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# Multi response optimization of surface roughness in hard turning with coated carbide tool based on cutting parameters and tool vibration

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**Abstract.** In the present work, the effects of cutting parameters on surface roughness parameters (Ra), tool wear parameters (VBmax), tool vibration (Vy) and material removal rate (MRR) during hard turning of AISI 4140 steel using coated carbide tool have been evaluated. The relationships between machining parameters and output variables were modeled using response surface methodology (RSM). Analysis of variance (ANOVA) was performed to quantify the effect of cutting parameters on the studied machining parameters and to check the adequacy of the mathematical model. Additionally, Multi-objective optimization based desirability function was performed to find optimal cutting parameters to minimize surface roughness, and maximize productivity. The experiments were planned as Box Behnken Design (BBD). The results show that feed rate influenced the surface roughness; the cutting speed influenced the tool wear; the feed rate influenced the tool vibration predominantly. According to the microscopic imagery, it was observed that adhesion and abrasion as the major wear mechanism.

**Keywords:** cutting parameter; surface roughness; wear; vibration; hard turning; coated carbide; multi-objective optimization

## 1. Introduction

Coated carbide cutting tools widely applied in material removal processes, in recent years an 80% of all machining operations are performed with coated carbide cutting tools Grzesik, W. (1998). However, their performance is limited in hard turning, hence, several manufacturing, looking for developing new coated carbide cutting tools especially for processing hardened steels with hardness above 50 HRC. Various studies have been conducted to investigate the performance of coated carbide in the machining of various hard materials. Surface roughness, tool wear and dynamic tool behavior are the most important studied factors in hard machining field (Behnam and Behzad 2015 and Devillez 2007).

The paper by Sahoo and Sahoo (2013) investigated the performance of TiN/TiCN/Al2O3/TiN multilayer CVD coated carbide insert in finish hard turning of AISI 4340 steel. A mathematical model and an optimization study on surface roughness and tool flank wear were developed based on the Response Surface Methodology (RSM) and grey Taguchi method. In addition, their results emphasize the machining cost per part to justify the economic feasibility of coated carbide tool in hard turning process. A comparative assessment of TiCN/Al2O3/TiN coated carbide tool and PCBN tools in hard turning was carried out by Aneiro *et al*. (2008). They observed that PCBN tool performed better tool life than the coated carbide tool; on the other hand the PCBN tool is relatively costly as compared to the coated carbide tool. They revealed that machining hardened steels with hardness above 45 HRC with TiCN/Al2O3/TiN tool have a tendency to be more productive. In another study performed by Suresh *et al*. (2012) analyzed the influence of cutting speed, feed rate, depth of cut and machining time on machinability characteristics such as machining force, surface roughness and tool wear in hard turning of AISI 4340 steel using coated carbide insert. They revealed that, the combination of low feed rate, low depth of cut and low machining time with high cutting speed is beneficial for minimizing the machining force and surface roughness. The same approach was performed by Lima *et al*. (2005) in hard turning of AISI 4340 steel (42 HRC) and D2 cold work tool steel (50 HRC) using ceramic and coated carbide inserts. The results indicated that mixed alumina tools produced a better surface finish than the coated carbide tools. They observed that the abrasion is the principal wear mechanism when turning the 42 HRC steel, while diffusion wear is predominant when machining the 50 HRC steel. In a recent paper by Keblouti *et al*. (2017) studied the machinability aspects such as flank wear and surface roughness in finish turning of AISI 1030 steel, using multilayer coated carbide (TiN/Al2O3/TiCN) insert and bi-layer coated carbide (TiAlN/TiN) insert under dry environment. Experimental results showed that multilayer (TiN/Al2O3/TiCN) coated carbide inserts performed better 5 times than the bi-layer coated carbide

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(TiAlN/TiN) insert in terms of tool life. In another study conducted by Keblouti *et al*. (2017) reported a comparative assessment of cutting performance while machining AISI 52100 steel between uncoated and coated (with TiCN-TiN coating layer) cermet tools. The substrate composition and the geometry of the inserts compared were the same. Experimental results showed that feed rate has the most effect on surface quality. However, cutting depth has the significant effect on the cutting force components. Also lower surface roughnesses were observed when using the PVD (TiCN-TiN) coated insert. Asiltürk and Akkus (2011) have investigated the relationship between cutting parameters and surface roughness in hard turning of AISI 4140 steel (51 HRC) with coated carbide cutting tools. They found that the feed rate has the most significant effect on Ra and Rz. In addition, the effects of two factor interactions of the feed rate - cutting speed and depth of cut - cutting speed appear to be important. Azizi *et al*. (2012) investigated the effects of cutting parameters and workpiece hardness on surface roughness and cutting forces, in hard turning of AISI 52100 steel, using response surface methodology (RSM). They applied an optimization study of machining conditions to produce the lowest surface roughness with minimal cutting force components using the desirability function approach for multiple response factor optimizations. They concluded that the feed rate, workpiece hardness and cutting speed have significant effects in reducing the surface roughness; whereas the depth of cut, workpiece hardness and feed rate are observed to have a statistically significant impact on the cutting force components than the cutting speed. The tool wear, surface roughness, cutting forces and metal volume removed were investigated by Bouacha *et al*. (2014) in hard turning of AISI 52100 steel using CBN tools. A mathematical model was developed for surface roughness and cutting force components based on the Response Surface Methodology (RSM). They found that the surface roughness is mainly influenced by the feed rate and the cutting speed, while the cutting depth has the most significant effect on cutting forces. Also, the cutting time has a considerable effect on cutting performances.

Several publications have appeared in recent years studied the effects of tool coating in hard machining. It has been shown that tool coating improves the cutting conditions: it protects the substrate, improves the crack resistance and creates a thermal barrier (Ciftci 2006 and Bouzakis 2003). The investigations conducted by Zhang *et al*. (2015) in dry cutting of hardened steel AISI 1045 using two types of coated cemented carbide. The first one had a nano-scale surface textured rake face, which was then coated with a hard-coating of Ti55Al45N hard-coatings. In the second insert, the order of coating layers was inverted. A significant decrease in cutting forces, cutting temperature and friction coefficient at the tool-chip interface were found. The textured tool reduces the contact area, thus the friction at the tool-chip interface.

In addition, the frictional behavior characterization was investigated experimentally by Rech (2006) of two new coatings such as (Ti,Al)N and (Ti,Al)N + MoS2, deposited on a WC–Co carbide substrate and of TiN coating such as reference. It is observed that, the sliding ability of the TiN coating is an important parameter to improve wear resistance, when compared to a (Ti,Al)N coating. Also, the tribological phenomenon at the tool - chip interface was investigated by Grzesik (1998) highlights the crucial effect of different types of coating on dry machining of carbon-based steel AISI 1045 and AISI 304 stainless steel. He used three types of coating layers: TiC, TiC/TiN, and TiC/Al2O3/TiN. He found that, considering the tool -chip interface, (TiC/Al2O3/TiN-AISI 1045) tool - workpiece material couple gave lower values of friction factor and contact pressure, compared to the couples of (TiC/TiN-AISI 1045) and (TiC-AISI 1045).

In addition to the aforementioned effects, tool vibration is another important factor affecting machining process, especially the surface roughness criteria (Risbood *et al*. 2003 and Arizmendi *et al*. 2009). The effects of cutting parameters and vibrations during turning of Ti–6Al–4V alloy were investigated experimentally by Upadhyay *et al*. (2013) using the acceleration amplitude of vibration in axial, radial and tangential directions. They found that the feed rate has the highest effect, followed by the acceleration amplitude of vibration in radial direction, depth of cut, and acceleration amplitude of vibration in tangential direction. The combined effects of cutting parameters and tool vibration on surface roughness were investigated by hissainia *et al*. (2013). They observed that the feed rate is the dominant factor affecting the surface roughness, whereas vibrations on both directions radial and main cutting force directions have a low effect on the surface roughness. Beauchamp and co-workers (1996) carried out various cutting tests at various cutting parameters such as cutting speed, feed rate, depth of cut, tool nose radius, tool overhang and workpiece length using a coated carbide tool in turning operation of mild carbon steel. They revealed that the dynamic force, related to the chip-thickness variation acting on the tool, is related to the amplitude of tool vibration at its natural frequency while cutting.

This study seeks to find out the effect of cutting parameters such as cutting speed, feed rate and depth of cut on the surface roughness value and cutting tool vibrations in radial directions during hard turning of AISI 4140 hardened steel using coated carbide tool. The RSM was employed to find the relationship between the input cutting parameters and the response factors. ANOVA method was used to test the significance of the quadratic regression model and each cutting variables. Additionally, Multi-objective optimization based desirability function was performed to find optimal cutting parameters to minimize surface roughness, and maximize productivity based on response surface methodology (RSM). The response surface methodology (RSM) and Taguchi's S/N methodology are widely used for solving multi response optimization problems (Çiçek *et al*. 2015, Yıldırım *et al*. 2019, Khettabi *et al*. 2017).

## 2. Materials and methods

### *2.1 Workpiece material and cutting inserts*

Turning runs were carried out in dry conditions using a universal lathe SN 40C type with 6.6 kW spindle power.

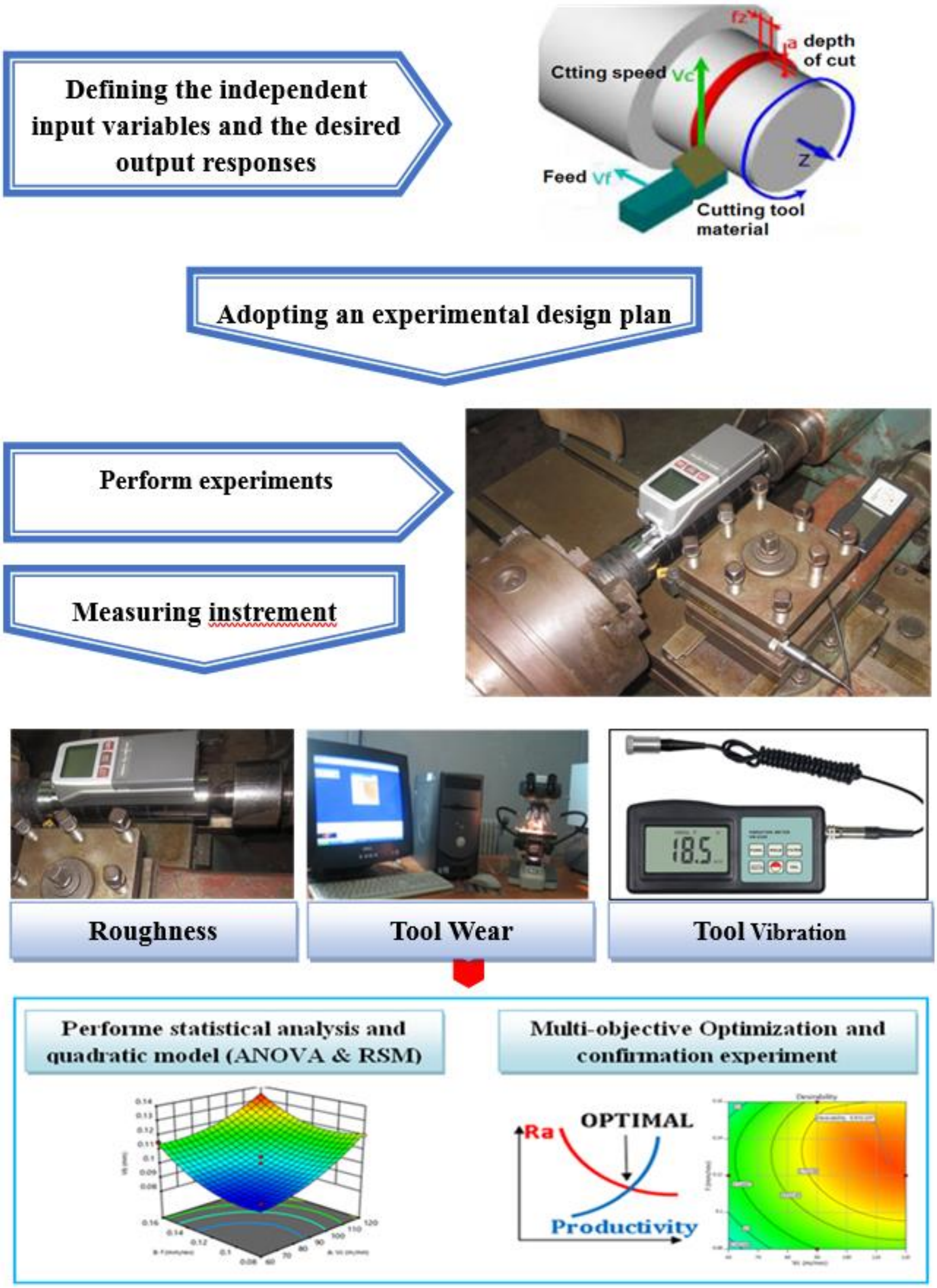


Fig. 1 Experimental design flowchart

The workpiece material was AISI 4140 steel in the form of round bars with 60 mm of diameter and 300 mm cutting length. This material is widely used in manufacturing of automotive components regarding to their properties like high tensile strength, shock resistance.

The chemical composition of workpiece in weight (%) is as follows: 0.397C, 0.389Si, 0.77Mn, 0.052P, 1.1Cr, 0.175Mo, 1.55Ni, 0.64W and 0.285Cu. The hardness of workpiece material after heat treatment was found to be 48 HRC.

An ISO P15 coated carbide insert with an ISO geometry SNMG 120408-PF GC 4015 was employed. The inserts have a thick, (14µm) CVD (TiCN- $Al_2O_3$-TiN) coating layers deposited on cemented carbide substrate. The inserts were mounted on a PSBNR2525K12 tool holder, with the following angles: clearance angle $\alpha 0 = 6°$, negative rake angle $\gamma 0 = -6°$, negative cutting edge inclination angle $\lambda s = -5°$ and cutting edge angle $\chi r = 45°$.

### 2.2. Measuring instruments

The measurement of the arithmetic surface roughness

Table 1 Operating conditions of cutting parameters

| Level | Low | Medium | High |
|---|---|---|---|
| Cutting speed, Vc(m/min) | 60 | 90 | 120 |
| Feed rate, f (mm/rev) | 0.08 | 0.12 | 0.16 |
| Cutting depth, d (mm) | 0.2 | 0.3 | 0.4 |

(Ra) was obtained from a Surftest 201 Mitutoyo roughness-meter. The measurements were repeated at three equally spaced locations around the circumference of the workpiece at 120° and the result was the average of these values. The surface roughness was directly measured on the workpiece, without dismounting from the lathe, in order to reduce measurement errors.

The acceleration amplitude of tool vibration was measured with VM-6360 piezoelectric accelerometer, which was connected to data acquisition PC with RS232 cable for digitization of the vibration signals. These digitized signals were then processed using TestRS232 data collecting system Software for vibrations maters, as showing in experimental design flowchart Fig. 1.

### 2.3. Experimental design

In this study, response surface methodology (RSM) has been used for establishing the relationship between the independent variables and the desired response. The RSM is a very effective method for modeling and optimizing the cutting conditions to achieve maximum or minimum value of desired response. In this research work, a standard RSM design called Box Behnken Design (BBD) has been employed to investigate the cutting conditions. The chosen experimental design involves variation of three factors at three levels (low, medium and high), including cutting speed (Vc), feed (f) and depth of cut (d) as indicated in Table 1. The selected experimental design requires 15 runs including three replications of centre point.

## 3. Experimental results and discussion

The plan of tests was developed for assessing the performance of multilayer coated carbide insert during hard turning of hardened AISI 4140 steel. In this study, the effect of cutting parameters, namely cutting speed (Vc), feed rate (f) and depth of cut (d) on surface roughness (Ra), tool radial vibration (Vy) and tool wear (VBmax) was experimentally studied. Experimental results of machining trials are presented in table 2.

The analysis of collecting experimental data was performed in three steps. The first step was concerned with the ANOVA and the effect of cutting parameters and their interactions. In order to identify the cutting parameters that significantly affects the response values. The second step allowed obtaining the relationships between machining parameters and output variables using response surface methodology (RSM) based quadratic models. Finally, a multi-objective optimization method was employed to optimize machining parameters.

### 3.1. Analysis of variance results

ANOVA method widely used to test and quantified the input parameter effects on response variables and to interpret experimental data. The obtained results are analyzed using design expert, statistical analysis software which is widely used in many engineering applications and previous research papers. The main outputs from an analysis of variance study are arranged in a table. The ANOVA table consists of sources of variation and their degrees of freedom, the total sum of squares, and the mean squares. The analysis of variance table also includes the (F-value) and (p-value). Use these to determine whether the predictors or factors are significantly related to the response. (F-value) is the ratio of mean square of the factor to the mean square of the experimental error; this ratio it can be compared against a critical (F) found in a table. Or use (p-value) to determine whether a factor is significant, typically it can be compared against an alpha value of 0.05. If the p-value is lower than 0.05, then the factor is significant for the developed model to be adequate for a specified confidence interval.

### 3.2 Effect of cutting parameters on surface roughness

The ANOVA results of surface roughness are given in table 3. From these values the **Model F-value** of 5.89 implies the model is significant. There is only a 3.25% chance that an F-value this large could occur due to noise. In addition, the **P-values** less than 0.0500 indicate model terms are significant. In this case the cutting speed, feed rate and the square of feed rate are significant model terms. However the **P-values** greater than 0.1000 indicate the model terms are not significant. Also, the percent contribution shows that the square of feed rate term (31.36%), the feed rate term (30.96%) and cutting speed term (12.21%) have great influence on the surface roughness. Lastly, the cutting depth gave lower influences on the surface roughness where its contribution was less than 1%. In this study the experimental results indicate that the surface roughness is proportional to the square of the feed rate. There are consistent with the results of the theoretical model of surface roughness in the machining process field. These results can be explained by the phenomenon of the grooving helicoidally furrows on the finish machining surface caused by the rising of feed combined with tool-workpiece movement. On the other hand, this phenomenon is explained by the reduce of feed caused low cutting forces, which results less vibration, providing a better surface finish. Similar investigations have been made in the same context. For example, Azizi *et al*. (2012). Found that the improvement of surface roughness (Ra) is caused by decreasing in the cutting forces at high cutting speeds, which also influences the machining system stability. For this raison a numerous investigations have been carried out to study the effect of cutting parameters and cooling/lubricating (MQL and dry processes) conditions on tool wear and surface roughness, were also pointed out by Yıldırım *et al*. 2019 and Khettabi *et al*. 2017 in their research papers.

Table 2 Experimental design and results

| Run | Cutting parameter | | | Surface roughness | Tool vibration | Tool wear VBmax | MRR |
|---|---|---|---|---|---|---|---|
| | Vc m/min | f mm/rev | d mm | Ra µm | Vy mm/s | VBmax mm | Q $mm^3/mn$ |
| 1 | 90 | 0.12 | 0.3 | 0.71 | 0.45 | 0.105 | 3240 |
| 2 | 60 | 0.12 | 0.4 | 1.16 | 0.57 | 0.085 | 2880 |
| 3 | 90 | 0.16 | 0.2 | 3.32 | 0.77 | 0.12 | 2880 |
| 4 | 90 | 0.08 | 0.2 | 1.01 | 0.47 | 0.105 | 1440 |
| 5 | 90 | 0.08 | 0.4 | 1.06 | 0.46 | 0.11 | 2880 |
| 6 | 90 | 0.12 | 0.3 | 0.84 | 0.57 | 0.07 | 3240 |
| 7 | 90 | 0.16 | 0.4 | 3.24 | 0.88 | 0.135 | 5760 |
| 8 | 60 | 0.12 | 0.2 | 1.26 | 0.41 | 0.08 | 1440 |
| 9 | 90 | 0.12 | 0.3 | 0.95 | 0.62 | 0.095 | 3240 |
| 10 | 60 | 0.08 | 0.3 | 1.08 | 0.4 | 0.095 | 1440 |
| 11 | 120 | 0.16 | 0.3 | 2.84 | 0.8 | 0.13 | 5760 |
| 12 | 120 | 0.08 | 0.3 | 1.29 | 0.45 | 0.125 | 2880 |
| 13 | 120 | 0.12 | 0.2 | 0.77 | 0.44 | 0.115 | 2880 |
| 14 | 120 | 0.12 | 0.4 | 1.04 | 0.38 | 0.12 | 5760 |
| 15 | 60 | 0.16 | 0.3 | 3.18 | 0.59 | 0.115 | 2880 |

Table 3 ANOVA results for surface roughness (Ra)

| Source | SS | df | F-value | p-value | PC |
|---|---|---|---|---|---|
| **Model** | 1.58 | 9 | 5.89 | 0.0325 | 91.33 |
| A-Vc | 0.2113 | 1 | 7.09 | 0.0447 | 12.21 |
| B-f | 0.5356 | 1 | 17.97 | 0.0082 | 30.96 |
| C-d | 0.0136 | 1 | 0.4568 | 0.5291 | 0.79 |
| AB | 0.1560 | 1 | 5.24 | 0.0708 | 9.02 |
| AC | 0.0072 | 1 | 0.2425 | 0.6433 | 0.42 |
| BC | 0.0049 | 1 | 0.1644 | 0.7019 | 0.28 |
| $A^2$ | 0.1345 | 1 | 4.51 | 0.0870 | 7.77 |
| $B^2$ | 0.5426 | 1 | 18.21 | 0.0080 | 31.36 |
| $C^2$ | 0.0010 | 1 | 0.0344 | 0.8601 | 0.06 |
| Residual | 0.1490 | 5 | | | 8.61 |
| Cor Total | 1.73 | 14 | | | 100.00 |

The 3D surface plot of mutual effects between feed rate and cutting speed is illustrated in Fig. 2 it can be observed that, the surface roughness strongly increase when the feed rate increased from 0.08 mm/rev to 0.16 mm/rev at a certain cutting speed. Then again surface roughnesses appear better with increasing cutting speed at a constant feed rate. Fig. 3 shows the mutual influence of cutting speed and depth of cut. It can be noted that the slope of Ra response surface is lowly. It revealed that the depth of cut has less effect on surface roughness. Moreover, the surface roughness is ordinarily sensitive to cutting speed; an increase in cutting speed weakly reduces the surface roughness. Fig. 4 shows the effect of depth of cut and feed rate on surface roughness (Ra). It is concluded that the lower feed rate and the lower depth of cut resulted in lower arithmetic surface roughness averages (Ra). From collected experimental results, it is obvious that, the arithmetic surface roughness averages (Ra) in many cutting conditions are within the recommendable

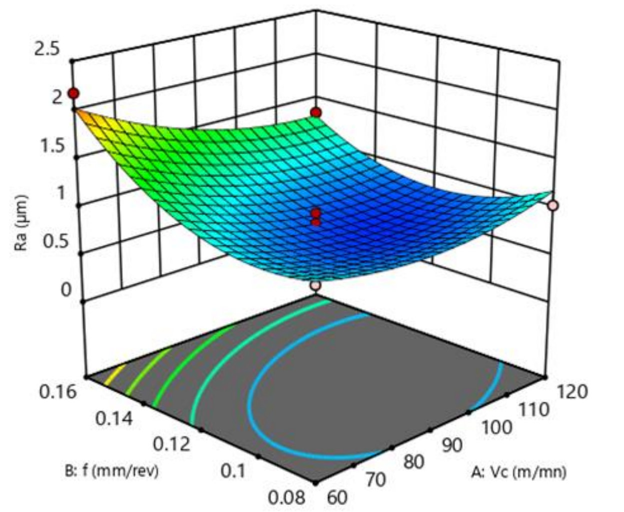


Fig. 2 3D surface graph for Interaction effects of feed rate and cutting speed on surface roughness

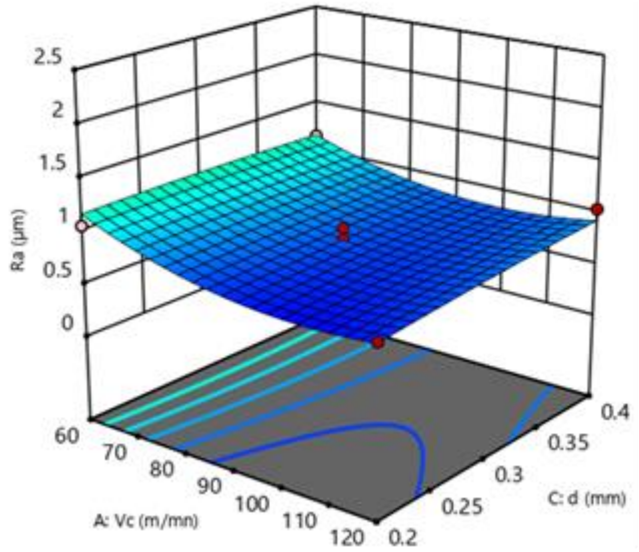


Fig. 3 3D surface graph for Interaction effects of depth of cut and cutting speed on surface roughness

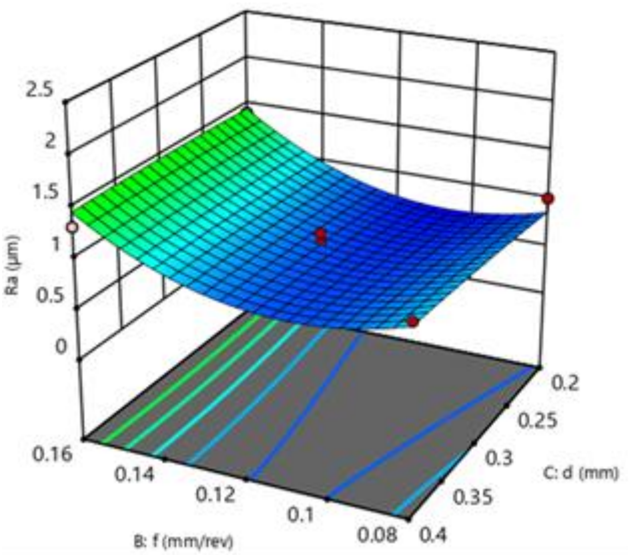


Fig. 4 3D surface graph for Interaction effects of feed rate and depth of cut on surface roughness limit of 1.6 µm comparable to cylindrical grinding.

Other than, at higher cutting speed, feed rate and depth of cut conditions, the surface quality (Ra) increases and go beyond the limit. This phenomenon mainly caused by the catastrophic tool wear and failure of tool edge. Better surface quality produced using coated carbide substantiate its application in hard machining, however, it is necessary the good selection of favorable machining conditions.

### *3.3 Effect of cutting parameters on tool radial vibration (Vy)*

From the analysis of Table 4, the main contribution is noted for feed rate (f) 66.99% and for the squared term of feed rate ($f^2$) 15.49%, there are only terms have statistical and physical significance on the tool radial vibration (Vy). P-values greater than 0.0500 indicate model terms are not significant. In this case cutting speed, depth of cut and all interaction between these terms are not significant model terms. The Model F-value of 9.79 implies the model is significant. There is only a 1.09% chance that an F-value this large could occur due to noise. Based on obtaining results, feed is the most significant factor on the tool radial vibration (Vy) evolution. This is consistent with the surface roughness results analysis subsection in this study. Besides, it can be noted that a strong effect of tool vibration on the surface roughness evolution.

The effects of cutting conditions such as cutting speed, feed rate and depth of cut on the tool radial vibration (Vy) are shown in Figs. 5-7. From 3D surface plots clearly displays that the amplitude of tool vibration strongly increases with an increase in the effect of feed (f). Whereas, presented weak increases with an increase in the effect of cutting speed (Vc) and some case with an increase in the effect of depth of cut (d). These results can be consistent and helpful in the analysis of surface roughness results. On the other hand, a qualitative comparison can be made; for example Hessainia *et al*. (2013) found that the feed rate is the most important factor affecting surface roughness, whereas accelerations amplitude of tool vibrations in radial and tangential directions has a low effect.

Table 4 ANOVA results for tool radial vibration (Vy)

| Source | SS | df | F-value | p-value | PC |
|---|---|---|---|---|---|
| Model | 0.3764 | 9 | 9.79 | 0.0109 | 94.62 |
| A-Vc | 0.0013 | 1 | 0.2925 | 0.6118 | 0.33 |
| B-f | 0.2665 | 1 | 62.35 | 0.0005 | 66.99 |
| C-d | 0.0050 | 1 | 1.17 | 0.3288 | 1.26 |
| AB | 0.0004 | 1 | 0.0936 | 0.7720 | 0.10 |
| AC | 0.0121 | 1 | 2.83 | 0.1533 | 3.04 |
| BC | 0.0036 | 1 | 0.8424 | 0.4008 | 0.90 |
| $A^2$ | 0.0160 | 1 | 3.74 | 0.1108 | 4.02 |
| $B^2$ | 0.0616 | 1 | 14.42 | 0.0127 | 15.49 |
| $C^2$ | 0.0035 | 1 | 0.8214 | 0.4063 | 0.88 |
| Residual | 0.0214 | 5 | | | 5.38 |
| Cor Total | 0.3978 | 14 | | | 100.00 |

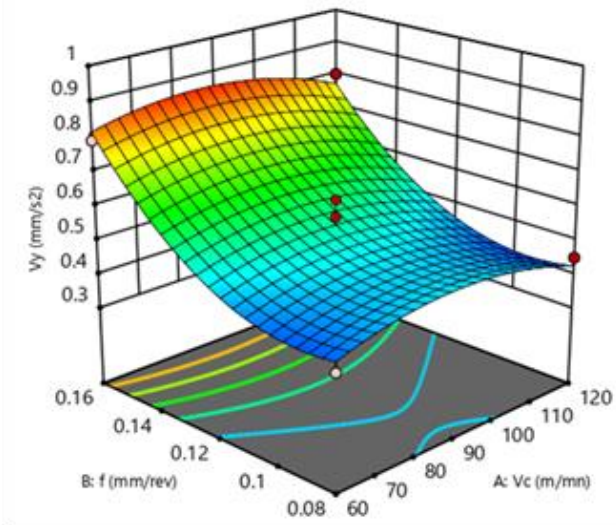


Fig. 5 3D surface graph for Interaction effects of feed rate and cutting speed on tool radial vibration (Vy)

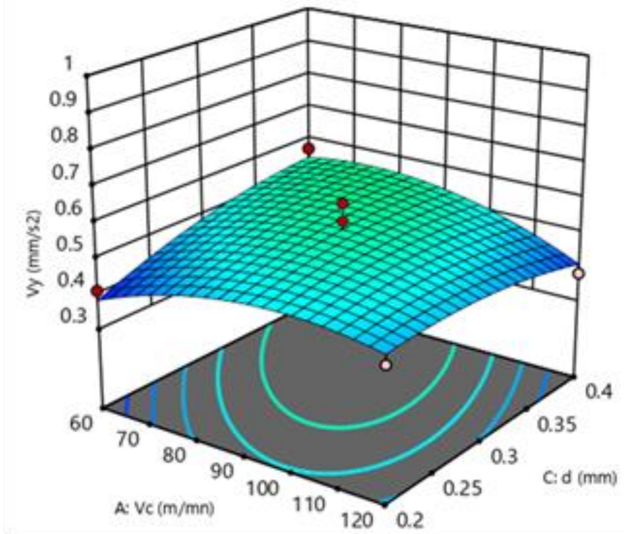


Fig. 6 3D surface graph for Interaction effects of cutting speed and depth of cut on tool radial vibration (Ve)

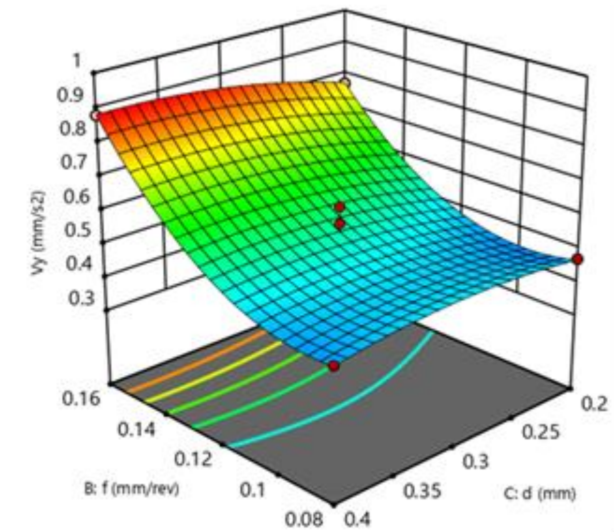


Fig. 7 3D surface graph for Interaction effects of feed and depth of cut on tool radial vibration (Vy)

Table 5 ANOVA results for tool wear (VBmax)

| Source | SS | df | F-value | p-value | PC |
|---|---|---|---|---|---|
| Model | 0.0032 | 9 | 8.58 | 0.0145 | 94.12 |
| A-Vc | 0.0014 | 1 | 33.41 | 0.0022 | 41.18 |
| B-f | 0.0007 | 1 | 17.05 | 0.0091 | 20.59 |
| C-d | 0.0006 | 1 | 14.85 | 0.0120 | 17.65 |
| AB | 0.0000 | 1 | 0.606 | 0.4715 | 0.00 |
| AC | 0.0001 | 1 | 1.36 | 0.2956 | 2.94 |
| BC | 6.E-06 | 1 | 0.151 | 0.7131 | 0.18 |
| $A^2$ | 0.0001 | 1 | 3.50 | 0.1204 | 2.94 |
| $B^2$ | 0.0003 | 1 | 6.85 | 0.0472 | 8.82 |
| $C^2$ | 0.0000 | 1 | 0.559 | 0.4882 | 0.00 |
| Residual | 0.0002 | 5 | | | 5.88 |
| Cor Total | 0.0034 | 14 | | | 100.00 |

### *3.4 Effects of cutting parameters on tool wear (VBmax)*

The ANOVA results of tool wear are given in table 5. From these values the Model F-value of 8.58 implies the model is significant. There is only a 1.45% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case cutting speed (Vc), feed rate (f), depth of cut (d) and the squared term of feed ($f^2$) are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The main contribution is noted for cutting speed (Vc) 41.18%, for feed rate (f) 20.59% for depth of cut (d) 17.65% and for the squared term of feed rate ($f^2$) 15.49%.

The experimental results of variations of flank wear at different cutting condition during machining with coated carbide inserts have been shown in Figs. 8-10. From the 3D surface plots, it can be revealed that, the cutting speed has the highest influence followed by feed rate and depth of cut. From Figs. 8 and 9, it can be observed that for some value of feed rate or depth of cut respectively, the flank wear increases with the increase in cutting speed. Also, the flank wear behavior has a tendency to increase with increase in feed rate and depth of cut. From the above analysis, it is obvious that in cutting condition at lower values of cutting speed, feed rate and depth of cut lead to lower tool wear. On the other hand, it can be noted that for the cutting edge of coated carbide insert in hard turning was unable to resist a machining condition as a depth of cut of 0.4 mm and feed rate of 0.16 mm/rev, in view of the fact that at this level of depth of cut while coupled with higher feed rate the coated carbide insert suffer catastrophic failure.

Fig. 11 shows the tool wear of the multilayer coated carbide insert observed with the optical microscopy after the machining tests. In hard turning process with multilayer coated carbide insert regarding their relatively lower hardness than the PCBN and ceramic tools, this makes abrasion the prevailing wear mechanism. From fig.11 it is clear that the coated carbide insert undergoing impressionable flank wear of the order of 0.135 mm. The flank wear formation on the flank face is mainly influenced

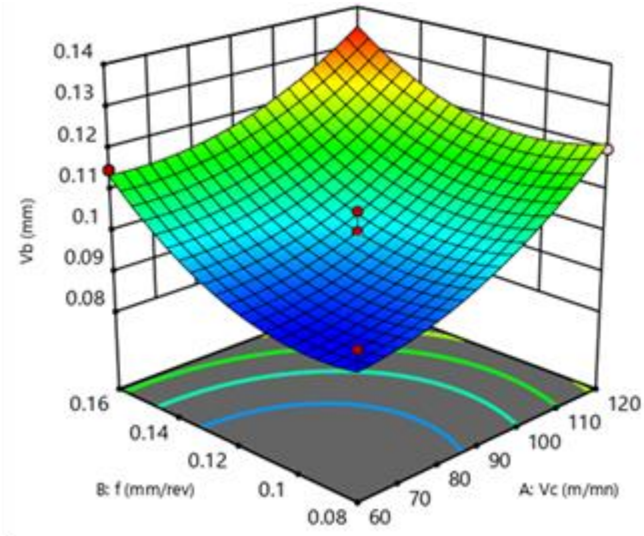


Fig. 8 3D surface graph for Interaction effects of feed and cutting speed on tool wear (VBmax)

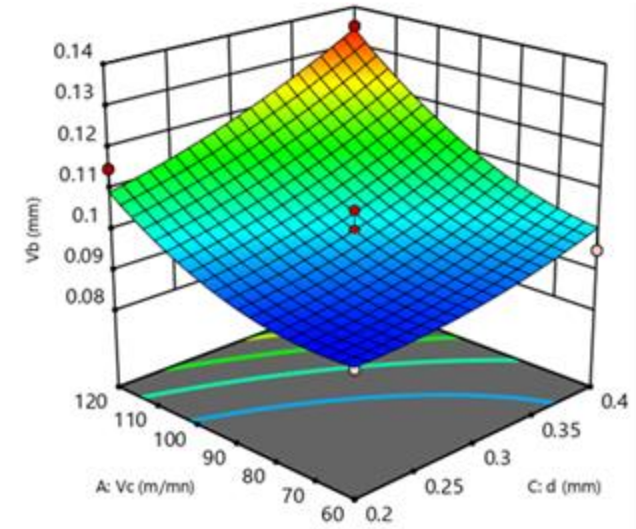


Fig. 9 3D surface graph for Interaction effects of depth of cut and cutting speed on tool wear (VBmax)

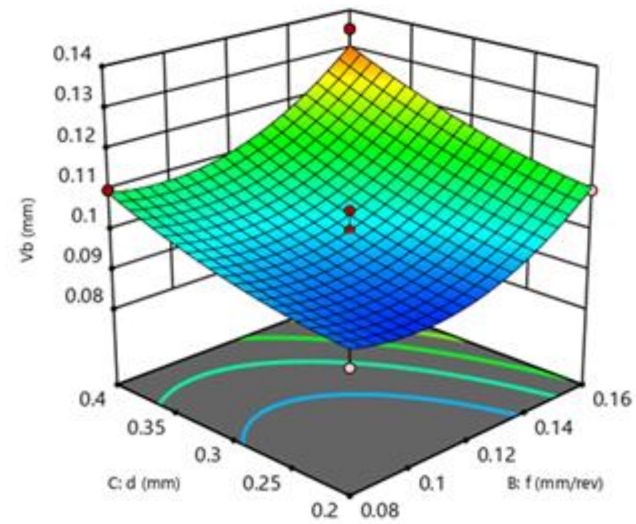


Fig. 10 3D surface graph for Interaction effects of feed and depth of cut on tool wear (VBmax)

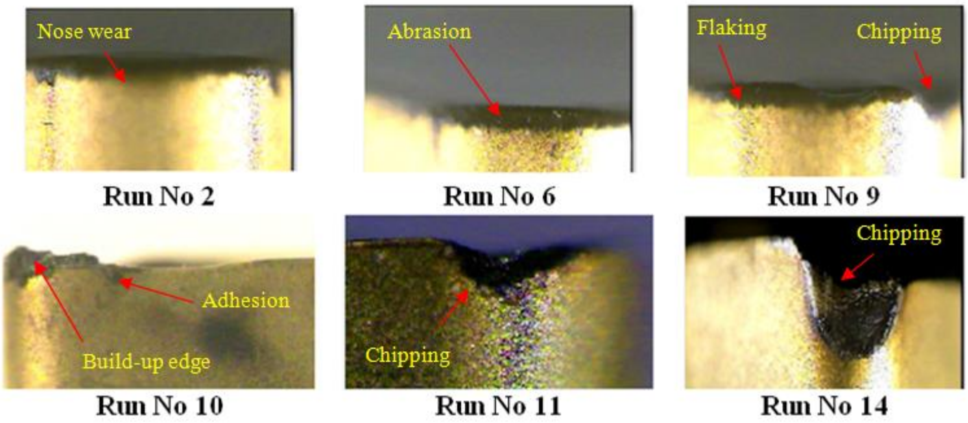


Fig. 11 Micro graphical of main wear mechanisms of coated carbide insert in hard turning [Run numbers according to table 2]

by abrasion wear mechanism and the amount of cutting heat associated with chemical wear. It can be revealed that in higher cutting speed the coating material layers are removed from the cutting edge in a short period of time after that the substrate becomes uncovered. This it can be contributed to reduce hardness and increase substrate thermal conductivity at the elevated cutting temperature. These results can be contributing to clear, the analysis of the variability of surface roughness results.

### *3.5 Quadratic model*

The relationship between the factors and the performance measures were modeled by the quadratic model for surface roughness (Ra), tool radial vibration (Vy) and tool wear (VBmax) during hard turning using coated carbide insert. The quadratic models were obtained from the experimental data. The values of the coefficients were calculated by (RSM) using Design-Expert software. Mathematical equations of the fitted models are given by Eqs. (1)-(3). The goodness of fit of the obtained models was tested through the coefficient of determination ($R^2$), which is the proportion of variation in the dependent parameter explained by the quadratic model. Table 6 gives the $R^2$ values of the obtained models, which also indicate very high correlation between the experimental and the predicted values of studying responses.

$$Ra=+3,73-0,028Vc-33,59f+1,187d-0,164Vc*f +0,0141Vc*d-8,75f*d+0,0002Vc^2+239,58f^2-1,66d^2 \quad (1)$$

$$Vy=-0,06+0,019Vc-16,31f+2,85d-0,008Vc*f-0,018Vc*d +7,5f*d-0,001Vc^2+80,73f^2-3,08d^2 \quad (2)$$

$$VBmax=+0,186-0,001Vc-0,98f-0,21d-0,002Vc*f+0,001Vc*d+0,312f*d+6,94E\text{-}06Vc^2 +5,46f^2+0,25d^2 \quad (3)$$

### *3.6. Multi objective optimization of surface roughness*

The aim of the present experimental study is to perform a Multi-objective optimization intended for minimizing roughness Ra and maximize the material removal rate by desirability approach, using the Design Expert Software. During the optimization process the aim was to find the optimal values of machining parameters in order to produce the lowest surface roughness (Ra) with maximum material removal rate. Table7 show the goals, parameter ranges and importance degrees for the output parameters. Multi-objective optimization results for surface roughness parameter (Ra) relative to the predicted values of studying technological parameters are reported in Table 8 in order of decreasing desirability level.

The optimum cutting parameters obtained, for minimizing Ra and maximizing MRR during hard turning using coated carbide insert are chosen in terms of the

Table 6 Fit Statistics of the fitted models

| Response | Fit Statistics | |
|---|---|---|
| Surface roughness | $R^2$ | 0,9138 |
| | $R^2_{Adjus}$ | 0,7588 |
| Tool vibration | $R^2$ | 0,9463 |
| | $R^2_{Adjus}$ | 0,8496 |
| Tool wear | $R^2$ | 0,9392 |
| | $R^2_{Adjus}$ | 0,8298 |

Table 7 Constraints for optimization of machining parameters

| Name | Goal | Lower Limit | Upper Limit | Importance |
|---|---|---|---|---|
| Vc (m/mn) | in range | 60 | 120 | 3 |
| f (mm/rev) | in range | 0,08 | 0,16 | 3 |
| d (mm) | in range | 0,2 | 0,4 | 3 |
| Ra Roughness (µm) | minimize | 0,71 | 2,18 | 3 |
| Tool vibration Vy ($mm/s^2$) | minimize | 0,38 | 0,88 | 3 |
| Tool wear VBmax (mm) | none | 0,09 | 0,135 | 3 |
| Q MRR ($mm^3/mn$) | maximize | 1440 | 5760 | 3 |

Table 8 Optimal solutions

| Number | Vc | f | d | Ra | Vy | VBmax | MRR | Desirability | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 114,323 | 0,126 | 0,400 | 0,906 | 0,478 | 0,131 | 5760,001 | 0,931 | Selected |
| 2 | 114,625 | 0,126 | 0,400 | 0,906 | 0,474 | 0,131 | 5760,016 | 0,931 | |
| 3 | 113,970 | 0,127 | 0,400 | 0,906 | 0,483 | 0,130 | 5760,002 | 0,931 | |
| 4 | 114,934 | 0,126 | 0,400 | 0,906 | 0,470 | 0,131 | 5760,000 | 0,931 | |
| 5 | 113,611 | 0,127 | 0,400 | 0,906 | 0,487 | 0,130 | 5759,970 | 0,931 | |

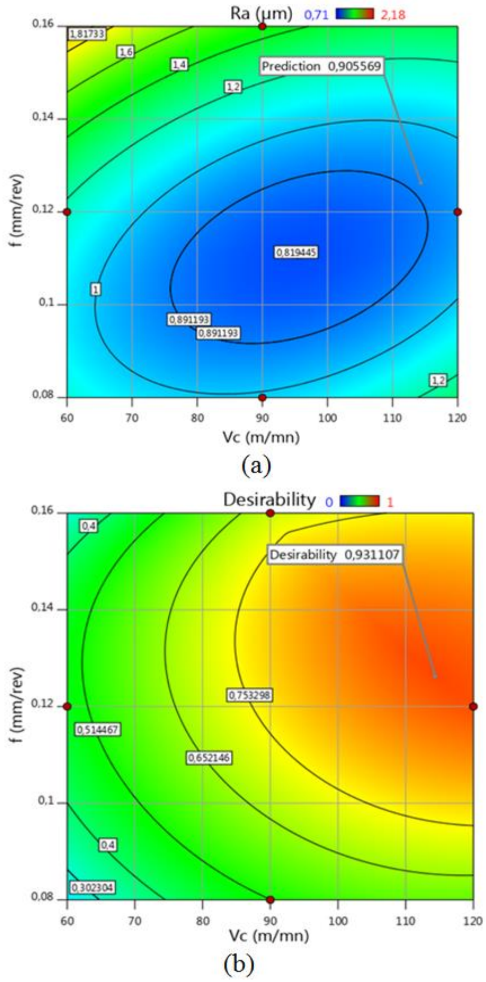


Fig. 12 Contour plot (a) for surface roughness and (b) for Desirability of multi-objective optimization, while (d) kept at the optimal value

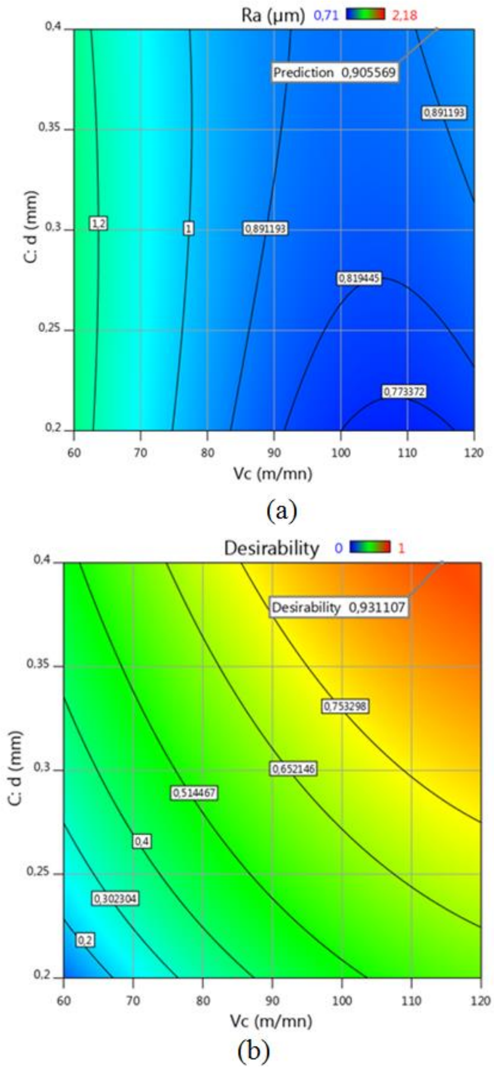


Fig. 13 Contour plot (a) for surface roughness and (b) for Desirability of multi-objective optimization, while (f) kept at the optimal value

highest desirability value are cutting speed (Vc) of 114,323 m/mn, feed rate (f) of 0,126 mm/rev and depth of cut (d) of 0.4 mm. The optimal solutions of surface roughness parameter are Ra = 0,906 µm, and 5760,001 $mm^3$/mn for MRR, with the desirability value of 0,931. Also multi-optimization, results presented predicted values of 0.478 $mm/s^2$ and 0.131 mm for tool radial vibration and tool wear, respectively.

Figs. 12-14 shows the Contour plot for Multi-objective optimization results for Desirability and surface roughness parameter (Ra) relative to the predicted values of studying technological parameters. From figs.12b, 13b and 14b the desirability value was obtained by combining all responses as a function of cutting speed, feed rate and depth of cut, for each plot, the variables not represented are held at the optimal value. The values of machining parameters for multi-objective optimization can be inferred from the desirability value (0.931), which is the red area. The Contour plot for Multi-objective optimization results for surface roughness parameter (Ra) is presented in Figs. 12a, 13a and 14a. In these plots, the minimum value of the surface roughness parameter (Ra) during the hard cutting process, which is the blue area, was at the maximum value of cutting speed, whereas feed rate and depth of cut were at their minimum values. Fig. 14a clearly shows a significant

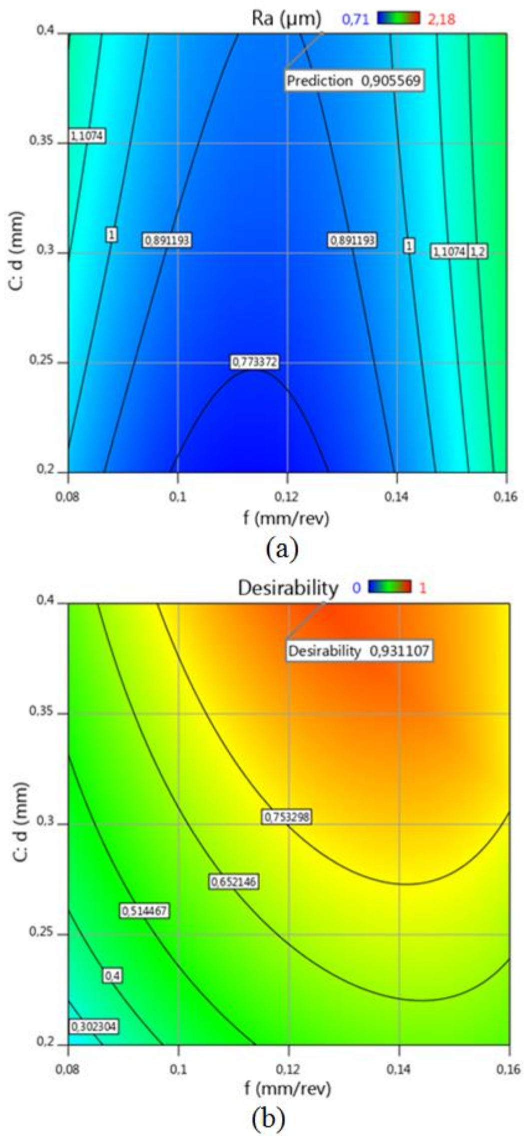


Fig. 14 Contour plot (a) for surface roughness and (b) for Desirability of multi-objective optimization, while (Vc) kept at the optimal value

change in the contour plot when the feed rate and depth of cut changed from low to high values. From the contour plots the optimal decrease in surface roughness was from 0.7 µm to 0.9 µm, where feed rate was within the range of 0.1-0.12 mm/rev, depth of cut in the range of 0.2-0.3 mm, and cutting speed in the range of 90 - 110 m/min.

## 4. Conclusions

This paper presents an experimental investigation of the impact of cutting parameters on surface roughness parameters (Ra), tool wear parameters (VBmax), tool vibration (Ve) and material removal rate (MRR) in hard turning of AISI4140 steel using coated carbide tool. The following conclusion can be drawn based on the experimental results obtained in the scope of this study:

From the ANOVA results, indicates that the surface roughness is proportional to the square of the feed rate. Which, there are consistent with the results of the theoretical model of surface roughness in machining process. Concerning the tool vibration (Vy), the ANOVA analysis showed that the feed rate is the most significant factor, which had a contribution of 66.99%, followed by the square term of feed rate with a contribution of 15.49%.

Among the main input parameters, cutting speed was the most significant factor on tool wear with a contribution of 41.18%, followed by feed rate at 20.59%, finally by the depth of cut with 17.65%. Based on the tool wear analysis, it is found that the adhesion and abrasion are two most dominant wear mechanisms. In hard turning with coated carbide insert the increasing of depth of cut caused rapid and destructive wear mode.

The 3D plot graphs clearly show that the surface roughness was minimized when feed rate and depth of cut were at their lowest levels. The multi-objective optimization results shows the minimum value of surface roughness, tool wear, tool vibration, and material removal rate, which were 0.9µm, 0.13 mm, 0.47mm/s and 5760mm$^3$/mn, respectively. It can be achieved at a cutting speed of 114 m/min, feed rate of 0.12 mm/rev, and 0.4 mm for depth of cut. The desirability value (0.931) can be used to expect the values of machining parameters for multi-objective optimization.

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