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Effect of cutting parameters on the dimensional accuracy and surface finish in the hard turning of MDN250 steel with cubic boron nitride tool, for developing a knowledged base expert system

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Abstract

In the machining operations, final surface finish and dimensional accuracy are the most specified customer requirements. Hard turning machining operation using cubic boron nitride tool as an alternative of grinding process is a type of turning operation in which hardened steel are machined with the hardness greater than 45 HRc. During the hard turning operation because of the hard condition, the variations of surface finish and dimensional accuracy are completely different from that of the traditional turning operation. Thus, the variation of surface finish and dimensional accuracy under various cutting parameters has been investigated in the hard turning with cubic boron nitride tools. The extracted knolwdge can be used for developing a knowledged base expert system. In order to have a comprehensive study, the variation of vibration, cutting forces, and tool wear has also been considered. The obtained results showed that depth of cut and spindle speed have the greatest effect on the dimensional accuracy, while feed rate is the most important factor affecting the surface roughness. The analysis of the vibration and tool wear proved that the flank wear has insignificant influence on the dimensional accuracy, whereas the vibration effect is considerable. The experimental results showed that when the feed rate is gradually increased from 0.08 to 0.32, the dimensional deviation first decreases unexpectedly until the lowest value is achieved at 0.16 mm/rev, then by further increasing the feed from 0.16 to 0.32 mm/rev, the dimensional deviation increases significantly. It was also seen that the best dimensional accuracy is achieved at the lowest level of the cutting depth, the medium level of the feed rate, and the spindle speed lower than its moderate level. The best surface roughness of 0.312 μm was obtained at 0.08 mm/rev feed rate, 0.5 mm depth of cut, 2000-rpm speed, and 1.2 mm insert nose radius, which is comparable with the surface finish obtained by the grinding operation.

Keywords: Cutting parameters, Surface finish, Dimensional accuracy, Expert system, Cutting force, Optimal condition, Hard turning

Introduction

Hard turning with cubic boron nitride (CBN) tools allows manufacturers to simplify their processes and still achieve the desired surface quality and accuracy (Lalwani et al. 2008; Yousefi et al. 2017; Zohoor and Yousefi 2018; Yousefi and Zohoor 2018; Thiele and Melkote 1999). Hard turning eliminates the additional heat treatment and grinding operations, and as a result, decreases lead-time, total production cost, and also improves the productivity and final quality. Consequently, substantial reduction in production cost and appropriate surface quality and accuracy can be achieved simultaneously. Hard turning in the dry condition causes the elimination of using environmentally high-risk lubricant (Saini et al. 2012; Sandvik Coromant 2010; Asiltürk and Akkuş 2011; Özel and Karpat 2005; Elbah et al. 2011).

Expert systems as an artificial intelligent system, are important tools in manufacturing and production systems. An expert system is a computer program that uses artificial

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intelligence technologies to simulate the behavior of a human that has expert knowledge and experience in a particular field. In this study, the final results of the experiments, as expert rules can be used for developing the knowledge base of a expert system. Cubic boron nitride (CBN) due to its high thermal shock resistance and hot hardness at elevated temperature is suitable for the turning of hardened steels with the hardness over 45 HRC (Yousefi and Zohoor 2018). The criteria like surface roughness, dimensional accuracy, cutting force, wear, and power consumed are usually used for the evaluation of the hard turning performance (Chavoshi and Tajdari 2010; Khrais and Lin 2007; Das et al. 2015; Aslan et al. 2007; Dhar et al. 2006; Dhar et al. 2007; Risbood et al. 2003; Dhar and Kamruzzaman 2007; Dhar et al. 2002; Shahabi and Ratnam 2010; Revel et al. 2016; Bartarya and Choudhury 2012). Nowadays, in metal cutting industries, special attention is paid to find the best-desired final surface quality and dimensional accuracy (Lalwani et al. 2008; Yousefi et al. 2017; Zohoor and Yousefi 2018; Yousefi and Zohoor 2018; Thiele and Melkote 1999; Saini et al. 2012).

The surface roughness (R_a) is an important factor that affects the properties of the machined component, like fatigue life, corrosion resistance, friction coefficient, wear resistance, and lubrication ability (Yousefi and Zohoor 2018). The dimensional accuracy is another important quality criterion, which significantly affects the machining cost and time. By selecting appropriate processing parameters, the dimensional accuracy improves, and therefore, the additional cutting pass is reduced. As a result, the machining cost and time will be reduced significantly. The factors, which have significant effect on the surface roughness and dimensional accuracy, can be categorized as workpiece properties, cutting tool geometry, cutting variables (i.e., cutting depth, cutting speed, and feed rate), and machine tool characteristics.

Among all of the mentioned factors, cutting depth, spindle speed, feed rate, and insert nose radius are the most effective controllable factors for the operator to achieve the desired surface roughness and dimensional accuracy during the turning operation (Zohoor and Yousefi 2018; Yousefi and Zohoor 2018; Thiele and Melkote 1999).

Despite the importance of dimensional accuracy in the dry hard turning, there are no any comprehensive studies in this field. In addition, the effect of vibration, cutting forces, and tool wear on the surface quality and dimensional accuracy in the hard turning using CBN is another important subject that should be studied for different hard steels.

Various research attempts have been performed for hard turning but none of them considered these issues simultaneously. Thiele and Melkote (1999) determined the effects of tool cutting edge geometry and workpiece hardness on the surface roughness and cutting forces in the finish hard turning of AISI 52100 steel. Cubic boron nitride inserts with various representative cutting edge preparations and through-hardened AISI 52100 steel bars were used as the cutting tools and workpiece material, respectively. Asiltürk and Akkuş (2011) determined the effect of cutting depth, feed rate, and cutting speed on the final surface of AISI 4140 with 51 HRc hardness. Their analysis showed that the feed rate is the most important factor that affects the R_a and R_z.

Özel and Karpat (2005) used neural network modeling to predict surface roughness and tool flank wear over the machining time for variety of cutting conditions in the finish hard turning of hardened AISI H-13 steel. Regression models were also developed to capture processing parameters.

Elbah et al. (2011) by using different ceramic inserts analyzed the surface roughness alteration for AISI 4140 with 60 HRC hardness. They found that for both conventional and wiper inserts, the quality of the machined surface is significantly affected by varying feed rate and cutting depth. They proposed the lowest feed rate and cutting depth and the highest spindle speed as the ideal combination to achieve a minimum surface roughness. In a similar research work, Chavoshi and Tajdari (2010) by using CBN inserts studied the effect of spindle speed and material hardness variations on the surface roughness of hardened AISI4140 steel. They found that the surface roughness variations strongly depend on the workpiece hardness, whereas speed has no critical effect. In addition, their results revealed that in the range of 35 to 55 HRC, increasing the workpiece hardness leads to increase in the surface finish, but further increase in the hardness deteriorates the surface finish. Some other researchers studied experimentally the variations of surface finish and tool wear during the hard turning of AISI4140 (Khrais and Lin 2007; Das et al. 2015; Aslan et al. 2007). Compared with the surface finish, the dimensional accuracy in the dry hard turning has been studied even more limited.

For example, Dhar et al. (2006; 2007) studied the influence of minimum quantity lubrication (MQL) on the dimensional accuracy and surface roughness of AISI4340 and AISI1040 steel during the conventional turning operation. In another research work, Risbood et al. (2003) demonstrated that the dimensional accuracy can be predicted accurately by measuring the cutting force and tool vibration. They proposed the neural network as an effective tool for the prediction of the dimensional deviation of carbon steel with 130 BHN hardness.

Some other researchers under cryogenic conditions studied the tool wear, dimensional accuracy, and surface roughness of alloy steel (Dhar and Kamruzzaman 2007; Dhar et al. 2002). They concluded that the cryogenic cooling by liquid nitrogen jets significantly decreases the tool wear, dimensional deviation, and surface roughness, compared to the dry and wet conventional turning. In addition, Shahabi and Ratnam (2010) used a machine vision approach to predict the surface roughness and dimensional accuracy in the conventional turning of AISI 304 stainless steel. They used 2D images of cutting tools to develop mathematical models for predicting the surface roughness and dimensional deviation.

In the hard turning process, due to the high workpiece hardness, small cutting depths is selected, and therefore, usually the cutting depth becomes lower than or equal to the insert nose radius, and the cutting zone is mainly limited within the tool nose area. Thus, unlike the traditional turning, the effect of the nose radius on the surface finish and dimensional accuracy becomes complicated. Thus, in this paper, the effect of processing parameters such as tool nose radius (r_ε), depth of cut (d), spindle/cutting speed (N/V), and feed rate (f) on the dimensional accuracy (Δd) and surface roughness (R_a) of hardened steel using CBN cutting tool is studied. Then, the influence of cutting forces, tool wear, and vibration is investigated on the surface finish and dimensional accuracy. Finally, the optimal combinations, which yield the best dimensional accuracy and surface finish, are proposed experimentally.

Methods/experimental

The experimental work was carried out on a CNC lathe (5.5 kW spindle power and 3500 rpm maximum rotational speed). Due to the importance of the dry machining in the modern industry, the tests were performed under the dry condition without any fluid, gas, and/or solid coolant. Standard CBN inserts (ISO code CNG A120404S010-30A, CNGA120408S010-30A, CNGA120 412S010-30A) made by Sandvik™ Coromant were used as the cutting tools with the following geometry: clearance angle = 0°, chamfer angle = 30°, chamfer width = 0.10 mm, edge thickness = 4.76 mm, edge length = 12 mm, and rhombic tip angle = 80°. The same inserts with different nose radius of 0.4 mm, 0.8 mm, and 1.2 mm were used for analysis of the nose radius effect. In order to have a stable cutting condition, each experiment was performed with a new sharp insert. The inserts grade was CB7025, which is completely suitable for hard turning operation. The tool holder used in the experiments was standard DCBNR/L-2525 M. According to the cutting tool manufacturer's recommendation, the inserts were clamped on the holder with the tightening torque of 3.9 Nm. Round bars of MDN250 steel with 35 mm diameter and 85 mm length were used for the experiments. In order to increase the hardness of the steel, according to the ASM International standard, the round bars have been heated at about 850 °C for 75 min, and then quickly quenched in the water (Dossett and Boyer 2006). Subsequent aging was performed for approximately 3 h at a temperature of 500 °C to produce a fine dispersion of $Ni_3(X,Y)$ intermetallic phases along the dislocations left by martensitic transformation, where X and Y are solute elements added for such precipitation. A pre-cut with 0.5 mm cutting depth was performed before hardening the steel to remove the rusts and oxide layers from the surface of the workpiece. Finally, the hardness level of 55 HRC was obtained by performing the heat treatment method for the round bars of MDN250 steel. Average surface roughness (R_a) values were recorded with a Surftest 301 Mitutoyo® roughness meter set to a cut-off of 0.8 mm. The surface roughness values were measured at five equally spaced locations along the cutting length. The average of this five roughness values was taken as the arithmetic surface roughness value (R_a). This measuring process was repeated three times for each test and their average was considered as the final surface roughness. A piezoelectric type vibration meter was used to measure and recorded the acceleration of the radial holder vibration. Three forces component, i.e., feed force, cutting force, and radial force, was measured precisely by using a Kistler piezoelectric turning dynamometer and a signal amplifier connected to a control unit, data acquisition board and microcomputer. The maximum flank wear (VB_{max}) was measured using a TM505 Mitutoyo® toolmaker's microscope with 1 μm resolution. The dimensional accuracy, which is defined as the difference between the desired cutting depth and the obtained depth of cut, was determined by measuring the final dimensional deviation. The diameter deviation was measured using a precision dial gauge with an accuracy of ± 0.01 mm. Diameter deviation was measured at five equally spaced points along the cutting length and the average of these five values considered as the final dimensional deviation value. In this paper, insert nose radius, feed rate, cutting depth, and speed were considered as the processing parameters. The values of the variables were chosen according to the recommendation of the cutting tool catalogs. In order to conduct a comprehensive study, the cutting depth and feed speed with a wider range were selected compared with the ranges chosen by the previous researchers in the hard turning operation. Furthermore, to increase the confidence level of the results, all the measurements were repeated three times for each test.

Results and discussions

According to the experimental results, it was observed that the feed rate with a 60% contribution is the most important factor affecting the surface roughness. The next important factor influencing the surface roughness is the insert nose radius with a 28% contribution. Compared to the feed and nose radius effect, the cutting depth and the spindle speed effect is insignificant. On the other hand, the cutting depth with 50% contribution has a critical effect on the dimensional accuracy, while the nose radius has insignificant influence. The spindle speed is the next important factor affecting the final dimensional accuracy.

The effect of insert nose radius

Nose radius with 28% contribution is the second important factor after the feed rate that affects the surface roughness. Small nose radius has low strength but reduces the vibration, and it is ideal for small cutting depths and where the length-to-diameter ratio is high. On the other hand, large nose radius, due to its stronger cutting edge, used at larger cutting depths and higher feed rates, but on the other hand, leads to higher radial forces and vibration compared with small nose radii (Sandvik Coromant 2010). Cutting zone in the hard turning process is mainly limited within the tool nose area because usually the cutting depth is chosen lower than or equal to the nose radius. As a result, the insert nose is exposed to severe pressure and temperature, which finally results in serious wear or even occurring sudden fracture. Therefore, the effect of the nose radius on the surface roughness and dimensional accuracy becomes more complicated, compare to the traditional turning operation. As shown in Fig. 1a, by increasing the nose radius, the surface roughness improves significantly. In all experiments, 0.4 mm nose radius yields the worst surface finish. This can be attributed to the low strength of the insert nose. It was also seen that the highest tool wear occurs at 0.4 mm nose radius. Furthermore, the relatively short contact length between the insert tip and the workpiece results in the lower heat dissipation from the shear zone, which finally cause higher stress and heat concentration in the zone. Thus, the possibility of the tool wear or even the thermoplastic deformation of the nose area is increased. When the nose radius is increased from 0.4 to 1.2 mm, the surface roughness improves about 45%. This is related to the reduction of the flank wear at the larger nose radius, as seen in Fig. 2a. The results reveal that at 0.08 mm/rev feed rate, the surface roughness becomes less sensitive to the changes in the nose radius. It is interesting to note that under different cutting conditions, $r_\varepsilon = 1.2$ mm leads to a more acceptable surface roughness, compared with the 0.8 mm nose radius. Figure 2a completely confirms this matter because the lowest flank wear is seen at 1.2 mm nose radius. It was also observed that the best surface roughness of 0.312 μm was obtained using 1.2 mm nose radius.

The analysis of the experimental results showed that the nose radius effect on the dimensional accuracy is neglect. As shown in Fig. 1b, the lowest dimensional deviation is obtained at 0.4 mm and 0.8 mm nose radii respectively. The highest dimensional accuracy is produced at the lowest level of the nose radius (i.e., 0.4 mm). As shown in Fig. 2b, by increasing the nose radius, the vibration is increased. By increasing the nose radius from 1.2 to 0.4 mm, the tool wear is exacerbated, but the dimensional accuracy is improved due to the lower generated vibration. Therefore, it can be said that at the dry hard turning operation, the insert flank wear increases by decreasing the nose radius, but the dimensional accuracy improves significantly. The lower dimensional accuracy at the larger nose radius can be related to the higher radial force and vibration, which enhance because of the larger contact area between the cutting tool and the workpiece surface.

The effect of spindle speed

The surface roughness variations under various cutting conditions are illustrated in Fig. 3. According to Fig. 3, increasing the spindle speed from 500 to 2000 rpm leads to the linearly decreasing of the surface roughness. This behavior is related to the decreasing of the cutting forces at higher cutting speeds. Perhaps, Fig. 4 supports this observation. As depicted in Fig. 4, due to the thermal softening of the workpiece, increasing the cutting speed leads to the cutting forces reduction. Hence, the highest spindle speed produces the best surface roughness. However, different results were reported for ceramic and coated carbide inserts. Researcher reported that, by increasing the cutting speed, the surface roughness decreases until the lowest value is obtained (first zone), then by a further increase in the cutting speed, the surface roughness increases with a high slope (second zone) (Asiltürk and Akkuş 2011; Das et al. 2015). Researchers have attributed this behavior to the restriction of the built-up edge formation (BUE) in the first zone and also increase in the machine vibration in the second zone. It was also seen that the surface roughness is improved about 45% when the spindle speed increases about 400%. The effect of the speed on the dimensional accuracy is shown in Fig. 5a. When the speed is increased gradually from 500 to 2000 rpm, the dimensional accuracy deteriorates significantly. This degradation is related to the higher tool vibration at the higher spindle speeds. The vibration variations under different machining conditions are depicted in Fig. 5b. As illustrated in Fig. 5b, increasing the spindle speed causes a higher tool vibration. As a result, this higher tool vibration deteriorates the dimensional accuracy. Furthermore, at higher spindle speeds, especially in the dry condition, due to the higher temperature in the cutting zone, thermal expansion of the workpiece becomes more serious. As a result, the material thermal expansion can be another negative factor affecting the dimensional accuracy in the dry hard turning operation. According to the results, the best dimensional accuracy is obtained at 500 rpm, while the best surface quality was achieved at 2000 rpm. It can be concluded that the spindle speed has a contradictory effect on the surface quality and dimensional accuracy. This effect has to be considered in the cases where a high dimensional accuracy is required along with great surface finish.

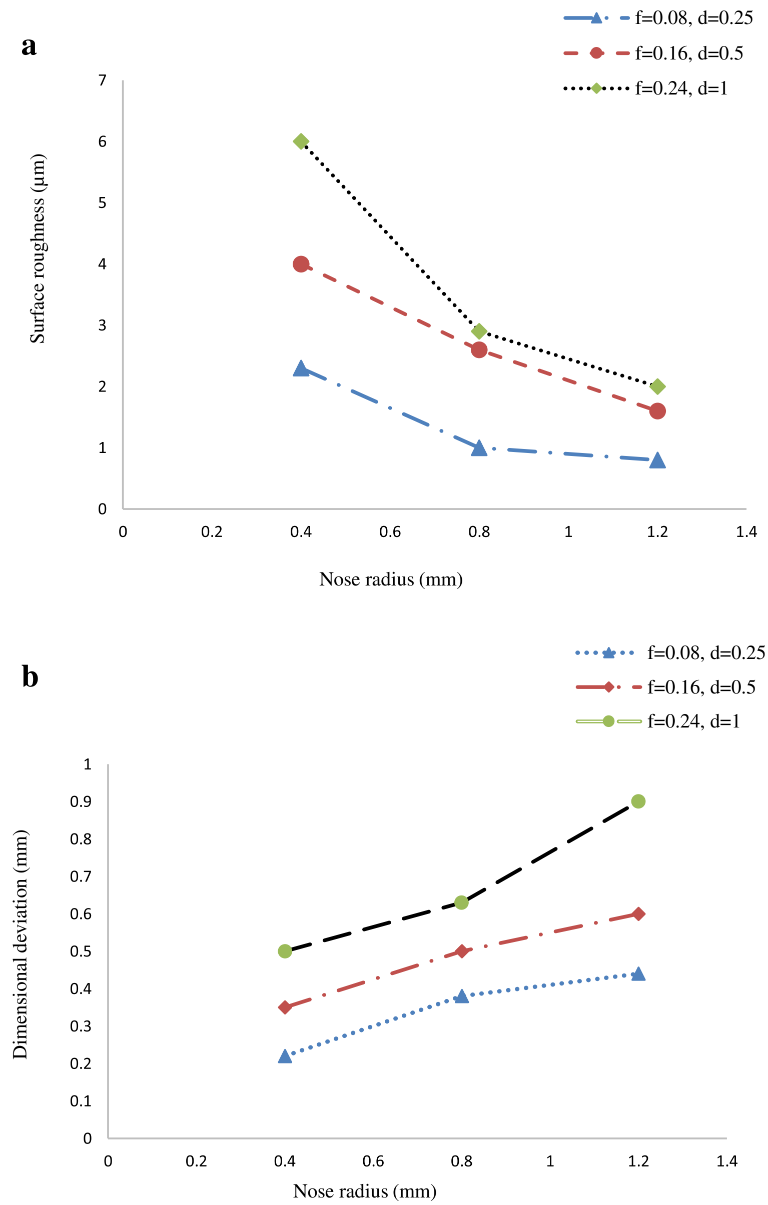

Fig. 1 a The insert nose radius effect on the surface roughness. **b** The effect of the insert nose radius on the dimensional deviation under different cutting conditions

The effect of feed rate

As discussed before, the feed rate with 60% contribution is the most important factor affecting the surface roughness. The experimental results reveal that when the feed rate increases from 0.08 to 0.32 mm/rev, the surface roughness average increases from 1.6 to 6.6 μm. This behavior is due to helicoid furrows, which generated because of the tool-workpiece surface relative displacement. As the feed rate increases, the furrows become wider and deeper and subsequently increase the surface roughness. The cutting forces analysis showed that by increasing the feed rate, all the cutting force elements increase significantly (see Fig. 6a). The cutting force increases by increasing the feed rate to create the required plastic deformation and hence, extra heat is produced in the cutting area. This extra heat increases the tool wear, and this finally leads to the surface finish degradation. As shown in Fig. 6b, when the feed rate increases, the tool wear is increased and the surface roughness is increased consequently. It was seen that the highest flank wear was observed at the highest feed rate. The results showed that for any level of the cutting depth, spindle speed, and nose radius, the best R_a is achieved at the lowest level of the feed rate.

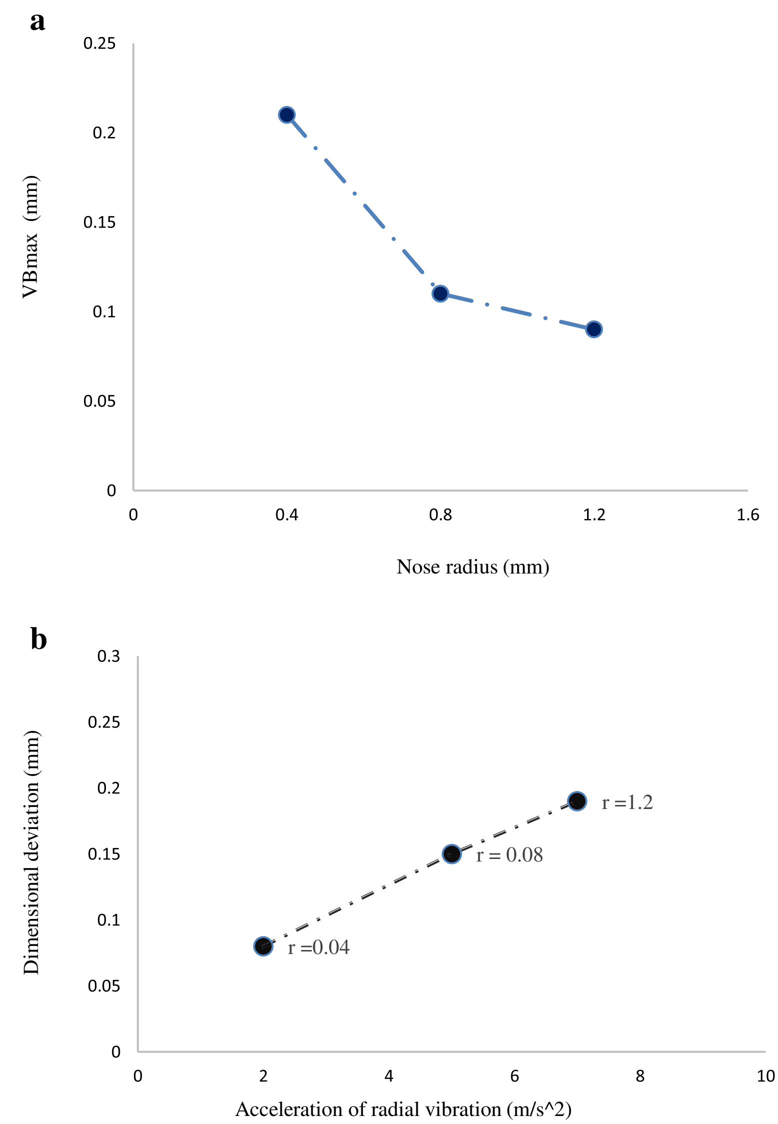

Fig. 2 a The nose radius effect on the maximum flank wear. **b** The effect of the nose radius on the vibration at 0.08 mm/rev feed rate, 0.5 mm cutting depth, and 1000-rpm speed

It is also interesting to note that at 0.4 mm nose radius, when the feed rate increases from 0.16 to 0.32 mm/rev, the average of the surface roughness is decreased from 8.32 to 6.93 μm, while at other nose radii, there is no such complicated behavior. As a result, it can be said that the effect of the feed rate on the variations of the surface roughness, especially at high-level feed rates, strongly depends on the insert nose radius.

Most of the researchers reported that by increasing the feed rate within the range of 0.04 mm/rev to 0.4 mm/rev, the surface finish is decreased significantly.

However, in the this research work, the obtained results showed that increasing the feed rate from a particular value not only leads to no significant changes in the surface roughness value but in some cases improves the surface roughness. This subject is important, especially in situations, where the total operation time or the total cost is more vital than the surface finish.

It is well known that strain hardening and thermal softening are two important factors affecting the surface quality. These two conflicting factors act completely opposite to each other. Strain hardening increases the hardness of the workpiece and the thermal softening reduces the workpiece hardness. At the feed rate relatively higher than 0.16 mm/rev, due to higher forces (see Fig. 6a), extra heat is produced in the cutting zone, compared with the lower feed rates. This extra heat leads to thermal softening of the workpiece material. On the other hand, CBN tools have an excellent hot hardness and the produced heat overcomes the strain hardening effects of the

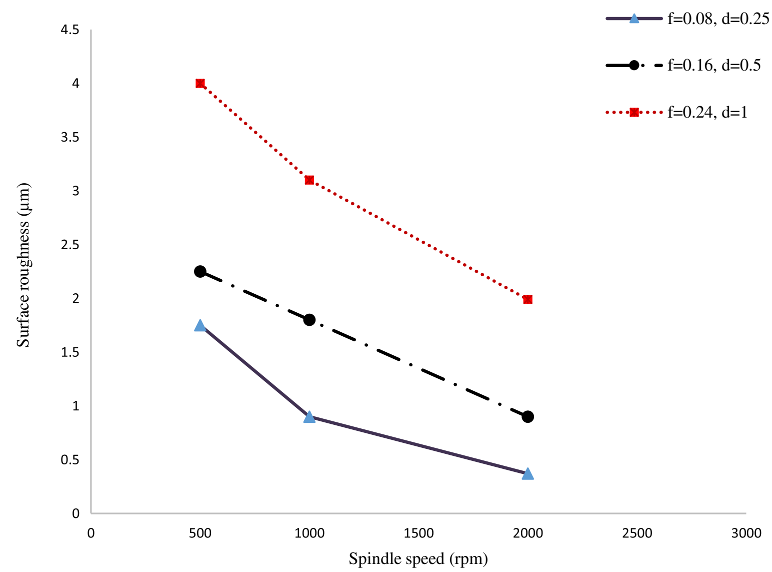

Fig. 3 The spindle speed effect on the surface roughness under different machining conditions

workpiece material and decreases its hardness and shear strength, especially at the interface of the workpiece and tool. Thus, the thermal softening of the workpiece material reduces the tool wear rate and therefore, the surface roughness is not increased.

As depicted in Fig. 7, the effect of the feed rate on the dimensional accuracy is completely different from that of surface roughness. When the feed rate is gradually increased from 0.08 to 0.32, the dimensional accuracy first increases unexpectedly until the best value is achieved at 0.16 mm/rev, then by further increasing the feed rate from 0.16 to 0.32 mm/rev, the dimensional accuracy decreases significantly. Some other researchers reported this unexpected improvement of the dimensional accuracy in the conventional turning operation when the feed rate increases up to a certain value. It seems that at very low feed rates (e.g., 0.08 mm/rev), the tool instead of cutting the chips by shearing action simply rides over and burnishes the machining surface and increases the dimensional deviation. On the other hand, as the feed rate gradually increases up to a certain value (e.g., 0.16 mm/rev), the chip removal action is improved and the dimensional accuracy is improved subsequently. At the higher feed rates (e.g., 0.32 mm/rev),

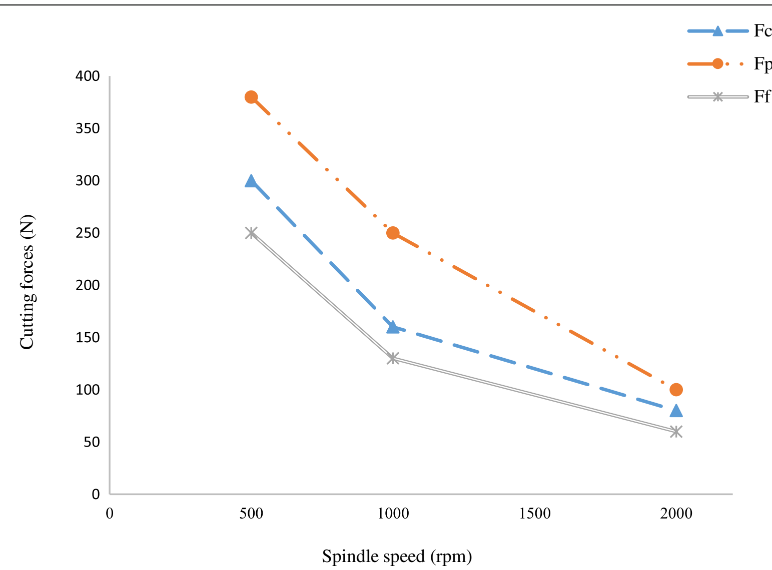

Fig. 4 The effect of the spindle speed on the cutting forces at 0.16 mm/rev feed rate, 0.5 mm cutting depth, and 0.8 mm nose radius

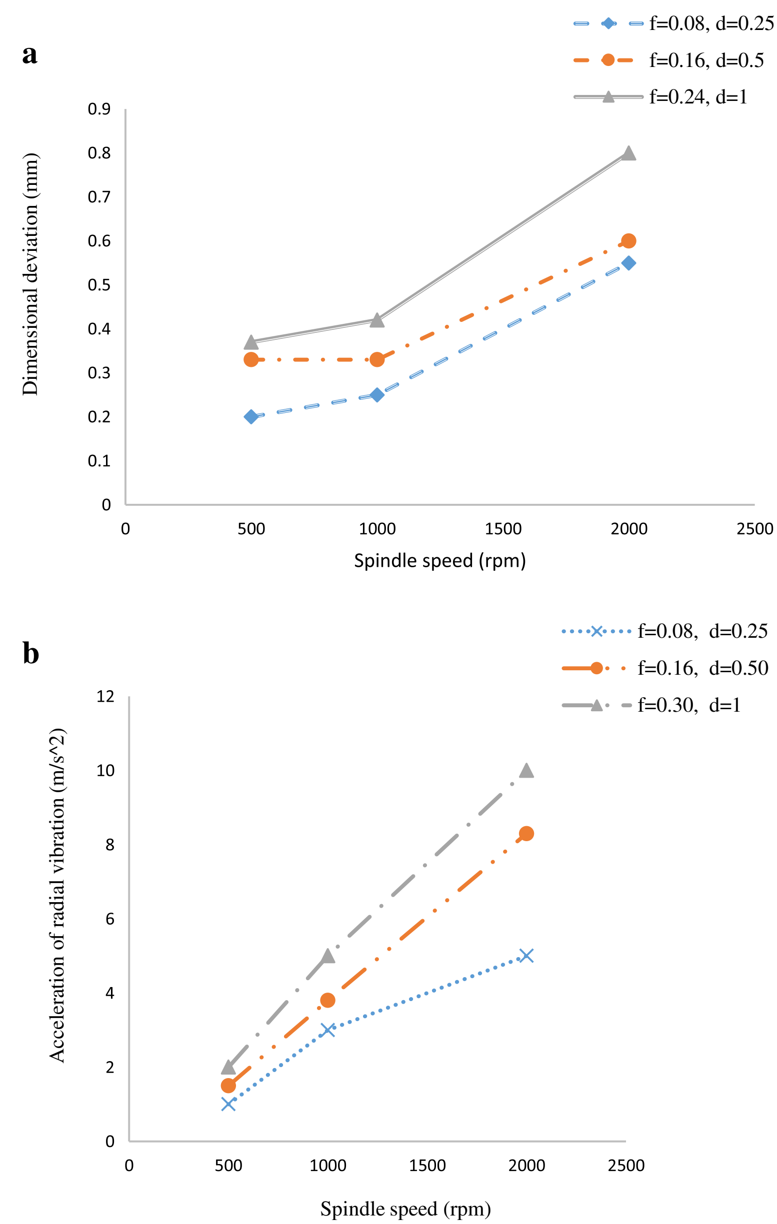

Fig. 5 a) The effect of the spindle speed on the dimensional deviation and **b**) the effect of the spindle speed on machining

the feed rate negative effects become dominant and start worsening the dimensional accuracy. The obtained results showed that almost in all cases, the moderate level of the feed rate (i.e., 0.16 mm/rev) results in the best dimensional accuracy (i.e., lowest dimensional deviation).

The effect of cutting depth (*d*)

As explained earlier, the impact of cutting depth on the surface roughness is insignificant. Some other researchers reported similar result by using carbide and ceramic tools (Asiltürk and Akkuş 2011; Das et al. 2015; Aslan et al. 2007). On the other hand, M. Elbah et al. (2011) claimed that for the wiper ceramic tools, the influence of the cutting depth on the surface roughness is considerable. The obtained results show that the surface roughness is decreased about 9% by increasing the cutting depth to 2 mm. Further increasing the cutting depth to about 3 mm leads to the surface roughness deterioration. This surface roughness deterioration is mainly due to the chatter phenomenon, which occurs at the high level of the cutting depths. According to the results, 0.312 μm is the best-obtained surface roughness that has been achieved with 0.5 mm cutting depth, 2000 rpm speed, 0.08 mm/rev feed rate, and 1.2 mm nose radius. This low surface roughness is comparable with the surface

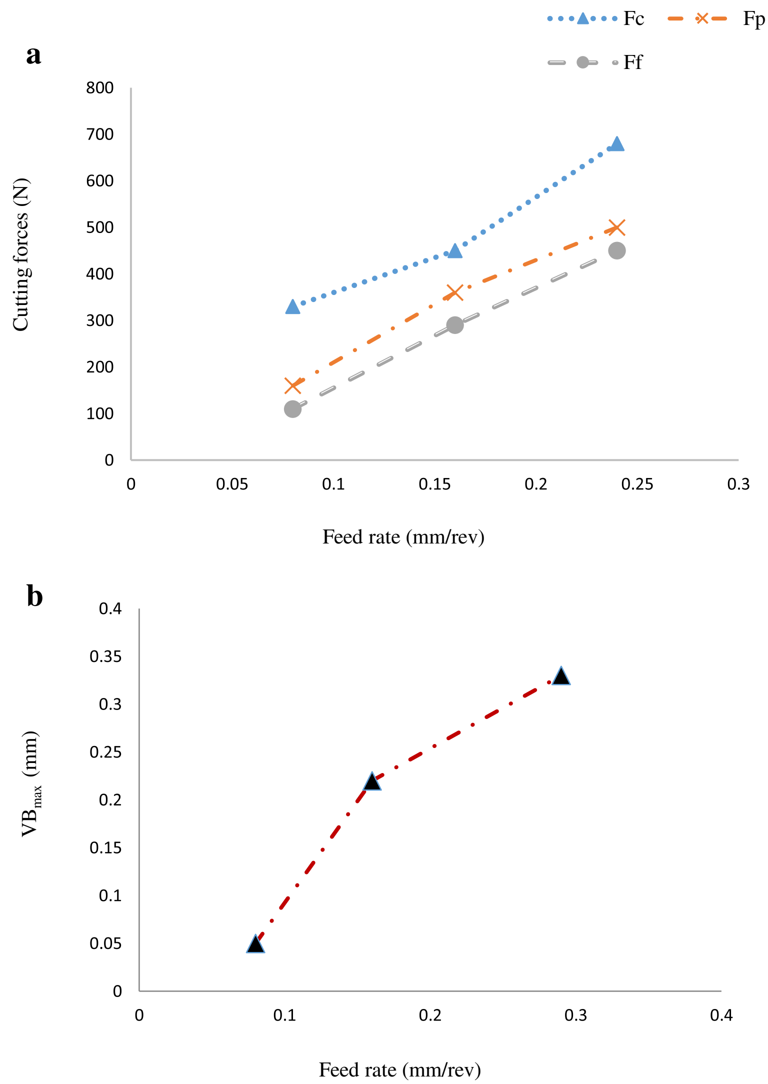

Fig. 6 a The effect of feed rate on the cutting forces and **b** the effect of feed rate on the maximum flank wear at 0.8 mm nose radius, 0.5 mm cutting depth, and 1000 rpm spindle speed

finish that is obtained under the conventional grinding operation. The cutting depth in the range of 0.05 to 0.3 mm is proposed by most researchers for the finish hard turning operation (Revel et al. 2016; Bartarya and Choudhury 2012). However, the obtained results showed that by using the CBN tools, a better surface finish can be achieved at higher cutting depths compared to the ceramic and carbide tools. Therefore, by using CBN inserts during the finish hard turning, the total cost and the operational time both will improve simultaneously.

The cutting depth effect on the dimensional accuracy is completely different from that of the surface roughness. It was observed that among all the processing parameters, the cutting depth has the greatest effect on the dimensional accuracy. As shown in Fig. 8, by increasing the cutting depth, the dimensional accuracy decreases drastically. The experiments also reveal that the best dimensional accuracy is always achieved at the lowest cutting depth (i.e., 0.5 mm). This is related to the lower generated vibration at the low cutting depth, which leads to the dimensional accuracy improvement. On the other hand, when the cutting depth increases, the machining vibration is increased and, as a result, the surface roughness is increased. These surface roughness and dimensional accuracy variations have to be considered in the final pass of the finish hard turning.

In order to find the optimal machining condition, the contour and 3D surface plots analysis are used. The results of the contour and 3D surface plots analysis are illustrated in Figs. 9 and 10. As it is obvious in Fig. 9, a good surface roughness can be achieved for any level of

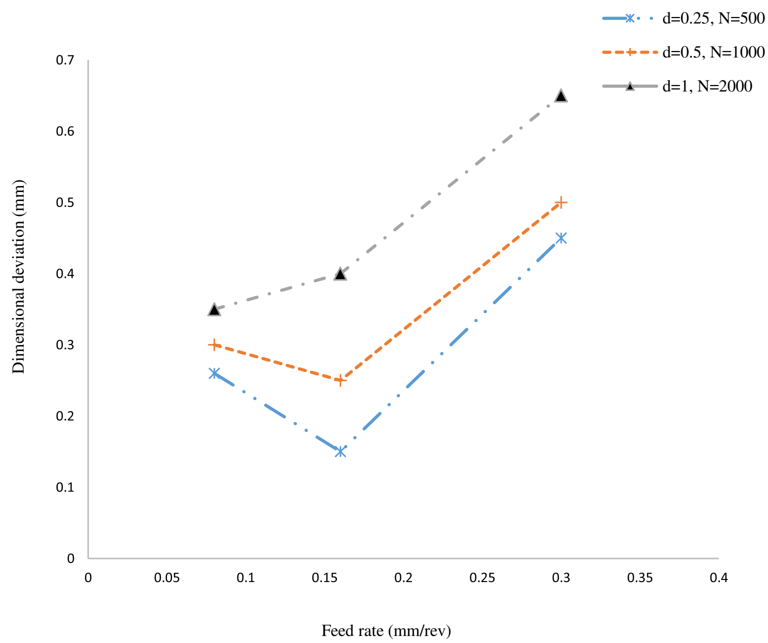

Fig. 7 The effect of feed rate on the dimensional deviation

the cutting depth, when the spindle speed is higher than 750 rpm and the feed rate is lower than 0.15 mm/rev. From Fig. 9, it can be observed that the worst values of the surface roughness are obtained at the lowest level of the spindle speed and nose radius. For any level of the nose radius, in the area limited to the lowest level of the feed rate, always the best surface finish is obtained. For the insert nose radius larger than 0.8 mm, this zone is wider than that of the smaller nose radius. Hence, a higher feed rate can be proposed with a larger nose radius, which can yield both a high good surface finish and material removal rate.

According to Fig. 9, by applying the medium level of the cutting depth, a desirable surface roughness is achieved. The analysis reveals that a proper surface finish is achieved when the spindle speed and nose radius are higher than their moderate level. From the above discussion, it can be concluded that the highest level of the spindle speed and nose radius, the moderate level of the cutting depth, and the lowest level of the feed

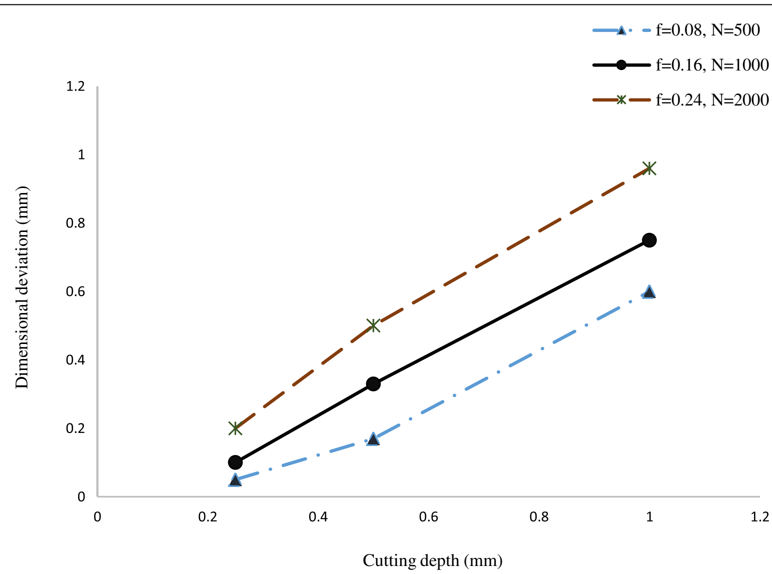

Fig. 8 The variations of the dimensional deviation at different depth of cuts

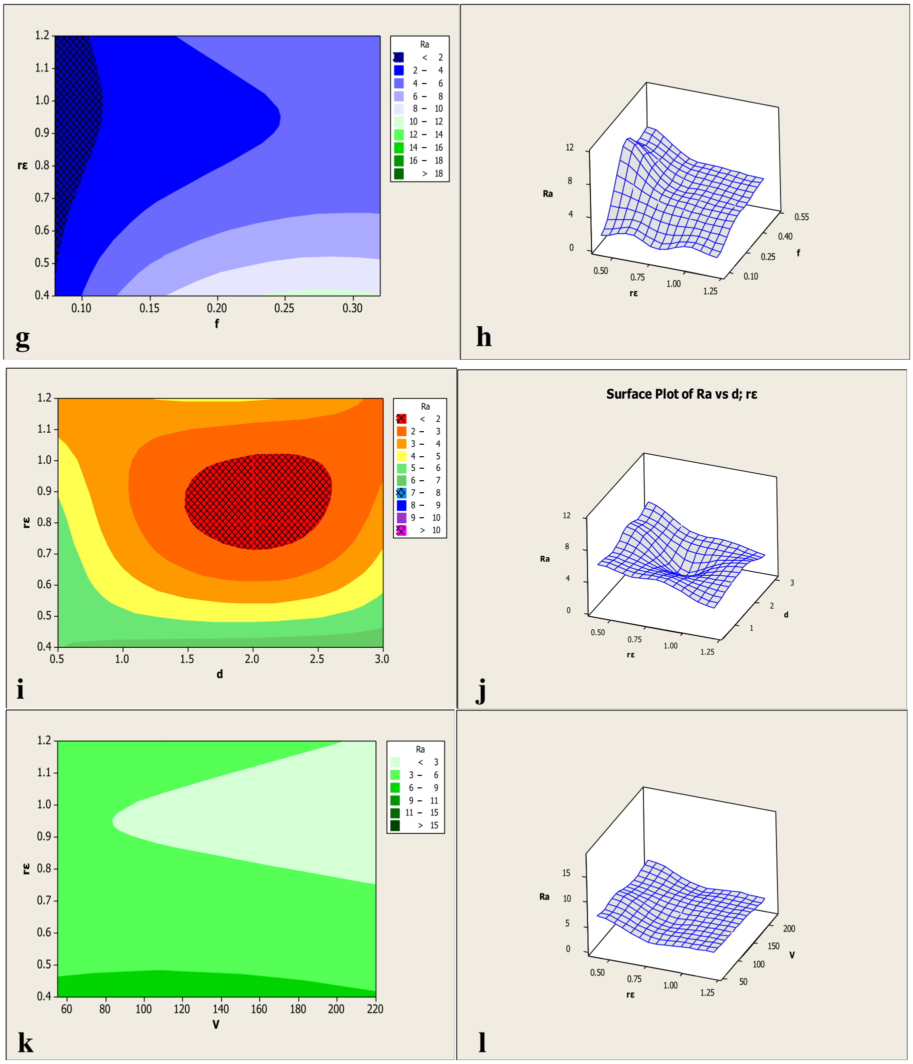

Fig. 9 Contour and 3D surface plots for the surface roughness (R_a) variations

rate is an ideal combination to achieve an acceptable surface roughness in the finish hard turning operation.

Figure 10 shows the dimensional accuracy variations under the various combinations of the processing parameters. The best dimensional accuracy is achieved when the dimensional deviation is equal to zero (i.e., $\Delta d = 0$). As depicted in Fig. 10a b, a high dimensional accuracy is obtained at the lowest level of the spindle speed and nose radius. In addition, as shown in Fig. 10c, d, the spindle speed between 700 and 1200 rpm along with the feed rate lower than 0.15 mm/rev is an ideal combination to achieve a high dimensional accuracy. It can be seen from Fig. 10g–j that for any level of the feed rate and spindle speed, the best dimensional accuracy is achieved at the cutting depth lower than 1.5 mm. According to the experimental results, 0.5 mm cutting depth, 0.8 mm nose radius, 0.16 mm/rev feed rate, and the speed lower than 1100 rpm provide the best dimensional accuracy. Therefore, it can be concluded that the lowest cutting depth level, the moderate feed rate, and nose radius level and the lowest level of the spindle speed always produce the best dimensional accuracy during the hard turning operation.

Conclusions

The impact of the cutting parameters on the surface roughness and dimensional accuracy of hardened steel with CBN cutting tools was studied experimentally. In order to perform a comprehensive study on the dimensional accuracy and surface roughness, the variation of vibration, cutting forces, and tool wear under various cutting condition was investigated. The obtained results showed that feed rate is the most important factor affecting the surface roughness, while cutting depth and

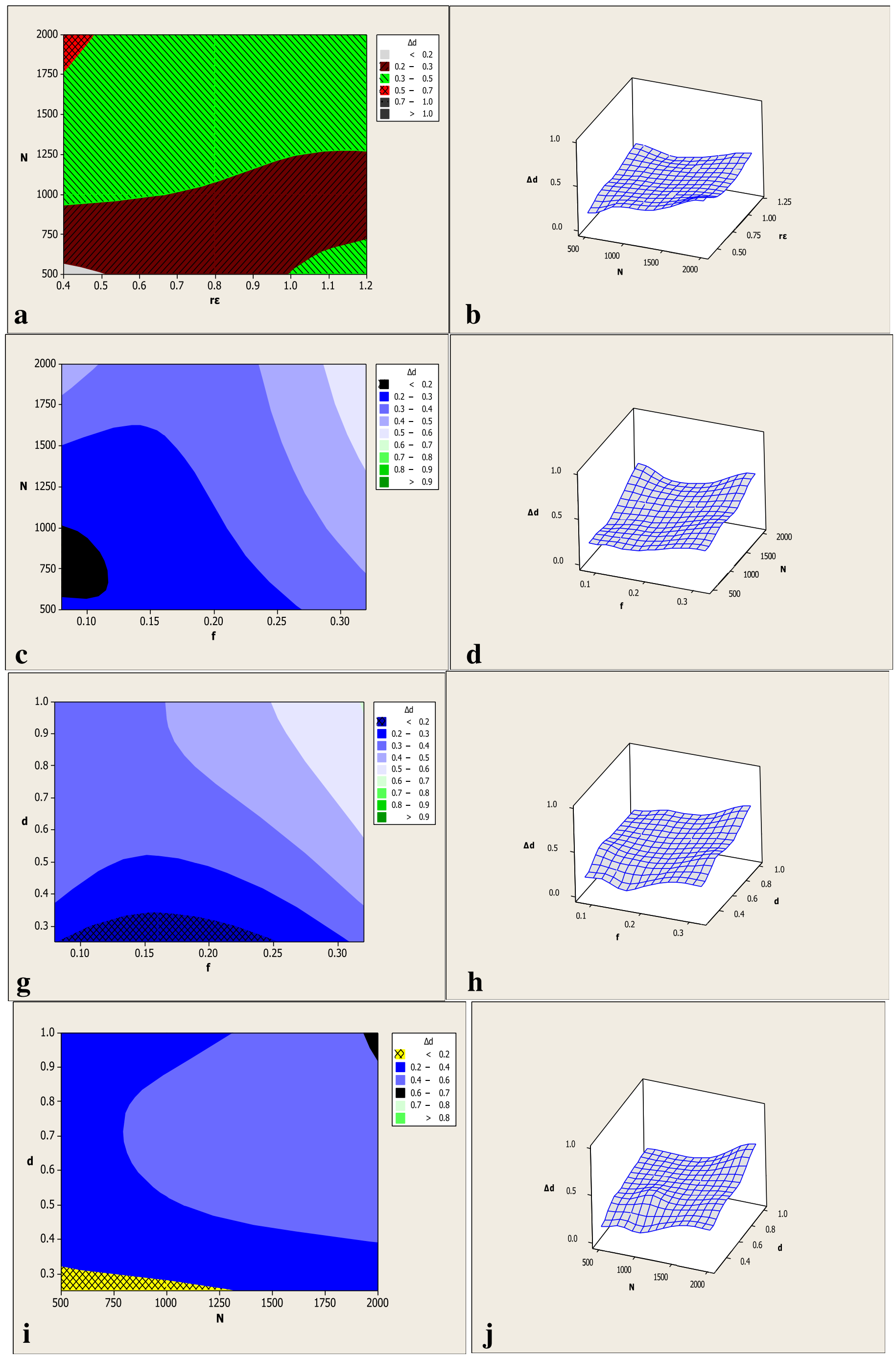

Fig. 10 Contour and 3D surface plots for the dimensional deviation (Δd) variations

spindle speed has no considerable effect on the surface roughness. On the other hand, the effect of cutting depth and spindle speed on the dimensional accuracy is significant, whereas nose radius has no considerable effect on the dimensional accuracy. The tool wear and vibration analysis showed that the effect of vibration on the dimensional accuracy is considerable compared with the tool wear effect on the dimensional accuracy. It was also observed that by increasing the feed rate from a particular value, the surface roughness not only has no significant changes, but in some cases, the surface roughness decreases significantly. The best surface roughness of 0.312 μm was obtained at the nose radius of 1.2 mm, the spindle speed of 2000 rpm, the feed rate of 0.08 mm/rev, and 0.5 mm cutting depth, which is comparable with that obtained by the grinding operation. According to the experimental results, 0.5 mm cutting depth, 0.16 mm/rev feed rate, and the speed lower than 1100 rpm produced the best dimensional accuracy. The highest level of the nose radius and spindle speed, the moderate level of the cutting depth, along with the lowest level of the feed rate is an ideal combination, which yields the best surface roughness for the finish hard turning operation. It was also concluded that by using the CBN cutting tools, a better surface roughness at both higher cutting speed and cutting depth can be achieved compared with the ceramic and carbide tools. Furthermore, by using CBN cutting tools in the finish hard turning, higher cutting depths can be used compared with the proposed range of 0.1–0.3 mm for other cutting tools. All of these obtained results can be used for developing aknowledged base expert system.

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Availability of data and materials
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions
SY and MZ conceived of the presented idea, developed the theory, and performed the computations. They also verified the analytical methods. All authors discussed the results and contributed to the final manuscript. Both authors read and approved the final manuscript.

Competing interests
The newness/scientific contributions of the work can be summarized as follows:
1- The effect of processing parameters on the variations of dimensional accuracy in dry hard turning operation (especially for hardened MDN250) has been studied for the first time.
2- The relationship between tool wear, cutting forces, and vibration and also their effects on the dimensional accuracy have been studied for the first time in dry hard turning operation.
3- Reported obtained surface roughness of 0.312 μμm, as super-finishing, has not been reported until now during hard turning operation. This research work has industrial application for machinist and machining researchers. In addition, due to the importance of hardened MDN250 μ machining in the automotive, and aerospace industries, the obtained results are completely valuable for engineers and process planers.

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