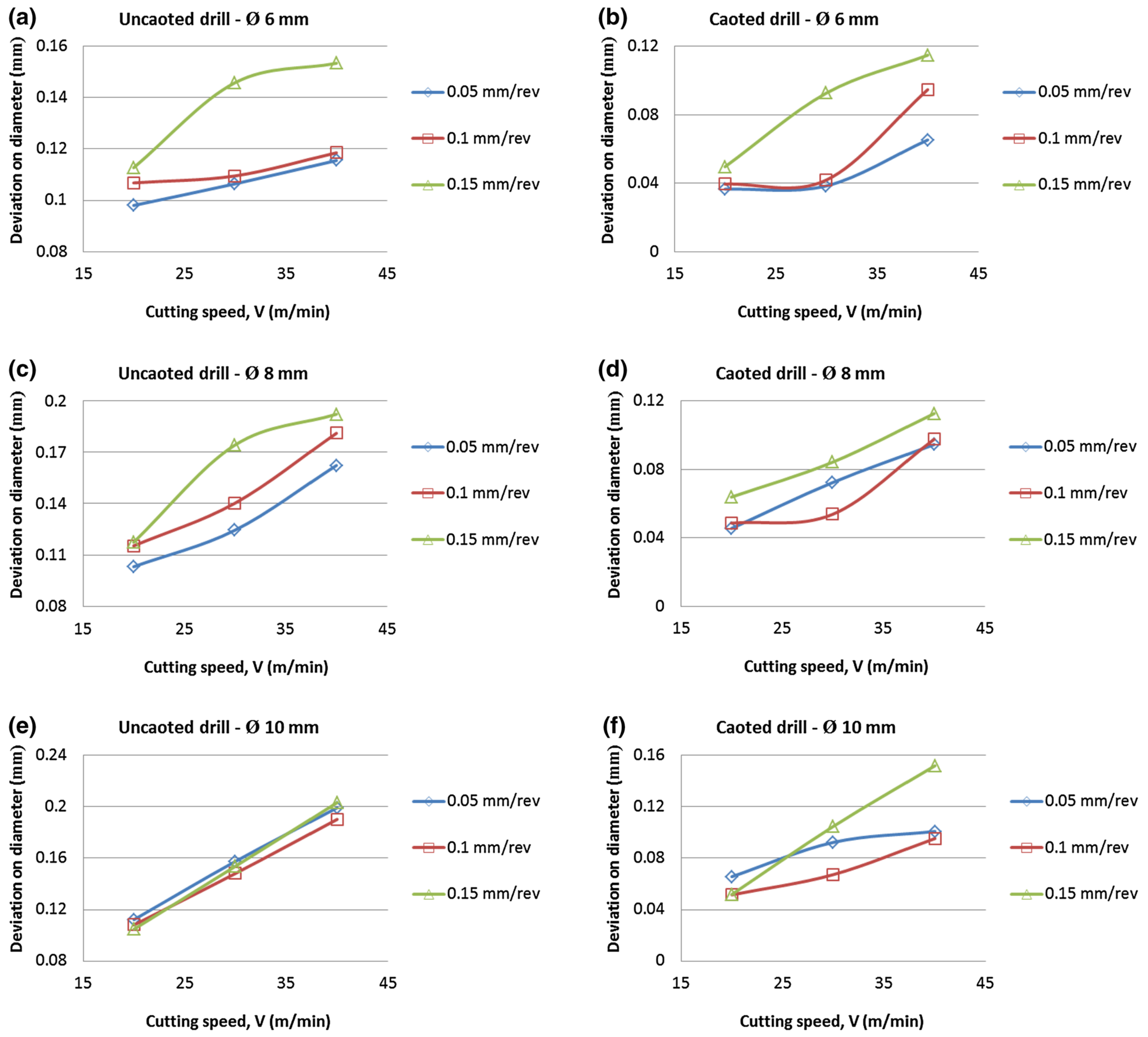

**Fig. 4** Results of deviation from diameter for **a** uncoated drill—Ø6 mm, **b** coated drill—Ø6 mm, **c** uncoated drill—Ø8 mm, **d** coated drill—Ø8 mm, **e** uncoated drill—Ø10 mm, **f** coated drill—Ø10 mm

## 3.1 Surface Roughness Evaluation

### *3.1.1 The Surface Roughness Obtained by Uncoated Tools*

The average surface roughness values (Ra) with changing cutting parameters in drilling of holes by Ø6, Ø8, and Ø10 uncoated tools are given in Fig. 2. The graphs in Fig. 2 indicated that average surface roughness values for all three diameters decreased with increasing the cutting speed and increased with an increase in feed rate. This situation once again verified the previous results in conventional machining processes. An improvement in surface quality was observed because the increasing temperature by heat energy as a result of increasing energy consumption with increasing cutting speed during the cutting processes made the plastic deformation and chip flow easier [17]. Chip disposal in drilling process is one of the most serious problems depending on the drilling depth as it causes the chip adhesion to cutting tool surface, resulting in poor surface quality, and the cutting tool breakage [18]. When the recommended values for the couple of materials (the workpiece and the cutting tool materials) were not exceeded, the drillability of workpiece can be easier during machining process. Experimental data obtained from this study also confirmed this. The cutting speed values were chosen according to the data of tool manufacturer and pilot experiments, and then, it was observed a

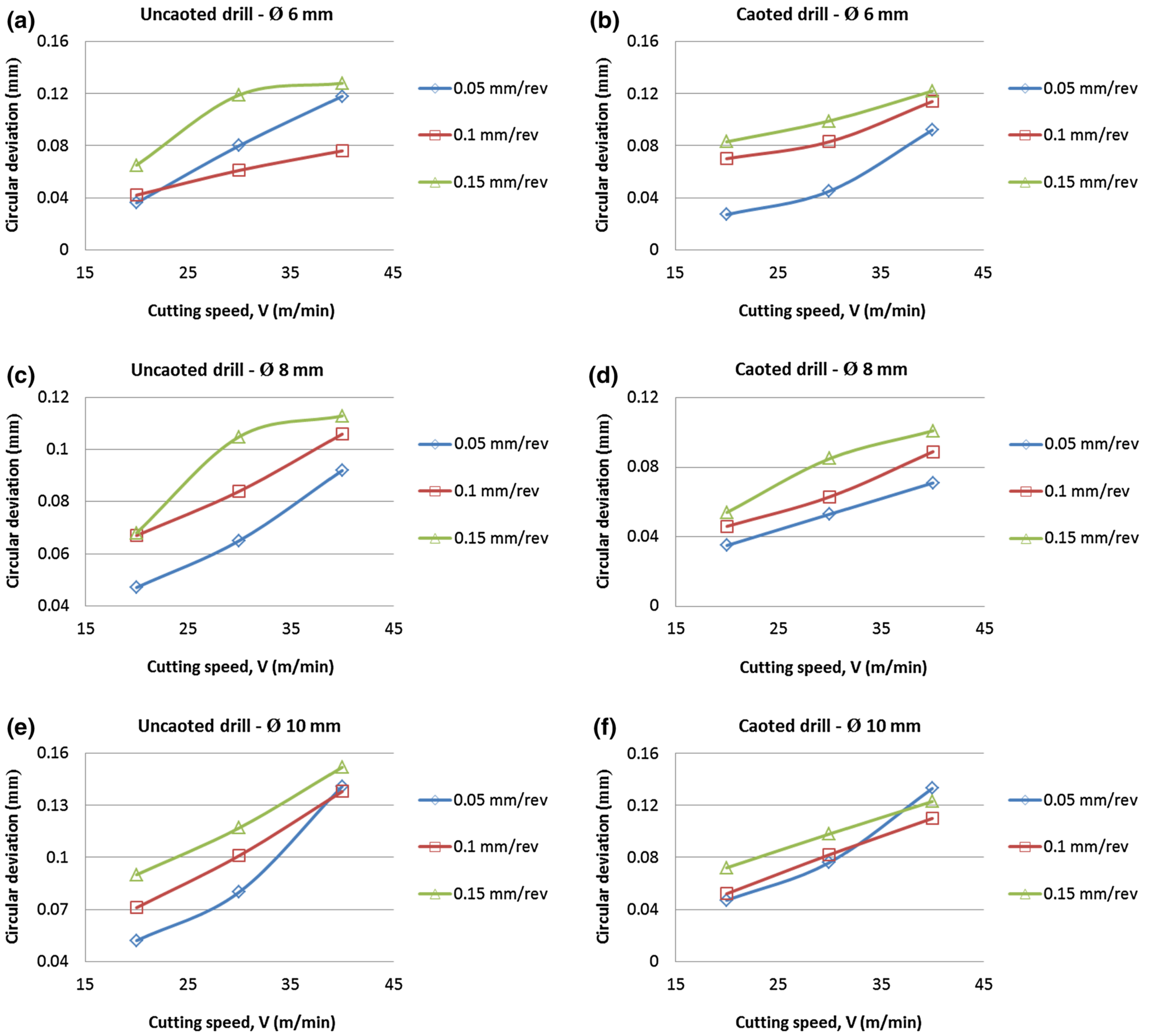

**Fig. 5** Results of circular deviation for **a** uncoated drill—Ø6 mm, **b** coated drill—Ø6 mm, **c** uncoated drill—Ø8 mm, **d** coated drill—Ø8 mm, **e** uncoated drill—Ø10 mm, **f** coated drill—Ø10 mm

significant improvement in surface quality as cutting speed was increased. An increase in level of process parameters will cause increased material removal rate per unit time, thereby increasing the cutting force [18]. The graphs in Fig. 2 showed that the additional loads on drilling tools have negative impact on the surface quality. For all three diameters, as the feed rate increased, the average surface roughness also increased. Especially in the 0.1 and 0.15 mm/rev for Ø6 and Ø8 diameters, deterioration in surface roughness was clearly seen compared with the values at the lowest feed rate of 0.05 mm/ rev. However, when it was considered that the roughness values obtained from all experiments were ranged between 1.722 and 2.358 µm for uncoated tools, all results were remained in the expected limits. Due to the problems caused by low feed rate and economical concerns, 0.1 and 0.15 mm/rev values can be recommended. Moreover, it should not be forgotten that the chip staying more time in the hole at the lower feed rate led to the chip adhesion to cutting tool surface, resulting in poor surface quality, and the cutting tool breakage. In the experiments, limiting the drilling length as 17 mm prevented such a problem, and the best surface quality was obtained at the lowest feed rate. The best results were obtained by using highest cutting speed ($Vc = 40$ m/min) for the holes drilled by Ø6 and Ø8 mm uncoated tools. As the surface quality values were particularly close to each other at 0.1 and 0.15 mm/rev feed rate ($Ra = 1.927$ µm and

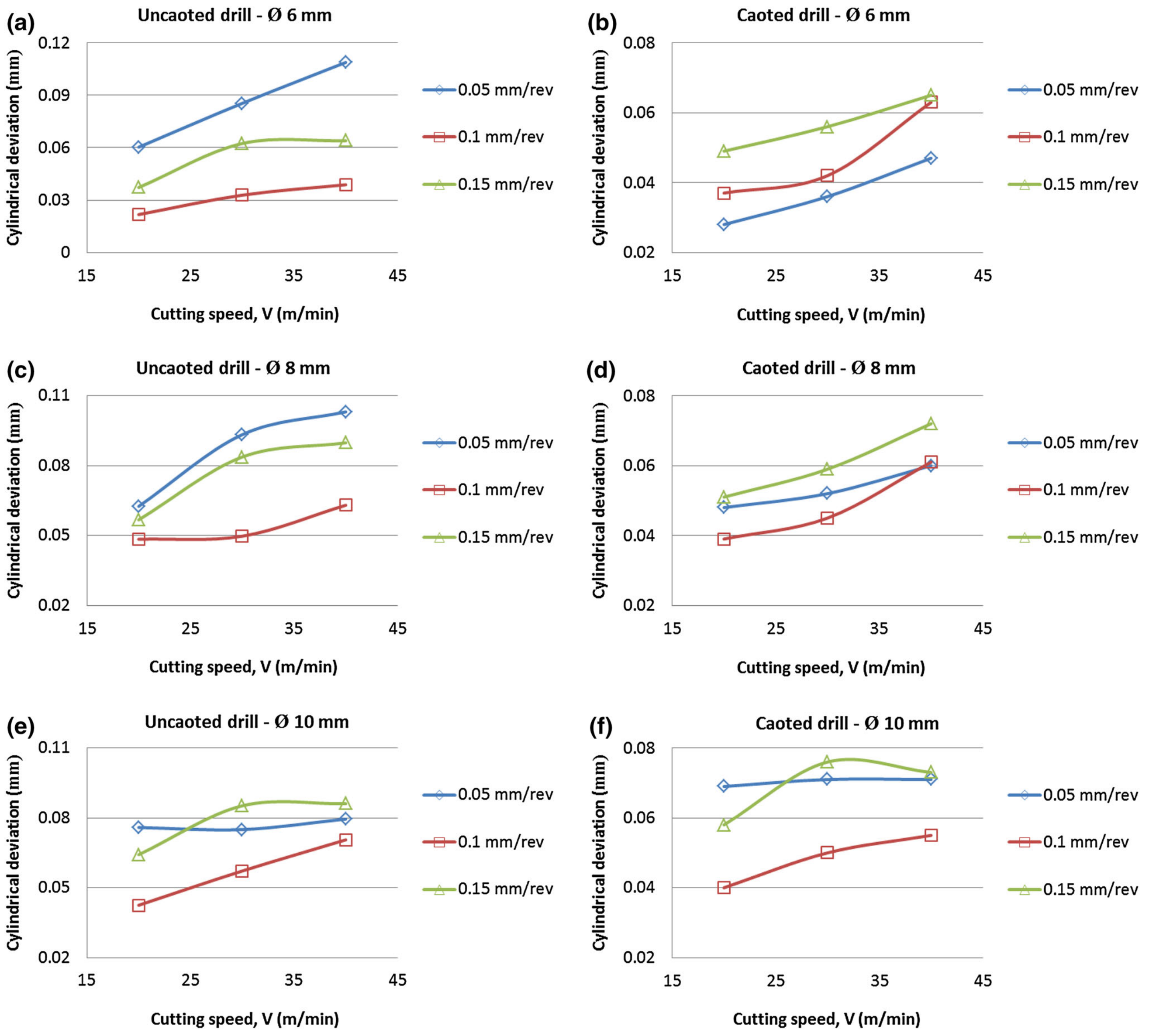

**Fig. 6** Results of cylindrical deviation for **a** uncoated drill—Ø6 mm, **b** coated drill—Ø6 mm, **c** uncoated drill—Ø8 mm, **d** coated drill—Ø8 mm, **e** uncoated drill—Ø10 mm, **f** coated drill—Ø10 mm

$Ra = 1.977\,\mu$m, respectively), it was recommended that 0.15 mm/rev feed rate should be used for these diameters in terms of the economic concerns. When surface roughness values obtained by 10-mm-diameter uncoated tools were evaluated (see Fig. 2), surface roughness values at cutting speed of 30 m/min were close to each other for all three feed rates. Therefore, the use of highest feed rate at this cutting speed will increase the efficiency. As the cutting speed was increased to 40 m/min, an increase in feed rate affected negatively surface quality. The decision about the final cutting speed should be concluded according to the required performance of surface quality/efficiency. It can be generally said for uncoated tools that an increase in the cutting speed affects positively the surface quality, while an increase in the feed rate affects negatively it. Likewise, as drill diameter was increased, the surface roughness also increased. This situation can be attributed to chip load increasing dramatically with high feed rate.

### *3.1.2 The Surface Roughness Obtained by Coated Tools*

The surface roughness values with changing cutting parameters in drilling of holes by Ø6, Ø8, and Ø10 TiAlN-coated tools are given in Fig. 3. When the graphs in Fig. 3, which is similar to the results obtained by uncoated tools in Fig. 2, were analyzed, it was seen that an improvement in surface quality with increasing cutting speed was observed. On the other hand, an increase in feed rate and drill diameter affected negatively surface quality. It was possible to explain the tendency about an improvement on surface quality depending on the cutting speed and a deterioration depending on the drill diameter and feed rate by the explanations discussed in Sect. 3.1.1. Unlike the uncoated tools, the variation in surface roughness depending on the feed rate became more regular, especially for Ø6 and Ø8 mm tools. The decreasing tendency of surface roughness with increasing cutting speed and the increasing tendency of surface roughness with increasing feed rate are parallel with graphs. In the experiments carried out with 10 mm coated tools, the surface quality values obtained from 0.1 and 0.15 mm/rev feed rates for 30 and 40 m/min cutting speeds were very close to each other. Therefore, at these cutting speeds, the efficiency will increase with using higher feed rate. The lowest surface roughness values were particularly obtained at cutting speed of 40 m/min for all three feed rates. This situation implied that higher cutting speed/higher feed rate combinations can be executed for larger diameter drills in terms of surface quality. The most important result for coated tools compared with uncoated tools was better surface quality. This showed that coating material contributes additional wear resistance to cutting tools, and as a consequence, it affected positively the surface quality. The reason of this was the low friction coefficient of the coating material providing easier chip flow, which resulted in a positive affect on the surface quality. The roughness values obtained in the experiments by uncoated and coated tools were generally between 1.686 and 2.358 µm. When it was considered that the surface roughness values obtained by drilling machine were between 1.6 µm (N7) and 3.2 µm (N8), the results obtained from the experimental studies also confirmed this. While medium-fine surface quality was achieved by using coated tools at high cutting speed/medium feed rate combination, medium-rough surface quality was obtained at low cutting speed/high feed rate combination.

## 3.2 Evaluation of Dimensional Accuracy and the Geometric Deviation

Achieving the desired hole quality in drilling processes is one of the most important issues in manufacturing industry. It is very difficult to ensure the dimensional accuracy and geometric circularity of the hole diameter within the desired tolerances for holes directly drilled by drilling machine. Similarly, there can also be axial deviations due to the effect of axial and radial forces depending on the drill length. In order to avoid these problems, generally reaming or boring operations are commonly applied as secondary operations [18]. However, the secondary processes have a negative impact on product cost by increasing the operational costs. However, such an additional operation will require more machining time, thereby increasing the production cost. There is an evaluation to determine how outputs are related with input parameters as following sections.

### *3.2.1 Dimensional Accuracy*

Achieving the desired hole diameter within tolerances is the main aim of drilling operations. The hole diameter obtained by drilling is usually greater than the nominal diameter. It is extremely important that this difference should be within acceptable limits. The application type (rotating drill/fixed workpiece or fixed tool/rotating workpiece), the stability of connecting devices, rigidity, the general situation of the machine tool, and cutting tool geometry affect the dimensional accuracy of the hole in drilling operations [15,18,19]. Furthermore, choosing the parameters correctly such as feed rate and cutting speed is also important. The effect of drill types (uncoated and coated), drill diameters (Ø6, Ø8, Ø10 mm), and cutting parameters (feed rate and cutting speed) on dimensional accuracy is given in Fig. 4. According to Fig. 4, the hole diameters were achieved greater than the nominal diameters for all conditions. In general, deviation from nominal diameter increased when the drill diameter, cutting speed, and feed rate (except for Ø10 mm) increased. Contrary to this situation, as the coated tools used, the deviation from nominal diameter decreased compared to the holes obtained by using uncoated tools under the same conditions. When the graphs in Fig. 4 compared with each other in terms of coated and uncoated tools, it was observed that applying the coating on the drills affected positively not only the surface quality, but also the dimensional accuracy. This situation can be referred to tool's resistance to wear and easier chip disposability due to low friction coefficient. The dimension differences between the hole diameter obtained by uncoated tools and the nominal diameter were calculated as 0.098–0.153 mm for Ø6 mm, 0.103–0.192 mm for Ø8 mm, and 0.112–0.203 mm for Ø10 mm. It can be said in general that the holes obtained by uncoated tools were 0.1–0.2 mm larger than nominal diameter. When holes obtained from TiAlN-coated tools were measured, it was seen that dimension differences between the hole diameters and the nominal diameter were 0.036–0.114 mm for Ø6 mm, 0.045–0.112 mm for Ø8 mm, and 0.065–0.1228 mm for Ø10 mm. It can be said in general that the holes were 0.03–0.12 mm larger than nominal diameter. The hole diameters obtained by uncoated tools and coated tools were, respectively, 1.6–2 % and 0.5–1.2 % larger compared to nominal diameter.

It can be clearly observed that when TiAlN-coated tools were used, deviation from hole diameter was 30–60 % lower than holes drilled by uncoated tools. According to these results, it is recommended to use the coated tools to obtain the hole dimension within tolerance limits. The increment in the deviation from diameter with increasing tool diameter became clearer especially at the highest cutting speed ($Vc = 40$ m/min). This increment with increasing tool can be attributed to the increment of the chip load. Similarly, an increase in the cutting speed has a negative effect on the deviation from diameter, which significantly increased the amount of deviation from diameter for all other parameters. This situation can be referred to the increase in axial misalignment of the tools due to the increment of machine-cutting tool vibration level with increasing the cutting speed. When the effect of feed rate on deviation from diameter was evaluated, it can be said that the increasing feed rate also increased the deviation from diameter except for exceptional circumstances. However, this increment was not as high as effect of other parameters. For the holes especially obtained by uncoated 10-mm-diameter tools, this change was quite small and can be ignored. Due to the difficulties in chip evacuation, even less feed rate caused large deviations from diameter. After these evaluations, it was recommended that the lower cutting speed, medium feed rate, and using the coated tools should be selected for dimensional accuracy.

### *3.2.2 Deviation from Circularity (Ovality)*

One of the biggest obstacles to use holes drilled with drills is that the full circular holes cannot be obtained. Reaming is mandatory as a second operation for a drilling application in which the geometrical circularity is important [15,20]. This matter is related to the fact that high-volume chips (chip load) are loaded into two cutting edges in drilling. Although reaming eliminates this problem, as previously mentioned, it results in an increase in product cost by negatively affecting the machining cost. The effect of drill types (uncoated and coated), drill diameters (Ø6, Ø8, Ø10 mm), and cutting parameters (feed rate and cutting speed) on deviation from circularity (ovality) is given in Fig. 5. The graphs in Fig. 5 showed that the most effective parameter on the circular deviation for drilled holes was the cutting speed. As an increase in drill diameter has very little effect on deviation from circularity, the circular deviation values obtained from coated tools compared to test results by uncoated tools were relatively less than impact on surface roughness and dimensional accuracy. According to Fig. 5, it was seen that the cutting parameters are more effective on the circular deviation rather than coating application and drill diameter. Circular deviation increased with increasing cutting speed and feed rate. As the cutting speed was increased from 20 to 40 m/min, the circular deviation also increased more than 100 %.

This situation was demonstrated that the cutting speed, which is the most effective parameter on tool life [19], is also the most important parameter on the circular deviation in drilling operations. When the effect of feed rate on circular deviation was evaluated, it can be generally said that as the feed rate was increased, the circular deviation also increased. Even though the effect of feed rate on circular deviation was not as high as cutting speed, the 100 % increase in feed rate caused an increase in circular deviation by 30–50 %. While the lowest circular deviation was measured as 0.0265 at the lowest cutting speed (20 m/min), lowest feed rate (0,05 mm/rev), and lowest drill diameter (6 mm coated tool), the highest circular deviation was measured as 0.1515 at the highest cutting speed (40 m/min), highest feed rate (0.15 mm/rev), highest drill diameter (10 mm uncoated tool). Especially when the graphs about circular deviation obtained by Ø10-mm tools were examined (Fig. 5e, f), some deviations were occurred at minimum feed rate (0.05 mm/rev) and cutting speed of 40 m/min. This case implied the risk of drilling operation in the low feed rate. It was thought that due to the higher chip volumes with increasing tool diameter, feed rate was inadequate, and so this situation by complicating the chip disposability was a negative effect on circular deviation. According to these results, the geometric precision of the holes, cutting speed, and feed rate were more effective parameters than drill diameter and coating application. When the circularity was important, it was recommended to select the cutting speed and feed rate parameters in lower values within the recommended range for the drilling operations.

### *3.2.3 Axial Misalignment (Cylindrical Deviation)*

In addition to the dimensional accuracy and circularity within the tolerances, the axial misalignment (cylindrical deviation) observed in drill length is an important parameter in terms of evaluating the geometrical precision of a hole. Especially for an application in which the hole depth/hole diameter (L/d) ratio is high, this criterion is more important. When the depth/diameter ratio of the tool is considered, the force components, especially the radial component of the force occurred during the drilling process, cause the deviation of drill from the drilling axis. The deviation from this axis makes a difference between the input and output axis, and affects negatively the geometrical precision in the cylindrical form of the hole. In this study, drilling depth was selected as 17 mm to ensure "$L < 3D$" condition (short hole). The effect of drill types (uncoated and coated), drill diameters (Ø6, Ø8, Ø10 mm), and cutting parameters (feed rate and cutting speed) on axial misalignment (cylindrical deviation) is given in Fig. 6.

When the graphs in Fig. 6 were evaluated, it was seen that the drilling diameter was an effective parameter on cylindrical deviation. Particularly, the holes drilled by uncoated tools have become more evident. The $L/D$ ratio for hole depth of 17 mm were calculated as 2.83 for Ø6 mm, 2.125 for Ø8 mm, and 1.7 for Ø10 mm. Because of increased moment caused by radial cutting forces, not only the deflection but also the axial misalignment was increased. Because the obtained values were very small, it was seen that they were not so different from each other. However, when they were associated with the drill diameter, they became more evident. Coating application like all other output parameters made a positive effect on the cylindrical deviation. Easier evacuation of the chip because of the low friction coefficient prevented the chip smearing between tool and surface and the growth of radial forces. As the cutting speed values were increased, the cylindrical deviation values also increased, but this increment was not linear. When cutting speed was increased from 20 to 30 m/min using uncoated tools, increment in cylindrical deviation was higher. On the other hand, when cutting speed was increased from 30 to 40 m/min, the increment in cylindrical deviation decreased. Unlike uncoated tools, as the cutting speed was increased from 30 to 40 m/min, the increment in the cylindrical deviation especially for Ø6 and Ø8 mm coated tools was much higher than the increment when the cutting speed was increased from 20 to 30 m/min. This case was referred to detaching the coating material in cutting edges of the tool in high cutting speeds. The increment in the feed rate affected the cylindrical deviation different from the cutting speed. The observed poor results obtained by uncoated tools at lower feed rate could be attributed to the additional radial loads created by jammed chip in the hole. The best results for all diameters of the uncoated tools were achieved for 0.1 mm/rev feed rate (medium level), and similarly, coated tools for Ø8 and Ø10 mm gave the best results in the mentioned feed rate. Better than feed rate of 0.1 mm/rev results on the cylindrical deviation was achieved only for 6-mm coated tools at the lowest feed rate of 0.05 mm/rev. Even though it was possible to generalize that axial misalignment increased with decreasing drill diameter, decreasing by using coated tools, it was recommended choosing the lower cutting speed and medium feed rate in order to avoid the cylindrical deviation.

### 3.3 Analysis of Variance (ANOVA)

Analysis of variance (also known ANOVA) is a statistical method that is used to identify the effect of control factors on the experimental results [21,22]. In the present work, ANOVA was used to determine the effect of feed rate, drill diameter, cutting speed and feed rate on the surface roughness, dimensional accuracy, circular deviation, and axial misalignment for both coated and uncoated tools. ANOVA results for uncoated drill and coated drill are given in Tables 3 and 4, respectively, for all responses. ANOVA was performed at confidence level by 95 % and significance level by 5 %. $F$ value of the control factors in ANOVA indicates the significance of control factors [22,23]. The percentage contribution of each parameter is shown in the last column of the ANOVA table. This column proves the influence rate of control factors on the experimental results. ANOVA results are also summarized as column chart in Fig. 7.

According to Table 3, the percent contributions of the factors such as drill diameter ($D$), feed rate ($f$), and cutting speed ($Vc$) on the surface roughness ($Ra$) were found to be 44.5, 20.1, 29.7, and 5.7 %, respectively. Therefore, most effective variable affecting the $Ra$ was drill diameter by 44.5 %. The percent contributions of the input parameters on the dimensional accuracy were by 20.2, 6.7, and 54.7 % for $D$, $f$, and $Vc$, and error became by 18.4 %. As a result of the assessment of circular deviation, the percentage contributions of factors were determined as 12.2, 15.1, and 58.9 %. According to this, the most effective parameter on dimensional accuracy and circular deviation was cutting speed. Moreover, the effect of control factors on the cylindrical deviation was obtained as 10.5, 47, and 25.6 %, and error became by 16.9 %. Therefore, this demonstrated that the most effective variable on cylindrical deviation was feed rate. ANOVA result for coated drill is shown in Table 4. According to Table 4, the most important parameter on the $Ra$ was drill diameter with percentage contribution by 58.9 %. The percent contributions of the input parameters ($D$, $f$, and $Vc$) on the dimensional accuracy were found to be 10.18, 17.1, and 57.2 %, respectively, and error became by 14.9 %. As a result of the assessment of circular deviation, the percentage contributions of factors were determined as 10.8, 17.7, and 59 %. Further, the effect of control factors on the cylindrical deviation was obtained as 25, 20.8, and 27.9 %,, and error became with percentage contribution by 26.6 %. According to these results, the most effective parameter was cutting speed on the dimensional accuracy, and circular deviation and cylindrical deviation with following contribution rates: 57.2, and 59 and 27.9 %, respectively.

### 3.4 Multi-objective Optimization with Desirability Function Analysis

Mono-response optimization is common and popular method to solve the problem for optimization approaches. However, this method cannot be effective to determine the optimal combination of process parameters for multi-output responses [24]. In this study, in order to overcome this problem, response surface methodology (RSM) based on desirability function was proposed for multi-response optimization in which to minimize simultaneously the surface roughness, deviation from diameter, circular cylindrical deviation was desired in drilling process. In the desirability function approach, the measured properties of each predicted response are converted into a dimensionless desirability value expressed as $d$ [25]. The scale of the desirability function ranges is between 0 and 1. If $d = 0$ or approaches to 0, then the response is clearly undesirable. If $d = 1$ or approaches to 1, then the response is perfectly of the target value. There are

**Table 3** Results of ANOVA for uncoated drill

| Variation in source | Degree of freedom (*DF*) | Sum of squares (SS) | Mean of squares (MS) | *F* ratio | *P* value | Contribution (%) |
|---|---|---|---|---|---|---|
| Surface roughness (*Ra*) | | | | | | |
| *D* | 2 | 0.31807 | 0.15904 | 78.42 | 0.000 | 44.5 |
| *f* | 2 | 0.14406 | 0.07203 | 35.52 | 0.000 | 20.1 |
| *Vc* | 2 | 0.21198 | 0.10599 | 52.26 | 0.000 | 29.7 |
| Error | 20 | 0.04056 | 0.00203 | | | 5.7 |
| Total | 26 | 0.71467 | | | | 100 |
| Dimensional accuracy | | | | | | |
| *D* | 2 | 0.0059315 | 0.0029658 | 10.99 | 0.001 | 20.2 |
| *f* | 2 | 0.0019627 | 0.0009814 | 3.64 | 0.045 | 6.7 |
| *Vc* | 2 | 0.0160446 | 0.0080223 | 29.73 | 0.000 | 54.7 |
| Error | 20 | 0.0053970 | 0.0002698 | | | 18.4 |
| Total | 26 | 0.0293358 | | | | 100 |
| Circular deviation | | | | | | |
| *D* | 2 | 0.0031703 | 0.0015851 | 8.81 | 0.002 | 12.2 |
| *f* | 2 | 0.0039356 | 0.0019678 | 10.94 | 0.001 | 15.1 |
| *Vc* | 2 | 0.0153799 | 0.0076899 | 42.76 | 0.000 | 58.9 |
| Error | 20 | 0.0035967 | 0.0001798 | | | 13.8 |
| Total | 26 | 0.0260825 | | | | 100 |
| Cylindrical deviation | | | | | | |
| *D* | 2 | 0.0012976 | 0.0006488 | 6.20 | 0.008 | 10.5 |
| *f* | 2 | 0.0058073 | 0.0029036 | 27.75 | 0.000 | 47 |
| *Vc* | 2 | 0.0031576 | 0.0015788 | 15.09 | 0.000 | 25.6 |
| Error | 20 | 0.0020925 | 0.0001046 | | | 16.9 |
| Total | 26 | 0.0123550 | | | | 100 |

three types of individual desirability functions: a) the larger the better, b) the smaller the better, and c) the nominal the better [26]. In this study, the desirability function was selected as the smaller the better because smaller the surface roughness, deviation from the diameter, the circular and the cylindrical deviation were desired in drilling process. The desirability function for a smaller-the-better case can be expressed as given in Eq. (1) [25]:

0

$$\begin{aligned} d_i &= 1 \quad if \quad y_i \le y_{\min} \\ d_i &= \left(\frac{y_i - y_{\max}}{y_{\min} - y_{\max}}\right)^r, \quad y_{\min} \le y_i \le y_{\max}, \quad r \ge 0 \qquad (1) \\ d_i &= 0 \quad if \quad y_i \ge y_{\max} \end{aligned}$$

where the $y_i$ is the found value of the $i$th output during optimization processes, the $y_{\min}$ and the $y_{\max}$ are the lower tolerance limit and the upper tolerance limit of the experimental data for the $i$th output, $r$ indicates the weight and is determined according to the requirement of the user. The individual desirability value of all the results can be combined with a single value called composite desirability ($d_{\mathrm{G}}$) with the help of the following equation Eq. (2) [25]:

$$d_G = \sqrt[w]{\left(d_1^{w_1} x d_2^{w_2} x d_3^{w_3} \ldots\ldots x d_i^{w_i}\right)} \qquad (2)$$

In Eq. (2), $d_i$ is the individual desirability for $i$th response; $w_i$ is the weight of the response; $w$ is the sum of the individual weights.

The higher composite desirability value means better product quality. Therefore, according to Eqs. (1) and (2), the parameter effect and optimum value were calculated on the basis of the composite desirability ($d_{\mathrm{G}}$) for each controllable parameter. The goal, lower value, target value, upper value, weight, and the importance of the factors are given in Table 5.

The multi-objective optimization was performed for a combination of goals. The goals apply to control factors and responses. The purpose of this study was to minimize simultaneously the surface roughness, deviation from the diameter, and circular and cylindrical deviation in drilling processes. The best global solution was achieved using the desirability-based approach. Highest desirability value is favored for the best solution. The best global solution was determined for the multi-response optimization as shown in Table 5. Further, Fig. 8 shows the plot of multi-response optimization.

**Table 4** Results of ANOVA for coated drill

| Variation in source | Degree of freedom ($DF$) | Sum of squares (SS) | Mean of squares (MS) | $F$ ratio | $P$ value | Contribution (%) |
|---|---|---|---|---|---|---|
| Surface roughness ($Ra$) | | | | | | |
| $D$ | 2 | 0.40612 | 0.20306 | 97.15 | 0.000 | 58.9 |
| $f$ | 2 | 0.11655 | 0.05827 | 27.88 | 0.000 | 16.9 |
| $Vc$ | 2 | 0.12452 | 0.06226 | 29.79 | 0.000 | 18.1 |
| Error | 20 | 0.04180 | 0.00209 | | | 6.1 |
| Total | 26 | 0.68899 | | | | 100 |
| Dimensional accuracy | | | | | | |
| $D$ | 2 | 0.0024027 | 0.0012014 | 7.30 | 0.004 | 10.8 |
| $f$ | 2 | 0.0037917 | 0.0018958 | 11.52 | 0.000 | 17.1 |
| $Vc$ | 2 | 0.0126803 | 0.0063402 | 38.52 | 0.000 | 57.2 |
| Error | 20 | 0.0032919 | 0.0001646 | | | 14.9 |
| Total | 26 | 0.0221667 | | | | 100 |
| Circular deviation | | | | | | |
| $D$ | 2 | 0.0022527 | 0.0011264 | 8.65 | 0.002 | 10.8 |
| $f$ | 2 | 0.0036981 | 0.0018490 | 14.20 | 0.000 | 17.7 |
| $Vc$ | 2 | 0.0123187 | 0.0061594 | 47.31 | 0.000 | 59 |
| Error | 20 | 0.0026041 | 0.0001302 | | | 12.5 |
| Total | 26 | 0.0208736 | | | | 100 |
| Cylindrical deviation | | | | | | |
| $D$ | 2 | 0.0010916 | 0.0005458 | 9.49 | 0.001 | 25 |
| $f$ | 2 | 0.0009096 | 0.0004548 | 7.91 | 0.003 | 20.8 |
| $Vc$ | 2 | 0.0012196 | 0.0006098 | 10.60 | 0.001 | 27.9 |
| Error | 20 | 0.0011500 | 0.0000575 | | | 26.3 |
| Total | 26 | 0.0043707 | | | | 100 |

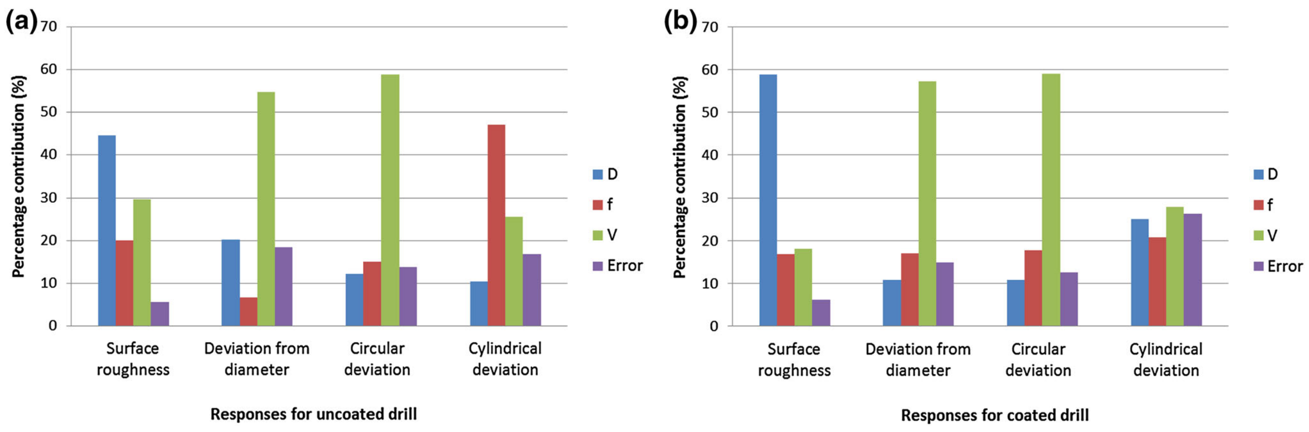

**Fig. 7** Histogram of the ANOVA results for **a** uncoated drill, **b** coated drill

According to Table 5 and Fig. 8, the best results were found to be 1.752 µm, 0.03551, 0.03938 mm, and 0.03300 for the surface roughness, deviation from the diameter, and circular and cylindrical deviation, respectively. Individual desirability values were 0.901788, 1, 0.900981, and 0.870250 as given in Table 5. Moreover, composite desirability value was 0.916993 for all responses. This result showed that composite desirability value was very close to 1. The levels of control parameters were found to be Ø6 coated drill, feed rate of 0.057 mm/rev, and cutting speed of 20 m/min for multi-response optimization in drilling of AISI 1050 steel.

**Table 5** Best global solutions for multi-optimization

| Response | Goal | Global solution (multi-optimization) | | | | Lower | Target | Upper | Weight | Import | Predicted | Desirability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Tool | *D* (mm) | *f* (mm/rev) | *V* (m/min) | | | | | | | |
| *Ra* | Min. | Coated | 6 | 0.057 | 20 | 1.686 | 1.686 | 2.358 | 1 | 1 | 1.7520 | 0.901788 |
| Deviation from dia. | Min. | Coated | 6 | 0.057 | 20 | 0.0365 | 0.0365 | 0.2032 | 1 | 1 | 0.03551 | 1 |
| Circular deviation | Min. | Coated | 6 | 0.057 | 20 | 0.0270 | 0.0270 | 0.152 | 1 | 1 | 0.03938 | 0.900981 |
| Cylindrical deviation | Min. | Coated | 6 | 0.057 | 20 | 0.0217 | 0.0217 | 0.1088 | 1 | 1 | 0.03300 | 0.870250 |

Composite desirability = 0.916993

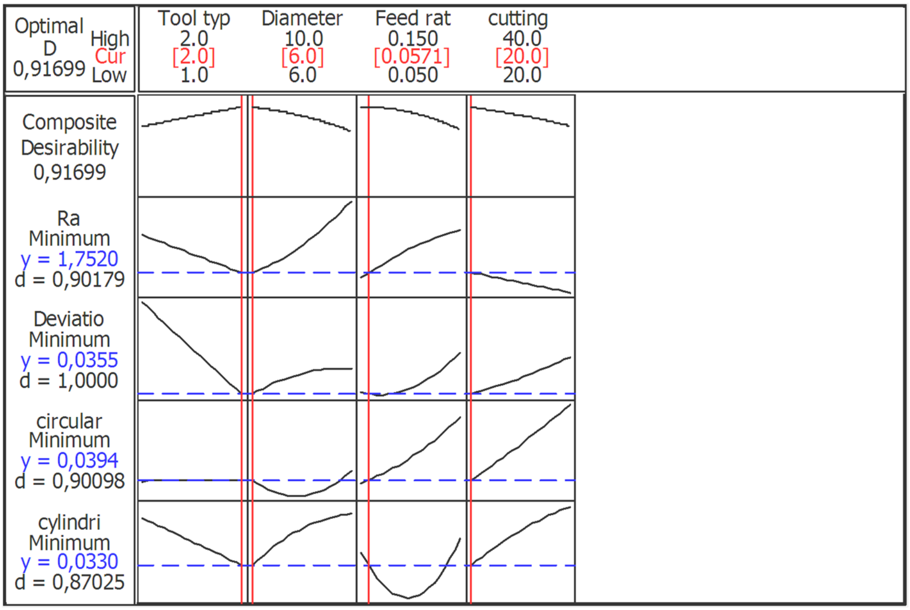

**Fig. 8** Plot of multi-response optimization

## 4 Conclusions

The results of this study can be summarized as follows:

- The most important result for coated tools compared with uncoated tools was better surface quality. While medium-fine surface quality was achieved by using coated tools at high cutting speed/medium feed rate combination, medium-rough surface quality was obtained at low cutting speed/high feed rate combination.
- It was recommended that the lower cutting speed, medium feed rate, and using the coated tools should be selected for dimensional accuracy.
- It can be said about the geometric precision of the holes the cutting speed and feed rate were more effective parameters than drill diameter and coating application. When the circularity was important, it was recommended to select the cutting speed and feed rate parameters in lower values within the recommended range for the drilling operations.
- Even though it was possible to generalize that axial misalignment increased with decreasing drill diameter, decreasing by using coated tools, it was recommended choosing the lower cutting speed and medium feed rate in order to avoid the cylindrical deviation.
- According to ANOVA results, while the most important parameter on surface roughness was drill diameter, the most effective parameter on dimensional accuracy, and circular and cylindrical deviations was cutting speed for both uncoated and coated tools except from cylindrical deviation occurring in uncoated drill.
- From the multi-response optimization results, the levels of control parameters were found to be Ø6 coated drill, feed rate of 0.057 mm/rev and cutting speed of 20 m/min for multi-response optimization in drilling of AISI 1050 steel. In drilling process, these levels of controllable parameters are recommended to obtain simultaneously the best results.

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