



# Experimental investigation of the effect of processing parameters on the surface roughness operation for using as expert system database

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## Abstract

In this paper, the effect of processing parameters including feed rate ( $f$ ), cutting depth ( $d$ ), nose radius ( $r_e$ ), cutting speed ( $V$ ) and also cooling condition such as dry condition, wet condition, and minimum quantity lubrication, on the surface quality of copper, as a low machinability material, was investigated. It was observed that the best surface quality and the lowest tool wear are achieved by minimum quantity lubrication, and the highest tool wear and the lowest surface quality are obtained under dry machining. However, there are no significant differences in surface quality and tool wear under dry machining when compared to minimum quantity lubrication and wet machining. Therefore, due to cost and environmental considerations, dry machining is recommended for turning commercially pure copper. According to the results, feed rate and nose radius are the most important factors affecting the surface roughness, respectively. At low feed rate, 1.2 mm nose radius is a good option to achieve the best surface roughness. Besides, at high feed rate, 0.8 mm nose radius is recommended. To achieve an acceptable surface roughness with suitable material removal rate, the combination of the lowest feed rate and the highest cutting speed, along with the moderate cutting depth and nose radius is suggested. The best surface roughness of 0.381  $\mu\text{m}$  has been achieved at  $r_e = 1.2$  mm,  $V = 220$  m/min,  $d = 0.5$  mm, and  $f = 0.08$  mm/rev, which is comparable with the surface quality obtained by the conventional grinding operation. The results also revealed that the existed empirical model can predict the surface roughness only at high feed rate and low cutting speed, and therefore, it cannot be recommended for predicting the surface finish of the materials with low machinability. Hence, a full quadratic model was developed for the prediction of the surface roughness, which can be used for the database of expert systems.

**Keywords** Surface roughness · Commercially pure copper · Dry turning · Empirical model for expert systems · Minimum quantity lubrication · Low machinability materials

## 1 Introduction

Machining is an important manufacturing process to produce products with high quality and low cost. Most shaped products, which are formed by castings, forgings, etc., need machining as the final shaping operation. In general, in the machining process, there are several cooling conditions which can be categorized as conventional wet (flooding)

condition, dry condition, and minimum quantity lubrication/near dry machining. Among these different techniques available in the machining processes, researches recently, have been more focused on minimum quantity lubrication (MQL) and dry condition, due to the reduction of the use of coolant, environmental impact, and their green nature. Within the MQL techniques, a minimum quantity of coolant and/or lubrication with 50–500 ml/h flow rate is commonly used during the machining process. In the dry machining, a material is machined without the use of any cutting fluid. Therefore, the negative impacts of using the cutting fluids such as environmental pollutions, allergy and skin injuries, and safety concerns are eliminated. In addition, in the green machining, because of the elimination of the cutting fluid, pretreatment/treatment lubricant costs,

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fluid system maintenance, and the disposal/cleaning costs, the total machining cost is reduced significantly. Hence, dry machining as a clean machining process is fast being adopted by metal cutting industries. In metal cutting industries, the appropriate selection of processing parameters plays a vital role in achieving high product quality along with low total cost. This can be achieved by using the expert systems with an extensive precise knowledge base, as an artificial intelligence tool. Such a database can be developed by experimental studying the influence of processing parameters on the performance of the process comprehensively. Turning is one of the most important machining operations in the manufacturing industry. Workpiece, cutting tool, and processing parameters have significant effect on the efficiency and performance characteristics of the turning operation. The criteria like surface roughness, material removal rate, tool wear, tool life, cutting force, and power consumption are used to evaluate the turning performance. However, nowadays, in the modern industries, special attention is given to the surface roughness and dimensional accuracy compared with the tool wear and cutting force [1–6]. Surface roughness is significantly affected by the cutting tool geometry, the rigidity of the machine tool, material properties, cooling, cutting depth, cutting speed, and feed rate. The surface roughness also has a significant effect on the friction coefficient, fatigue life, corrosion resistance, wear resistance, thermal resistance, appearance, and cost of the machined product [7–10]. Turning the materials with low machinability is different from the conventional turning of common materials, particularly when a high surface quality is required. Therefore, studying the effect of the processing parameters on the surface quality is necessary for the workpieces with low machinability. Hence, in this paper, the effect of processing parameters on the surface roughness ( $R_a$ ) of commercially copper with low machinability has been investigated, which can be used as the expert systems database.

Pure copper is a ductile metal with high thermal and electrical conductivity. The major applications of copper are in the electrical industry and industrial machinery [10, 11]. Copper is frequently used as a pure metal, but when a higher hardness is required, it is combined with other materials as alloys such as brass and bronze. Pure copper is soft and malleable and because of high ductility, has low machinability [11]. As a result, copper due to low machinability is not easy to machine especially in the finishing operation when a high quality is required.

Despite the importance of the copper machining, few and limited investigations have been done in this domain. However, the existed research works have been focused only on optimization techniques and metallurgical aspect of copper machining. Furthermore, the effect of cutting

variables and cooling mechanisms on the final quality of the copper finish turning has not been studied up to now comprehensively. For example, Raja et al. [12] used particle swarm optimization technique (PSO) to determine only the optimal condition for minimizing the machining time during the copper, aluminum, brass, and mild steel conventional turning. They recommended high cutting speed, along with low feed rate and cutting depth to achieve a good surface roughness. In a similar research work, Taguchi technique and principal component analysis method were used to find the optimal machining parameters for minimizing the cost in the copper machining [13]. In their experiments, depth of cut, cutting speed, feed rate, and rake angle were considered as the processing parameters.

From the metallurgical aspect of the copper machining, several research works were conducted. For example, Filiz et al. [14] investigated the machinability of oxygen-free high conductivity pure copper in micro-scale milling. Vignal et al. [15] also studied the effect of post-machining thermal treatment (PMTT) on the corrosion behavior of commercially pure copper. The effect of crystallographic orientation on the machinability of copper single crystals in ultra-precision diamond turning was studied by Lee et al. [16]. Sub-micrometer structures generated during the dry machining of copper were analyzed by Alpas et al. [17].

Gravier et al. [18] also investigated the influence of cutting parameters on the surface and subsurface characteristics of copper during the super finish turning. The numerical analysis indicated that feed rate, nose radius, and lubricant have significant effect on the mechanical, microstructural, and topographical state of the surface and the near-surface layer of the machined samples. Different erosion tests and thermodynamics analysis were also conducted by researchers to study the tool wear mechanisms in the diamond turning of copper [19].

As discussed in the literature review, most of the researchers studied the metallurgical aspects of the copper machining or focused only on optimization techniques and selecting optimal combinations. Hence, studying the effect of processing parameters on the surface quality of the copper with low machinability is crucial for machining industry.

In the turning operation, several factors affect the surface quality such as processing parameters, cutting tool variables, and workpiece properties. The cutting tool variables include tool material and its coating, cutting edge geometry, and entering angle. The workpiece properties are hardness and other mechanical properties. The processing parameters are also categorized as: machine tool characteristics, cooling, cutting speed, feed rate, and cutting depth [7–9].

Under real workshop condition, it is not possible to change and control all of the factors affecting the surface quality [20]. For example, in a workshop, the workpiece properties cannot be modified, because the client determines the product material. In addition, selecting the cutting tool variables strongly depends on its availability in the warehouse. Therefore, there exist limited choosing options to achieve desired surface quality and accuracy. These options can be categorized as follows: cooling, depth of cut, spindle speed, feed rate, and cutting tool geometry [21, 22]. Studying the literature revealed that among all the factors, the nose radius from the tool geometry variables, and depth of cut, cutting speed, feed rate along with cooling from the processing parameters, have the most effective effect on the surface quality [2, 7]. Therefore, in this paper, first, the effect of different cooling conditions such as wet, dry, and minimum quantity lubrication (MQL) on the surface quality is investigated. Then, the effect of cutting speed, depth of cut, feed rate, and nose radius on the surface roughness of the commercially pure copper is studied under the appropriate cooling condition. The capability of the empirical models in predicting the surface roughness of copper with low machinability is also examined. Finally, a new mathematical model is also developed for predicting the surface roughness of copper.

## 2 Materials and methods

Pure copper in the form of round bar with 37 mm diameter and 120 mm length was used for the experiments. The diameter and the cutting length of the samples for studying the effect of the machining processing were 35 and 100 mm, respectively. The mechanical and chemical properties of the workpiece are presented in Tables 1 and 2. A pre-cut with 2 mm cutting depth was performed before starting the experiments to remove the rust and oxide layers from the surface of the workpiece. The experiments were conducted using an industrial TOR-NADO T10 CNC lathe machine with a 26 kW motor power and maximum 3500 rpm spindle speed. For increasing the rigidity of the machining during the experiments, the workpieces were fixed between three-jaw chuck and tailstock. To study the effect of the cutting parameters, standard VCGX160404, VCGX160408, and VCGX160412

SANDVIK-coated cemented carbide inserts were used with three different nose radii. The chosen GC1810 grade is a diamond-coated insert with CVD coating for excellent wear resistance and reduced built-up edge, which results in high surface quality. This grade is appropriate for finishing to roughing of aluminum, magnesium, copper, brass, and plastics. The tool holder used in the experiments was standard SVVBN2525M16. To keep the cutting conditions unchanged, each test was conducted with a new sharp insert. Figure 1 shows the flow chart of the experiments, and the workpiece and the experimental setup. The experiments were conducted under three different cooling conditions: dry (green) condition, conventional wet condition (flood coolant), and MQL condition. A solution containing boron oil and water with the ratio of 1:20 was used as the coolant for the wet and MQL conditions. The coolant at the MQL condition was applied at the flow rate of 60 mL/h. The coolant in the MQL was pulverized through a nozzle and an air compressor at 6 bars and the final high pressure mixture is supplied at the interface of work piece-cutting tool. The surface roughness ( $R_a$ ) and the tool flank wear ( $VB_{max}$ ) were measured instantly after finishing each 100 mm cutting length of the samples. The cutting length deviation was also measured accurately using a precision dial gauge with an accuracy of  $\pm 0.01$  mm. After each individual test, the surface roughness measurements were carried out immediately using Mitutoyo (SJ-201P) roughness tester with 0.8 mm cut-off value and measuring length of 2.5 mm with 0.01  $\mu\text{m}$  accuracy and 0.5 mm/s scanning speed, in accordance to ISO/DIS 4287/1E and a signal amplifier (type 5233A) connected to a control unit, data acquisition board, and microcomputer. A 2  $\mu\text{m}$  radius diamond tip probe with induction mode has been used for measuring the roughness of the surface. The surface roughness values were measured at five equally spaced locations along the cutting length. The average of the roughness values was taken as an arithmetic surface roughness ( $R_a$ ). This measuring process was repeated three times for each test and the average was considered as the final surface roughness. The maximum flank wear ( $VB_{max}$ ) was also measured and recorded after each test using an OLYMPUS optical microscope. It is important to note that the measurements were repeated three times for each test. The temperature of the measurement environment was standard  $20 \pm 1$  °C.

**Table 1** Mechanical properties of the workpiece

Properties	Hardness, brinell	Modulus of elasticity (GPa)	Bulk modulus (GPa)	Poisson's ratio	Shear modulus (GPa)	Tensile strength (N/mm <sup>2</sup> )
Copper	90	110	140	0.35	46	360

**Table 2** Chemical and physical properties of the workpiece

Properties	Atomic Mass	Density (g/cc) (temperature 20.0 °C)	Atomic number	Melting point (°C)	Thermal conductivity (W/m–K)	Specific heat capacity (J/g °C)
Copper	65.546	8.96	29	1083.6	385	0.385

**Fig. 1** Flow chart of the experiments, and the experimental setup



The number of the experiments was determined based on the full factorial design method. This method was chosen due to its high confidence limit, proper precision, and the reliability of the experimental data [20, 22]. Consequently, the general 3<sup>n</sup> experimental design was adopted for this work. Three level tests for each variable were used, because a non-linear relationship exists between the parameters and the surface roughness. According to the full factorial design, 3<sup>4</sup> (i.e., 81) experiments were carried and a random order was used for performing the tests. The level of the variables was determined based on the studied previous literatures such as Ahilan et al. [2], Lee et al. [6], Gökkaya et al. [7], and also the recommendations of the machining catalogues and the cutting tool manufacturer’s handbook [23]. The selected range of the variables is completely compatible with the finishing and semi-roughing operation, which surface quality is an important criteria. The variables and their levels for studying the effect of the cutting parameters on the surface roughness are shown in Tables 3 and 4. After collecting all the data, the experimental results were analyzed carefully with Minitab 16. Finally, analysis of variance method (ANOVA) with the confidence level of 95% through statistical analysis

**Table 3** Selected ranges of the processing parameters for studying the surface roughness variations

	Cutting parameters (units)	Symbol	Level 1	Level 2	Level 3
A	Nose radius (mm)	$r_e$	0.4	0.8	1.2
B	Cutting speed (m/min)	$V$	55	110	220
C	Feed rate (mm/rev)	$f$	0.08	0.16	0.32
D	Depth of cut (mm)	$d$	0.5	2	3

**Table 4** Cutting parameters related to the cooling experiments

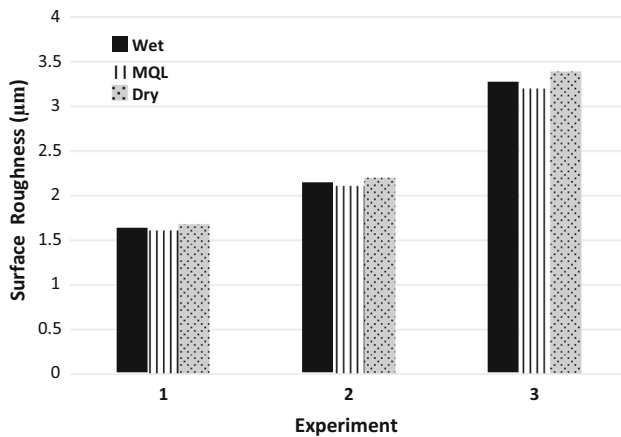
Experiment	$f$ (mm/rev)	$d$ (mm)	$V$ (m/min)	$R_e$ (mm)
1	0.08	0.5	55	0.4
2	0.16	2	110	0.8
3	0.32	3	220	1.2

software Design-Expert was used to build a predictive regression model.

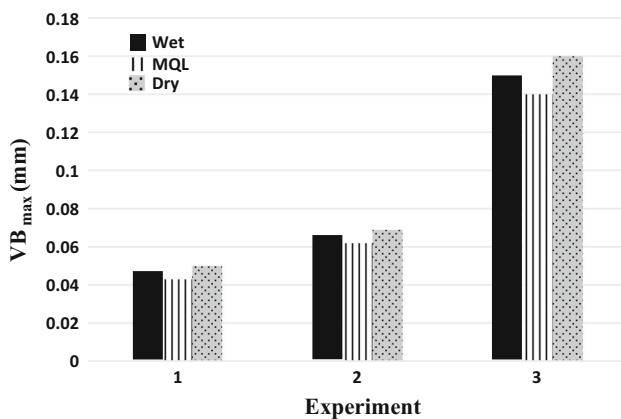
### 3 Results and discussion

#### 3.1 The effect of cooling condition

To evaluate the effect of cooling methods on the machining performance of copper with low machinability, tool life and surface roughness are compared under various cutting conditions. As explained earlier, the experiments are conducted under three different cooling conditions: dry (green) condition, wet condition (flood coolant), and MQL condition. The obtained results are shown in Figs. 2, 3. Figure 2



**Fig. 2** Surface roughness comparison for all three cooling conditions and under different cutting parameters



**Fig. 3** Tool wear comparison for all three cooling conditions and under different cutting parameters

shows the effect of different cooling conditions on the surface roughness. In these experiments, the best surface quality is achieved using MQL, compared to dry and wet conditions. The surface roughness under the wet condition is also better than that of the dry condition. This pattern is similar for all the experiments. This subject is related to the tool wear variations under various cooling conditions. In experiment 1, the tool wears in all three cooling conditions are less than those of experiments 2 and 3. This can be attributed to bigger cutting depth, cutting speed, and feed rate in experiments 2 and 3, which results in higher tool wear and lower tool life. According to Fig. 3, in all experiments, the lowest tool wear is observed under the MQL conditions. On the other hand, the tool wear under the wet condition is lower than that of the dry machining. Therefore, it can be concluded that this lower surface quality under the dry and wet conditions is mainly due to the higher tool wear under the dry and wet conditions, compared with the MQL. It is obvious that under the dry machining, due to higher cutting temperature and also the

higher rate of build-up edge (BUE) formation, tool wear increases and the surface quality is decreased consequently, compared with the wet and MQL conditions. On the other hand, under the conventional wet condition, the coolant cannot reduce the chip–tool interface temperature effectively, because the fluid can hardly penetrate into that zone particularly at higher feed rate and cutting speed [26–29]. Therefore, under the wet condition, higher tool wear and lower surface quality are obtained, compared with the MQL (see Figs. 2, 3). In the MQL system, due to the high pressurized spray of the coolant along the tool rake angle, coolant jet can easily penetrate into the chip–tool interface, and either the chip breakage or the interface temperature reduction is improved effectively, and therefore, the tool wear is decreased significantly. In addition, the MQL jet causes favorable chip–tool interaction and even eliminates the trace of built-up edge formation in the turning operation [27]. Thus, it can be concluded that for copper turning, using MQL results in the best surface quality and the lowest tool wear, and dry turning leads to the highest tool wear and lowest surface quality. However, the differences between the obtained  $R_a$  under these three cooling conditions, in all cases were less than 7%, which is negligible. Therefore, it can be said that the surface quality for dry and MQL machining is almost similar. On the other hand, there is no significant difference in tool wear under dry machining when compared to MQL and flood machining. Furthermore, dry machining is actually four times cheaper than wet and MQL cutting, because machining using cutting fluid has equipment, maintenance, and disposal costs [26, 27]. Moreover, in dry machining, the negative impacts of using the cutting fluids such as environmental pollutions, allergy and skin injuries, and also safety concerns are eliminated. As a result, dry condition can be recommended for turning commercially pure copper with low machinability. Due to the importance of the dry machining in modern industry, to study the effect of cutting depth, feed rate, cutting speed, and nose radius on the surface roughness of copper, the remaining experiments have been conducted under the dry condition without any fluid, gas and/or solid coolant.

### 3.2 The effect of cutting parameters

The results showed that the feed rate and the nose radius are the most important factors affecting the surface roughness, respectively. The obtained results also reveal that the quadratic effect of the nose radius on the surface roughness is significant. Furthermore, only the interaction of feed rate–cutting depth and feed rate–nose radius has statistically significant effect on the surface roughness values.

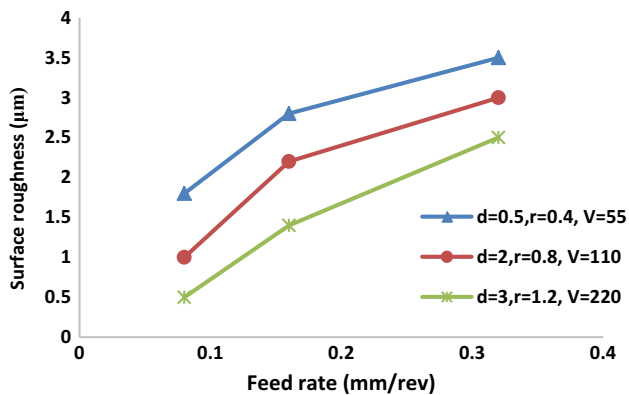


Fig. 4 Effect of feed rate on the surface roughness

According to the results (Fig. 4), by increasing the feed rate, the surface roughness increases expectedly. When the feed rate is gradually increased from 0.08 to 0.32 mm/rev, the average of the surface roughness values increased significantly. This behavior is mainly due to helicoids furrows that generated because of the tool tip-workpiece relative movement. As the feed rate increases, the furrows become wider and deeper, and thus, the surface roughness is deteriorated. On the other hand, by increasing the feed rate, the cutting force increases to create the required plastic deformation. As a result, extra heat is produced in the cutting zone. The extra heat causes the thermal softening of the copper, and this thermal softening finally increases the surface roughness. It is clear that the best surface roughness is obtained at the lowest level of the feed rate. Therefore, it can be concluded that like other materials, the lowest level of the feed rate is the best option to achieve the best surface roughness in the copper dry turning.

Small nose radius decreases the vibration during the turning operation. Inserts with small nose radii are also suitable for small cutting depth due to low strength. On the other hand, because of the stronger edge, the large nose radius is used at higher cutting depth and feed rate. Unlike smaller nose radius, the radial forces and vibration increase using large nose radii [23]. Therefore, it can be concluded that nose radius is a key factor affecting the surface roughness and dimensional accuracy. As explained before, insert nose radius is the second important factor affecting the surface roughness in copper dry turning. As shown in Fig. 5, when the nose radius increases from 0.4 to 1.2 mm, the surface roughness first decreases until the lowest value is reached, then by further increasing the nose radius (0.8–1.2 mm), the surface roughness increases. From Fig. 5 it is clear that, except for  $f = 0.08$  mm/rev, for each level of the cutting depth, feed rate, and cutting speed, the best surface roughness is achieved at 0.8 mm nose radius. The highest surface roughness has also been obtained at

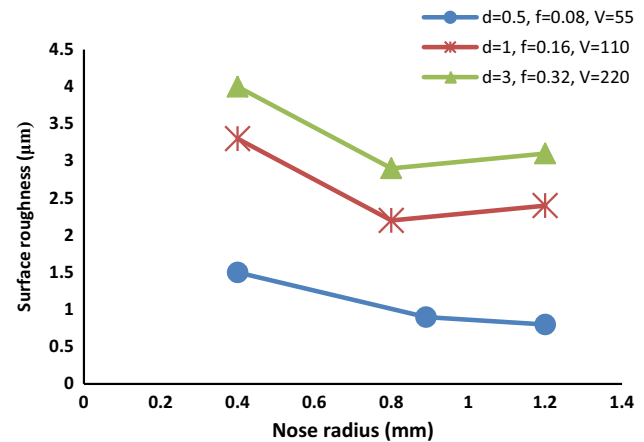


Fig. 5 Effect of nose radius on the surface roughness

0.4 mm nose radius. This high surface roughness can be due to the low strength of the insert tip and, as a result, the higher rate of wear. Moreover, the relatively short contact length between the workpiece and the insert cutting edge at 0.4 mm nose radius results in the higher stress concentration and lower heat dissipation, which in turn increases the heat in the shear zone [23–25]. Copper is a soft material with high ductility and low yield strength. Therefore, the produced heat and thermal softening further decrease the copper machinability. Hence, thermal softening is another adverse factor, which can cause the surface roughness deterioration at 0.4 mm nose radius. The surface roughness deterioration at 1.2 mm nose radius can be due to the high vibration, which occurs because of a larger contact length between the workpiece and the cutting tool. From Fig. 5, it can be seen that only at  $f = 0.08$  mm/rev, by increasing the nose radius from 0.4 to 1.2 mm, the surface roughness decreases continuously. At  $f = 0.08$  mm/rev, because of lower feed rate and low cutting forces, the vibration is not a dominant factor influencing the surface roughness. Thus, at  $f = 0.08$ , the best surface roughness is achieved at the largest nose radius (i.e., 1.2 mm). The results revealed that the best surface roughness of 0.381 µm was also obtained at 1.2 mm nose radius. It is interesting to note that this 0.381 µm surface roughness is comparable with the surface quality obtained by the conventional grinding operation. Therefore, it can be concluded that for the lowest level of the feed rate, 1.2 mm nose radius is a good option to achieve the best surface roughness in copper finish dry turning. On the other hand, at high feed rate, 0.8 mm nose radius is suggested to achieve a good surface quality.

According to Fig. 6, the surface roughness is decreased by increasing the cutting speed from 55 to 220 m/min. The experimental results showed that the surface roughness values obtained at 220 m/min are scattered in a lower range compared with those of obtained at 55 and 110 m/min. In all cases, the best surface roughness is obtained at the

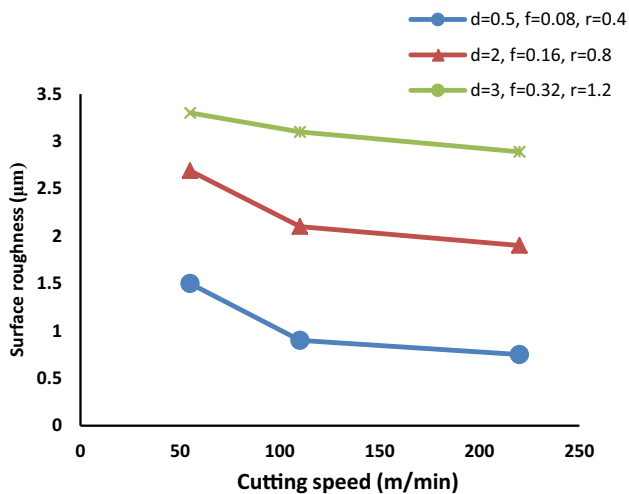


Fig. 6 Effect of cutting speed on the surface roughness

highest cutting speed. Thus, it can be concluded that the higher level of the cutting speed is preferred in the copper finish dry turning. The best surface roughness is also obtained at the highest level of the cutting speed. The improvement of the surface roughness by increasing the cutting speed is due to the restriction of the formation of built-up edge (BUE) at high cutting speed. At high cutting speed, the higher cutting temperature and the thermal softening of the material restrict the BUE formation, and therefore, the surface roughness is improved. The results also revealed that the surface roughness is not sensitive to the simultaneous variation of  $V$  with the other cutting parameters ( $f$ ,  $d$ ,  $r_e$ ).

The variation of the surface roughness with the cutting depth is shown in Fig. 7. It can be seen that by increasing the cutting depth from 0.5 to 3 mm, the surface roughness first decreases until the lowest value is reached at

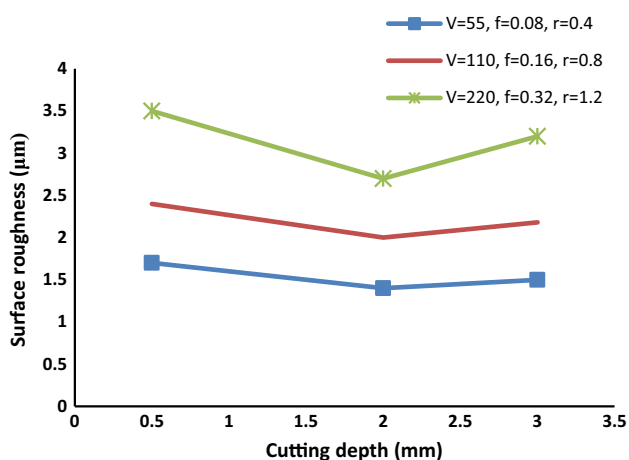


Fig. 7 Effect of cutting depth on the surface roughness

$d = 2$  mm, and then, by further increasing the cutting depth to 3 mm, the surface roughness slightly increases. This slight increase in the surface roughness can be due to the higher rate of chatter that usually occurs at high cutting depths. It was also observed that in all cases, 2 mm depth of cut yields the best surface roughness. The results contradict with the common expectation that in the finish turning the surface roughness increases by increasing the cutting depth. Although the lowest surface roughness was obtained at 0.5 mm depth of cut, generally, by increasing the cutting depth to 2 mm, both the surface roughness and material removal rate are improved simultaneously. According to the obtained results, under the dry machining, the best surface roughness of  $0.381 \mu\text{m}$  has been achieved at  $r_e = 1.2$  mm,  $V = 220$  m/min,  $d = 0.5$  mm, and  $f = 0.08$  mm/rev, which is comparable with the surface quality obtained by the conventional grinding operation.

### 3.3 Contour and surface plots

Contour and 3D surface plots are used to find the optimal machining condition that produces the desired surface roughness. Figures 8, 9, 10, and 11 all show the surface roughness contours and 3D graphs related to the conducted experiments. In 3D surface plot, interpolation is used to generate a three-dimensional picture of the response surface. In a contour plot, two variables are depicted on the x- and y-axes, while the response is represented by shaded region, which called “contour”. The curved lines in the contour plots prove that there is a non-linear relation between the processing parameters and the desired response. Figures 8 and 9 clearly show that for any level of the cutting depth and cutting speed, the best surface roughness is achieved at the lowest level of the feed rate. It was also observed that the highest spindle speed with the cutting depth greater than the medium level (i.e., 3 mm) provide a better surface roughness compared with other combinations of the cutting depth-cutting speed. This phenomenon can be due to the restriction of the BUE formation at high cutting speed. Figure 10 obviously shows that for any level of the cutting depth, the inserts with 0.8 mm nose radius produce a better surface roughness compared with 1.2 and 0.4 mm inserts. Furthermore, according to Fig. 11, using 0.8 and 1.2 mm nose radius, a higher feed rate can be chosen to obtain the desired surface finish compared with 0.4 mm nose radius. This choice may improve both the material removal rate and machining time in the dry turning of materials with low machinability. It is also interesting to note that using 220 m/min cutting speed both the 0.8 and 1.2 mm nose radii can be used to achieve the desired surface finish.

From the above discussion, it can be concluded that during the dry turning of commercially pure copper, to

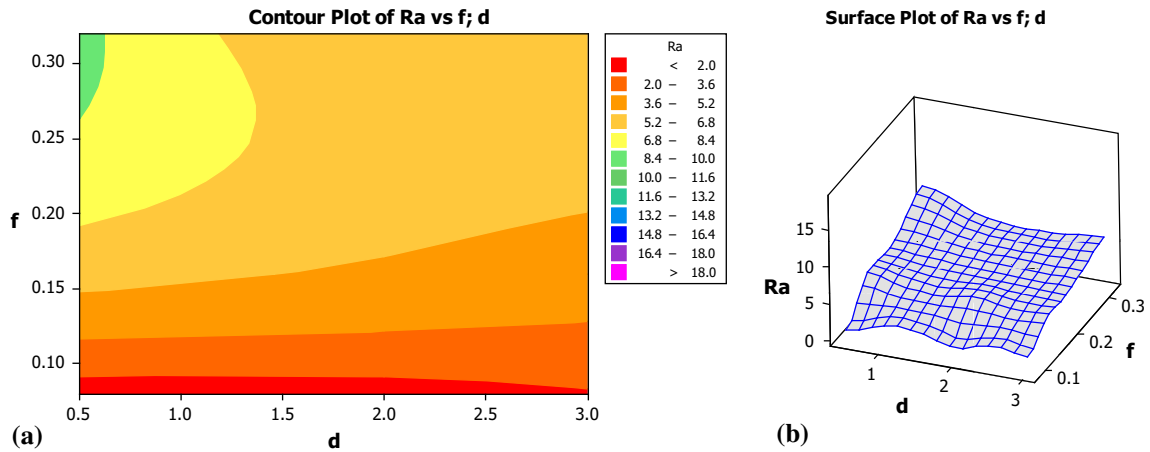


Fig. 8 Contour and 3D surface plots for the effect of feed rate and depth of cut on surface roughness at  $r_e = 0.8$  mm,  $V = 220$  mm/min

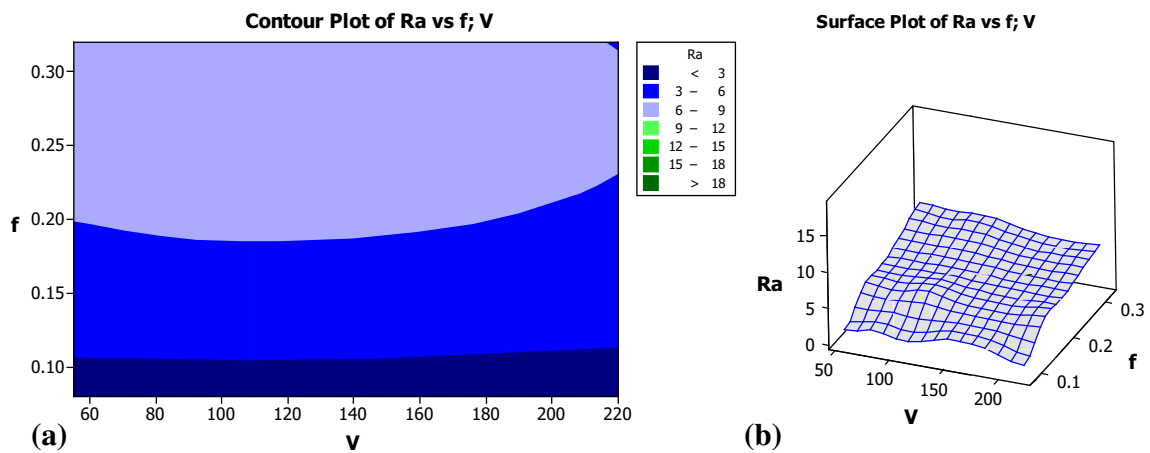


Fig. 9 Contour and 3D surface graphs for the effect of feed rate and cutting speed on surface roughness at  $r_e = 0.8$  mm,  $d = 2$  mm

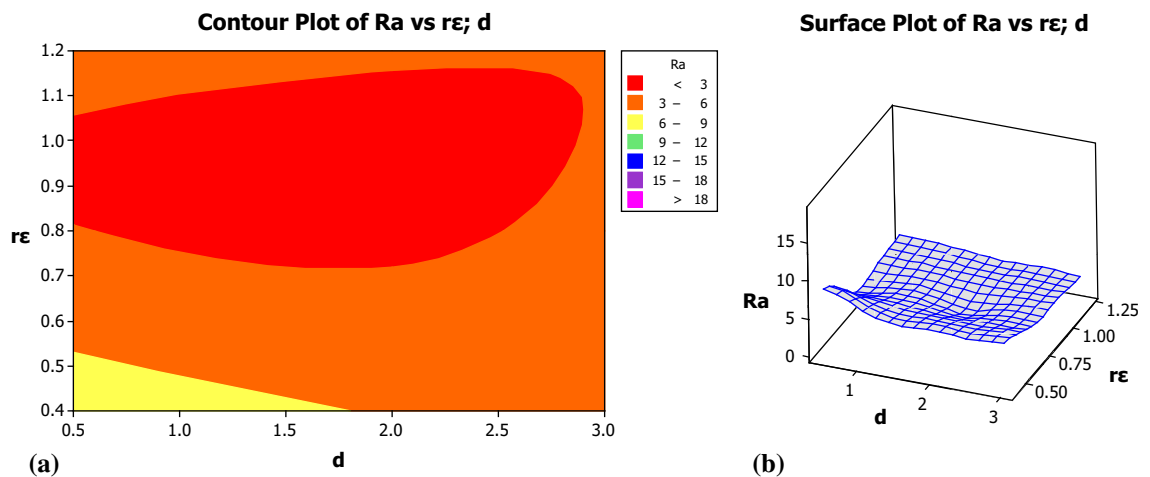


Fig. 10 Contour and 3D surface graphs for the effect of nose radius and depth of cut on surface roughness at  $f = 0.08$  mm,  $V = 220$  mm/min

achieve an acceptable surface roughness with suitable material removal rate and machining time, the combination of the lowest feed rate, and the highest cutting speed along

with the moderate cutting depth and nose radius is suggested.



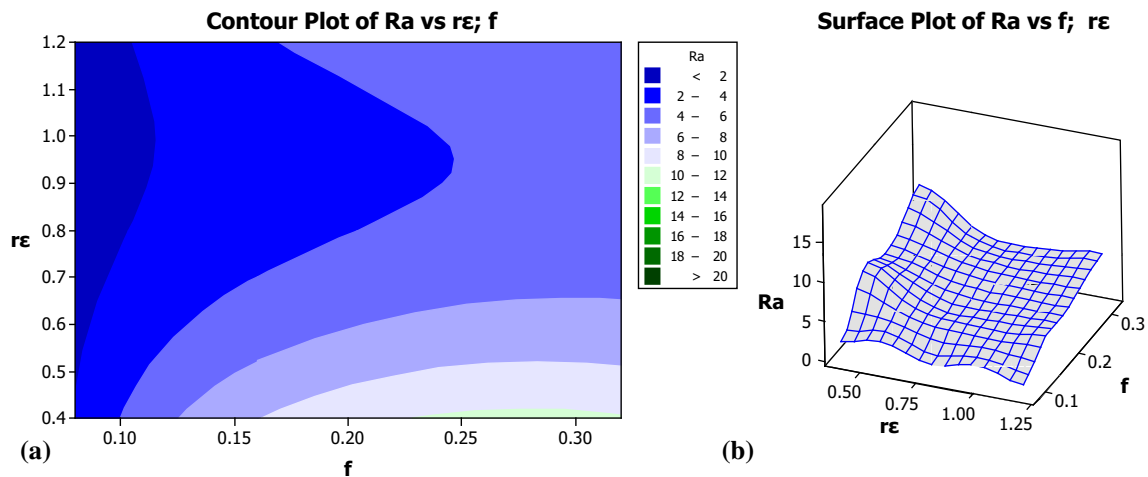


Fig. 11 Contour and 3D surface graphs the effect of nose radius and feed rate on surface roughness at  $V = 220$  mm/min,  $d = 2$  mm

### 3.4 Predictive models

In the conventional turning operation, a known empirical model is often used for predicting the surface roughness [23, 30–34]. The model is written as follows:

$$R_a \approx f^2 / (32 \times r_e), \tag{1}$$

where  $R_a$  is the surface roughness,  $f$  is the feed rate, and  $r_e$  is the tool nose radius. In this empirical model, it has been assumed that the feed rate and the insert nose radius are the only factors affecting the surface roughness. According to Eq. (1), the surface roughness is improved either by increasing the nose radius or by decreasing the feed rate. Many researchers have used this model for predicting the surface roughness in their research works. However, reported results revealed that the surface roughness values predicted by Eq. (1) do not match the real surface roughness values [17]. This difference can be even more critical for the materials with low machinability such as copper, especially in the dry condition. Therefore, a comparison was made between the surface roughness values that predicted by the empirical model and the real surface roughness values measured during the experiments. The results are shown in Figs. 12, 13. Furthermore, Tables 5, 6, 7 represent the relative error between the measured and the predicted surface roughness under various cutting conditions. The relative error is calculated by Eq. (2), which is written as follows:

$$\text{Relative error (\%)} = \frac{|\text{Predicted value} - \text{Measured value}|}{\text{Measured value}} \times 100. \tag{2}$$

From Tables 5, 6, 7, it is clear that in the most cases the relative error is greater than 30%. Furthermore, the

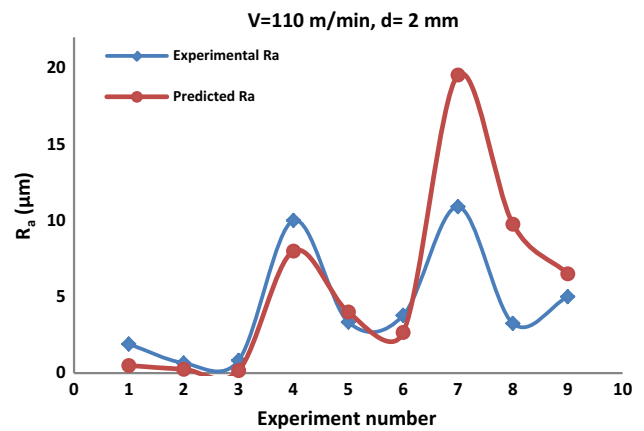


Fig. 12 Comparison between the measured and the predicted surface roughness ( $R_a$ ) at  $V = 110$  m/min and  $d = 2$  mm

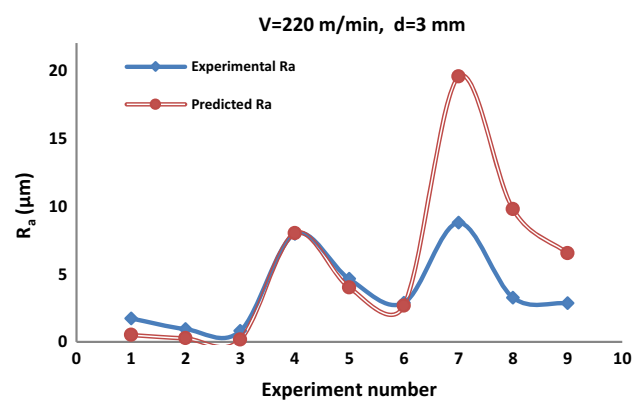


Fig. 13 Comparison between the measured and the predicted surface roughness ( $R_a$ ) at  $V = 220$  m/min and  $d = 3$  mm

predicted value occasionally was higher than measured value and sometimes was lower than the measured value. This disordered variations and high relative errors both

**Table 5** Relative error between the measured and the  $R_a$  predicted by Eq. (1) at  $V = 55$  m/min and  $d = 0.5$  mm

Exp. number	Nose radius (mm)	Feed rate (mm/rev)	Measured $R_a$ ( $\mu\text{m}$ )	Predicted $R_a$ ( $\mu\text{m}$ )	Relative error (%)
1	0.4	0.08	1.638	0.5	69
2	0.8	0.08	1.233	0.25	79
3	1.2	0.08	1.378	0.16	88
4	0.4	0.32	8.898	8	10
5	0.8	0.32	4.219	4	5
6	1.2	0.32	5.615	2.66	52
7	0.4	0.5	13.248	19.53	47
8	0.8	0.5	5.313	9.76	84
9	1.2	0.5	7.752	6.51	16

**Table 6** Relative error between the measured and the  $R_a$  predicted by Eq. (1) at  $V = 110$  m/min and  $d = 2$  mm

Exp. number	Nose radius (mm)	Feed rate (mm/rev)	Measured $R_a$ ( $\mu\text{m}$ )	Predicted $R_a$ ( $\mu\text{m}$ )	Relative error (%)
1	0.4	0.08	1.9	0.5	73
2	0.8	0.08	0.66	0.25	62
3	1.2	0.08	0.83	0.16	81
4	0.4	0.32	9.62	8	17
5	0.8	0.32	3.34	4	20
6	1.2	0.32	3.781	2.66	30
7	0.4	0.5	10.90	19.53	79
8	0.8	0.5	3.25	9.76	200
9	1.2	0.5	5.63	6.51	15.5

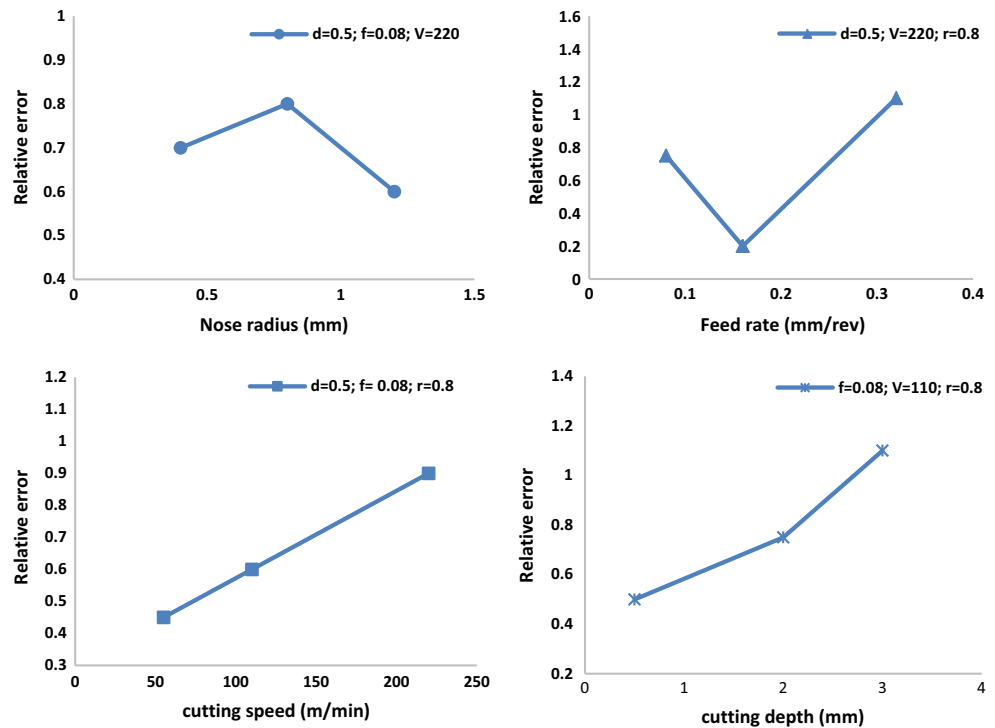
**Table 7** Relative error between the measured and the  $R_a$  predicted by Eq. (1) at  $V = 220$  m/min and  $d = 3$  mm

Exp. number	Nose radius (mm)	Feed rate (mm/rev)	Measured $R_a$ ( $\mu\text{m}$ )	Predicted $R_a$ ( $\mu\text{m}$ )	Relative error (%)
1	0.4	0.08	1.725	0.5	71
2	0.8	0.08	0.936	0.25	74
3	1.2	0.08	0.790	0.16	80
4	0.4	0.32	7.944	8	1
5	0.8	0.32	4.628	4	13
6	1.2	0.32	2.875	2.66	7
7	0.4	0.5	8.770	19.53	138
8	0.8	0.5	3.254	9.76	200
9	1.2	0.5	2.833	6.51	130

prove that the empirical model is not suitable for predicting the surface roughness in the dry copper turning. The results show that at low feed rate (i.e., 0.08 mm/rev), which is usually used for the finishing operation, the difference between the predicted  $R_a$  and real  $R_a$  is significant. On the other hand, low relative errors are seen under medium and high feed rates, which proves that the empirical model is only appropriate for predicting the surface roughness at

medium and roughing operations. Therefore, it can be concluded at low feed rate, ignoring the effect of cutting speed and depth of cut in the empirical model is more crucial and results in a higher relative error. To study the effect of the cutting parameters on the relative error, the variations of the relative error is shown in Fig. 14. As shown in Fig. 14, the relative error increases by increasing the cutting speed and the cutting depth. Thus, it can be

**Fig. 14** Effect of cutting parameters on the relative error under various cutting conditions



concluded that the empirical model is completely inefficient for predicting surface roughness at high cutting speed and depth of cut. Since in the finish turning relatively high cutting speeds are used, the empirical model due to the high relative errors is incapable of predicting the surface roughness. The results also revealed that the lowest error is obtained at 1.2 mm nose radius and 0.32 mm/rev feed rate. On the other hand, as discussed earlier, the relative error is higher for low feed rate. Therefore, it can be concluded that the empirical model can only predict the surface roughness at medium and high feed rate along with low cutting speed. The combination is not suitable and reasonable for the finish turning. This subject also shows that at roughing operation, the effect of the cutting speed and depth of cut is insignificant compared with the finishing operation under the dry condition. Therefore, the empirical model is not suitable for predicting the surface roughness in the dry finish turning of copper with low machinability, especially in the dry finishing. The existed high relative error is due to the ignoring some important factors affecting the surface roughness such as depth of cut, cutting speed, and the workpiece hardness. In addition, some adverse factors like

tool vibration, built-up edge, and chatter can be another reason for such high errors. For example, the high difference between the  $R_a$  values in experiments 7, 8, and 9, is due to these adverse factors which become more serious at high feed rate.

According to the above reasons, a new model has to be developed to predict the surface roughness during the dry finish turning. To express the relationship between the cutting parameters and the surface roughness, a new mathematical predictive model based on regression method was developed. The selected ranges for developing the new model are given in Table 8. The obtained full quadratic uncoded model for predicting the  $R_a$  is given below:

$$\begin{aligned}
 R_a = & 3.62 - 12.60 \times r_e + 0.00558 \times V + 34.948 \times f - 0.031 \\
 & \times d + 7.91 \times r_e \times r_e - 0.00436 \times r_e \times V - 12.73 \\
 & \times r_e \times f - 0.0544 \times r_e \times d - 2.11e - 005 \times V \\
 & \times V - 0.000509 \times V \times f + 0.0011 \times V \\
 & \times d - 5.06 \times f \times f - 4.21 \times f \times d + 0.16 \times d * d.
 \end{aligned}
 \tag{3}$$

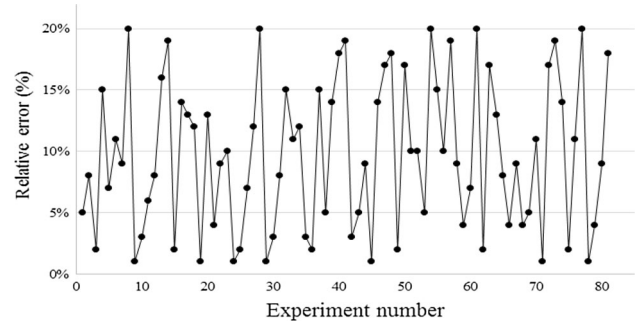
**Table 8** Selected ranges of the processing parameters for developing a regression predictive model

	Cutting parameters (units)	Symbol	Level 1	Level 2	Level 3
A	Nose radius (mm)	$r_e$	0.4	0.8	1.2
B	Cutting speed (m/min)	$V$	55	110	165
C	Feed rate (mm/rev)	$f$	0.08	0.16	0.24
D	Depth of cut (mm)	$d$	0.5	1.5	2.5

**Table 9** ANOVA for the surface roughness predictive model

Term	Coef	<i>T</i>	<i>P</i>
Constant	3.620	2.50049	0.016
$r_e$	- 12.60	- 4.85199	0.000
<i>V</i>	0.0055	0.42227	0.675
<i>f</i>	34.94	9.42514	0.000
<i>d</i>	- 0.031	- 0.12499	0.901
$r^*r$	7.910	5.22306	0.000
$V^*V$	- 2.11e-005	- 0.52995	0.598
$f^*f$	- 5.060	- 3.366	0.319
$d^*d$	0.160	- 1.00661	0.281
$r^*V$	- 0.00436	- 0.82176	0.415
$r^*f$	- 12.730	- 6.38827	0.000
$r^*d$	- 0.0544	- 0.10650	0.916
$V^*f$	- 0.000509	- 0.05735	0.954
$V^*d$	0.0011	0.74186	0.461
$f^*d$	- 4.210	- 6.39693	0.000
$R^2$ (adj) = 92.91%	$R^2 = 94.60%$	$R^2$ (pred) = 90.45%	

The suitability of a model is usually determined based on  $R^2$  statistic and ANOVA results. The  $R^2$  values and ANOVA results are given in Table 9. The value of  $R^2 = 94.60\%$  indicates that 94.60% of the  $R_a$  variation is explained by the proposed model. Large  $R^2$  value does not necessarily prove that the regression model is suitable for predicting the process response because by adding even additional terms to the model the value of  $R^2$  increases [20]. Therefore, it is possible that a model with a large value of  $R^2$  yields poor predictions. To perform a better comparison the adjusted  $R^2$  statistic [ $R^2$  (adj)] is used, which is applied to calculate the percentage of variation explained by only the independent variables that actually affect the dependent variable [1, 20, 22].  $R^2$  (adj) = 92.91% means that the model explain 92.91% of the total variability.  $R^2$  (pred) is another statistic that shows the predictive capability of a model. The value of  $R^2$  (pred) = 90.45% is also compatible with the adjusted  $R^2$  statistic. Therefore, the  $R^2$  statistics all prove that the proposed model is suitable for predicting the surface roughness. A comparison was also made between the surface roughness values that predicted by Eq. (3) and the real surface roughness values measured during the experiments. The results are shown in Fig. 15. As explained earlier, the relative error was calculated by Eq. (2). It is obvious from Fig. 15 that the calculated relative error for the experiments was between 1 and 20%, and the highest relative error was 20%. The relative error lower than 20% completely confirms that the proposed empirical model is

**Fig. 15** Comparison between the measured  $R_a$  and the predicted  $R_a$  by Eq. (3)

capable of predicting surface roughness in the copper dry turning operation precisely.

## 4 Conclusions

In this paper, the impact of the most effective processing parameters in the turning operation including feed rate, cutting depth, nose radius, cutting speed, and cooling conditions on the surface finish of commercially pure copper was studied. To evaluate the effect of cooling condition, various experiments were conducted under three different cooling conditions: dry condition, wet condition, and minimum quantity lubrication condition. It was observed that the best surface quality and the lowest tool wear are achieved under minimum quantity lubrication, and the highest tool wear and the lowest surface quality are obtained by dry condition. However, in all cases, the differences between the surface roughness and also tool wear under these three cooling conditions are less than 7%. According to the results, feed rate and nose radius were the most important factors affecting the surface roughness. At low feed rate, 1.2 mm nose radius is a good option to achieve the best surface roughness in copper dry finish turning. To achieve an acceptable surface roughness with suitable material removal rate and machining time, the combination of the lowest feed rate and the highest spindle speed with the moderate depth of cut and nose radius is suggested. The best surface roughness of 0.381  $\mu\text{m}$  was achieved at  $r_e = 1.2$  mm,  $V = 220$  rpm,  $d = 0.5$  mm and  $f = 0.08$  mm/rev under the dry condition, which is comparable with the surface quality obtained by the conventional grinding operation. The results also revealed that the empirical model of  $f^2/(32 \times r_e)$  can predict the surface roughness only at high feed rate, and low spindle speed and, therefore, is not useful for predicting the surface roughness in the finish dry turning. Thus, a full quadratic prediction model was developed using regression methods to predict the surface roughness in copper dry turning. The

$R^2$  values, ANOVA results, and residual plots all proved that the proposed model is capable of predicting the surface roughness and also it is applicable as a database for developing turning expert systems.

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