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ARCHIVE OF MECHANICAL ENGINEERING

Volume 67 2020 Number 1

DOI: 10.24425/ame.2020.131684

Key words: hard turning, hard steel, ISO 13565 standard, surface texture, bearing area curve (BAC)

Amine Hamdi[1,2], Sidi Mohammed Merghache[2], Toufik Aliouane[1]

Effect of cutting variables on bearing area curve parameters (BAC-P) during hard turning process

Hard turning is a machining process that is widely used in the precision mechanical industry. The characterization of the functional surface texture by the ISO 13565 standard holds a key role in automotive mechanics. Until now, the impact of cutting conditions during hard turning operation on the bearing area curve parameters has not been studied (ISO 13565). The three parameters R_{pk}, R_k and R_{vk} illustrate the ability of the surface texture to resist friction. In this work, the main objective is to study the impact of cutting conditions (Vc, f and ap) of the hard turning on three parameters of the bearing area curve. The statistical study based on response surface methodology (RSM), analysis of variance (ANOVA) and quadratic regression were performed to model the three output parameters and optimize the input parameters. The experimental design used in this study is the Taguchi L_{25} orthogonal array. The results obtained show that the cutting speed has a greater effect on the bearing ratio curve (R_{pk}, R_k and R_{vk}) parameters with a percentage contribution of 37.68%, 37.65% and 36.91%, respectively. The second significant parameter is the feed rate and the other parameter is significant only in relation to R_{pk} and R_k parameters.

1. Introduction

The machining and finishing processes of functional surfaces by material removal are very numerous, among which one can mention turning, milling, grinding, hard turning, belt grinding, etc. Hard turning has proven to be an interesting process in dry machining. It contributes significantly to reducing the total cost of machining precision parts.

✉ Amine Hamdi, e-mail: hamdi_amine@ymail.com

[1]Laboratory of Applied Optics (LAO), Institute of Optics and Precision Mechanics, University Ferhat Abbas Setif 1, 19000, Algeria.

[2]Institute of Sciences & Technology, University Center of Tissemsilt, 38000, Algeria.

Hard turning process (HTP) is defined as a turning operation of hard metals (steel and cast iron) [1]. These materials are treated and thermally hardened, with hardness in the range 45–65 HRC [2] or between 45 and 70 HRC [3]. The tools used in this case have specific properties such as wear resistance, temperature resistance, good chemical stability, etc. Ceramics and cubic boron nitride (CBN) have rendered possible industrial use of this technology. The development of this process was motivated by the need to find an alternative to costly traditional grinding processes. The latter is often long, costly, not flexible and damaging to the environment. Its environmental hazard is due to the coolants used during the machining of precision mechanical parts [4, 5]. Hard turning offers the advantages of reduced costs, reduced production time, improved product quality and achieve close tolerances in terms of surface finish [6]. Hard turning of steel parts with a hardness greater than 60 HRC with mixed ceramic cutting tools and PCBN is one of the most interesting processes for precise finishing [7, 8]. Currently, this process is desirable instead of grinding, in order to increase productivity [9]. During manufacturing process by hard turning, a white layer at surface layer of the machined part appears. The layer formed during hard machining is generally a hard and brittle phase, what exactly is a problem in the commissioning phase. According to Duan et al. [10], the relationship between the white layer thickness and feed rate, carbon content and hardness of material is proportional. According to Revel et al. [11], the AISI 52100 bearing steel turning of medium hardness (61 HRC) using CBN cutting insert improves surface integrity. Therefore, the roughness average Ra of 0.1 to 0.2 μm is within the limits obtained by grinding. In addition, this process produces a white layer < 1 μm on the machined part surface and induces compressive residual stresses.

Until now, many studies were conducted on surface texture, material removal rate, cutting tool wear, cutting efforts, cutting power and cutting tool vibration, related to hard turning operations. Saini et al. [12] used response surface methodology (RSM) and the BOX-Behnken design of experiments to predict surface roughness and tool wear. The experimental data were obtained through 29 turning tests of hardened AISI H-11 steel (48–50 HRC). The data show that good surface quality can be obtained with low feed rate and high cutting speed. However, the drawback of a high cutting speed is a higher wear of the cutting tool. In this respect, Manivel and Gandhinathan [13] studied via the Taguchi method L_{18} orthogonal array, optimization and interactions of cutting parameters on surface roughness (Ra) and tool wear (Vb). The machined material is austempered ductile iron (grade 3), hardness 45 HRC and tensile strength 1241 MPa. A CVD coated carbide cutting tool was used. The ANOVA analysis indicates that the cutting speed has a contribution of 49.1% and 50.2%, respectively. They found that cutting speed is the most influential parameter on both input parameters (Ra and Vb). Bartarya and Choudhury [14] reported that depth of cut is the first factor affecting the three cutting forces (Fx, Fy and Fz) when turning EN31 steel (60 ± 2 HRC) using uncoated CBN tool. The second factor is the feed rate and the last is the cutting speed. The study was based on experimental and numerical results of hard turning cold work tool steel AISI D3 (60 HRC) using a ceramic cutting tool and a complete factorial plan 3^3 (27 trials).

Aouici et al. [15] investigated the impact of three machining parameters of dry hard turning (*Vc*, *f* and *ap*) and the workpiece hardness (*H*) by machining hot work steel AISI H11. Three different levels of workpiece hardness (40, 45 and 50 HRC) and CBN cutting tool, commercially known as CBN7020 (the standard designation is SNGA12 04 08 S01020) were used. After a statistical analysis by ANOVA and mathematical modeling by RSM of four output parameters (*Ra*, *Fa*, *Fr* and *Fv*), the results show that the workpiece hardness and the depth of cut (*H* and *ap*) are primarily influenced by the three components of the cutting force. Furthermore, workpiece hardness and feed rate have particular influence on the surface roughness. According to Azizi et al. [16], the three machining parameters most affecting arithmetic average roughness (*Ra*) during hard turning of AISI 52100 bearing steel by coated Al_2O_3 + TiC mixed ceramic cutting tool are: feed rate (*f*), workpiece hardness (*H*) and cutting speed (*Vc*). Moreover, the depth of cut (*ap*), the workpiece hardness (*H*) and feed rate (*f*) are the most influential parameters on the three cutting force components. Shihab et al. [17] presented a micro-channel development in the insert to supply the cutting fluid directly at the tool-chip interface. This new design has been shown to reduce the flank wear by 48.87% during dry hard turning and 3.04% during wet hard turning. The authors found that this tool saves about 87.5% in the consumption of volume of cutting fluid and energy.

In his works, Jouini et al. [18, 19] examined the relationship between rolling contact fatigue life (RCFL) and surface quality. Precision hard turning (PHT) tests using CBN cutting tool were made on AISI 52100 hardened bearing steel rings with an average hardness of 61 ± 1 HRC. The conclusion drawn from these practical studies highlights a relationship between the RCFL and the roughness amplitude *Ra*. The RCFL reaches 5.2 million cycles for $Ra = 0.11$ µm, 1.2 million cycles for $Ra = 0.2$ µm and 0.32 million cycles for $Ra = 0.25$ µm. Therefore, the RCF life of the ground bearing components reaches 3.2 million cycles for $Ra = 0.05$ µm. Furthermore, the surface roughness of precision hard turning is of the order of 0.1 to 0.2 µm. The grinding process produces values close to or less than the precision hard turning values. In general, the precision hard turning process (PHTP) improves the surface integrity of functional surfaces (surface texture, residual stresses and white layer) [20]. Rotella et al. [21] did a comparative study in 2012 between dry and cryogenic hard turning. The material and cutting inserts used are hardened steel (AISI 52100) and cubic boron nitride (CBN). After a series of experiments under different conditions of cutting speed and feed rate, the researchers in question indicate that cryogenic cooling improves surface integrity, product life and functional performance.

Meddour et al. [22] studied the impact of cutting parameters and the nose radius of mixed ceramic tool on both output parameters: the arithmetic mean roughness (*Ra*) and the three force components (*Fx*, *Fy* and *Fz*). Hard turning experiences are made on AISI 52100 bearing steel (59 HRC) and through a central composite design (CCD) of 30 tests. The results of the statistical analysis (ANOVA) and graphic (RSM) in question researchers have shown that the depth of cut is the first machining parameter influencing the three force components, followed by the feed rate. Moreover, the nose radius affects only the thrust force (Fy). However, the feed rate and nose radius are two parameters with significant influence on surface roughness. More recently, Meddour et al. [23] modeled the surface roughness (Ra) and the three cutting force components when turning AISI 4140 hardened steel (60 HRC). The cutting tool used in the experimental part was of mixed ceramic (70% Al_2O_3 and 30% TiC). The modeling was performed through three approaches. The first is quadratic regression by the response surface method. The others are the artificial neural networks (ANN) and the non-dominated sorting genetic algorithm (NSGA-II). The output responses are better predicted by the ANN technique than by quadratic regression. On the other hand, the results of optimization by NSGA-II are more efficient than those of the desirability function method (DF), which uses second-order RSM models. In addition, the tool nose radius was shown to affect the surface roughness more than the technological parameters during hard turning of AISI 52100 steel (60 HRC) by coated CBN tool [24].

The present study aims at statically analyzing the impact of hard machining parameters (cutting speed (Vc), feed rate (f) and depth of cut (ap)) and their interactions on the parameters of material ratio curve (R_{pk}, R_k and R_{vk}) and finding the role of each machining parameter. This analysis employs RSM, ANOVA and the quadratic regression to model the output parameters. The purpose of this study is to minimize R_{pk} and R_k parameters while maximizing R_{vk} parameter to improve the quality of bearing area curve (BAC).

2. Experimental procedures

2.1. Workpiece material, cutting insert and tool holder

The studied material is a 16MC5 casehardened steel (%C 0.14/0.18), subjected to induction hardening and quenched in oil at a temperature of 860°C, followed by income to 200°C. Its surface hardness after income was 52 HRC. The chemical composition is given in Table 1. This steel is recommended especially for the manufacture of parts subjected to high efforts such as camshafts, gears, etc.

Table 1.
Chemical composition of 16MC5 steel

% by mass	% C	% Mn	% Cr	% Si	% S
Measured value	0.16	1.22	0.63	0.06	0.01

The samples of 30 mm diameter were machined using a conventional lathe with 6.6 KW power and a ceramic tool having good edge retention, strong toughness and high wear resistance. Its designation according to the ISO standard is: SNGN 12 08 08 (see Fig. 1) while that of the tool holder used is: CSSNR3225 P12.

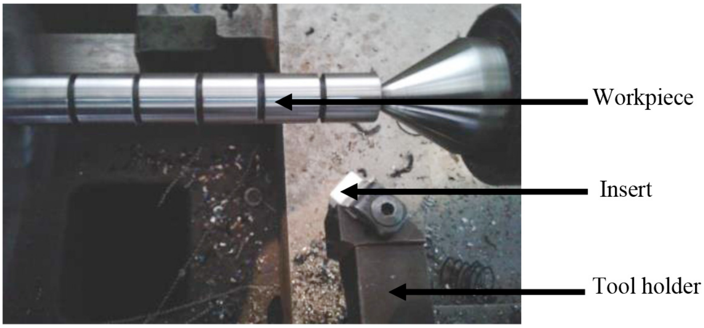


Fig. 1. Work-tool setup in lathe

2.2. Measurements of the parameters of bearing area curve

The parameters measurements of the bearing ratio curve were made on a 2D Taylor Hobson profilometer with a diamond stylus radius of 2 µm (Precision Measurement System Form Talysurf 120), using a Gaussian filter and a cut-off wavelength set to 0.8 mm. The roughness profiles were measured over an evaluation length equal to $Ln = 4.8$ mm, according to ISO 13565 standard. Each surface was characterized by three measurements in different locations and the average value is used in the study.

The measured parameters of the material ratio curve (MRC) during all hard turning tests are: R_{pk} – reduced peak height, R_k – core roughness depth, R_{vk} – reduced valley depth (ISO 13565 standard). The functional parameters R_{pk}, R_k and R_{vk} are determined from the Abbott-Firestone curve "bearing area curve: bearing ratio curve: material ratio curve" (see Fig. 2).

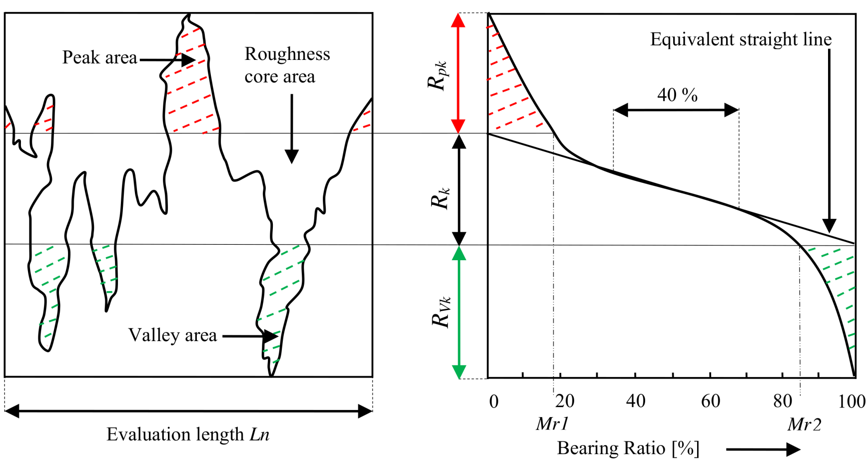


Fig. 2. Bearing area curve (Abbott-Firestone curve)

2.3. Planning of experiments

To reduce the number of tests compared to full factorial design (FFD), the experiment was based on Taguchi L_{25} orthogonal array (25 trials). This method for optimizing cutting parameters offers, compared to others, the advantages of efficiency, simplicity and methodology [25]. Moreover, the Taguchi method is increasingly utilized in machining research [26]. For our study, a factorial plan of three factors was selected with five levels for each. The levels shown in Table 2 were selected in the intervals recommended by the cutting tools manufacturer.

Table 2.

Cutting conditions and their levels

Level	*Vc* [m/min]	*f* [mm/rev]	*ap* [mm]
1	24	0.050	0.10
2	34	0.106	0.15
3	48	0.142	0.20
4	68	0.198	0.25
5	96	0.256	0.30

The diagram in Fig. 3 represents the three input factors and the three measured responses (outputs).

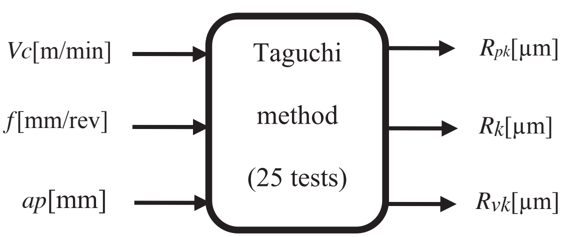


Fig. 3. Input/output parameters

RSM is widely used in science and technology, especially when several input variables influence the results. This analysis technique has been successfully applied to response prediction, design optimization and model validation [27]. The relationship between the cutting conditions (INPUT) and response variations (OUTPUT) is given as follows:

$$Y = F\left(Vc, f, ap\right), \tag{1}$$

where F is the response function and Y is the corresponding response (R_{pk}, R_k and R_{vk}).

In this work, the second-order mathematical model based on the polynomial regression is selected:

$$Y = a_0 + \sum_{i=1}^{k} a_i X_i + \sum_{ij}^{k} a_{ij} X_i X_j + \sum_{i=1}^{k} a_{ii} X_i^2 , \tag{2}$$

where a_0 is the free term of the regression equation, the coefficients a_1, a_2, . . . , a_k and a_{11}, a_{22}, a_{kk} are the linear and the quadratic terms, respectively. While a_{12}, a_{13}, a_{k-1} are the interacting terms. X_i is the input parameters (Vc, f and ap).

3. Experimental results and discussion

3.1. Output data table and theirs S/N rations

The analysis of the impact of cutting conditions (Vc, f and ap) on experimental results and their S/N ratios are given in Table 3.

3.2. ANOVA analysis

Analysis of variance (ANOVA) of experimental results is useful for determining the influence of control factors and their interactions (machining conditions: Vc, f and ap) on the response variation (R_{pk}, R_k and R_{vk}). A factor or interaction can be significant or not when the probability p value is [28]:

- if p value < 0.05, the parameter is significant,
- if p value > 0.05, the parameter is insignificant.

The equation of the sum of (SS_f) squares is:

$$SS_f = \frac{N}{N_{nf}} \sum_{i=1}^{N_{nf}} (\bar{y}_i - \bar{y})^2 , \tag{3}$$

where N is the total number of experiments, N_{nf} is the level of each factor f, $\bar{y}_i$ is the average response observed in experiments where factor f takes its i^{th} level and $\bar{y} = 1\big/N \sum_{i=1}^{N} y_i$ is the average of responses.

Mean squares are estimated by following equation:

$$Ms_i = \frac{SS_i}{df_i} . \tag{4}$$

The index F-ratio is given by following equation:

$$F_i = \frac{Ms_i}{Ms_e} . \tag{5}$$

M_{se} are the mean squares of error.

Table 3.
Experimental results of three output parameters (R_{pk}, R_k and R_{vk}) and their S/N ratios

Trail no.	A: Vc	B: f	C: ap	R_{pk} [μm]	S/N [dB]	R_k [μm]	S/N [dB]	R_{vk} [μm]	S/N [dB]
1	24	0.050	0.10	1.12	−0.98	2.42	−7.67	0.69	−3.22
2	24	0.106	0.15	2.41	−7.64	3.31	−10.39	1.28	2.14
3	24	0.142	0.20	2.47	−7.85	3.43	−10.70	1.33	2.47
4	24	0.198	0.25	2.85	−9.09	3.85	−11.70	1.51	3.57
5	24	0.256	0.30	3.06	−9.71	3.95	−11.93	1.60	4.08
6	34	0.050	0.15	1.01	−0.08	2.09	−6.40	0.57	−4.88
7	34	0.106	0.20	1.78	−5.00	2.80	−8.94	0.84	−1.51
8	34	0.142	0.25	2.14	−6.60	3.23	−10.18	1.21	1.65
9	34	0.198	0.30	2.60	−8.29	3.68	−11.31	1.44	3.16
10	34	0.256	0.10	2.55	−8.13	3.57	−11.05	1.42	3.04
11	48	0.050	0.20	0.54	5.35	1.52	−3.63	0.40	−7.95
12	48	0.106	0.25	1.06	−0.50	2.29	−7.19	0.64	−3.87
13	48	0.142	0.30	1.73	−4.76	2.69	−8.59	0.77	−2.27
14	48	0.198	0.10	1.86	−5.39	2.97	−9.45	0.91	−0.81
15	48	0.256	0.15	1.96	−5.84	3.13	−9.91	1.05	0.42
16	68	0.050	0.25	0.45	6.93	1.44	−3.16	0.38	−8.40
17	68	0.106	0.30	0.75	2.49	1.68	−4.50	0.43	−7.33
18	68	0.142	0.10	1.00	0.00	1.94	−5.75	0.55	−5.19
19	68	0.198	0.15	1.06	−0.50	2.26	−7.08	0.62	−4.15
20	68	0.256	0.20	1.16	−1.28	2.54	−8.09	0.78	−2.15
21	96	0.050	0.30	0.43	7.3	1.36	−2.67	0.36	−8.87
22	96	0.106	0.10	0.26	11.70	1.08	−0.66	0.31	−10.17
23	96	0.142	0.15	0.32	9.89	1.18	−1.43	0.35	−9.11
24	96	0.198	0.20	0.82	1.72	1.78	−5.00	0.48	−6.37
25	96	0.256	0.25	0.96	0.35	1.86	−5.39	0.51	−5.84

The contribution is given by the following equation:

$$Cont.\% = \frac{SS_f}{SS_T} \times 100. \tag{6}$$

The 95% confidence level ($\alpha = 5\%$) is used for the analysis of variance. Tables 4–6 summarize the ANOVA of the experimental results (R_{pk}, R_k and R_{vk}).

Table 4 shows that among the significant cutting parameters on the reduced peaks height (R_{pk}), the cutting speed is the most significant one with a contribution of 37.68%, followed by the feed rate with 21.67%, while the depth of cut is the least significant parameter with a percentage of 1.346%. Regarding interactions and products one can clearly see that the two most significant products are: $Vc \times Vc$ and $f \times f$ with a contribution of 1.269%, 0.852%, respectively.

Table 4.

ANOVA for R_{pk} parameter

Source	*DF*	*SS*	*MS*	*F* value	*P* value	*Cont.* %	Remarks
Model	9	17.2982	1.92202	68.41	< 0.0001	97.62	Significant
Vc	1	6.6771	6.6771	237.67	< 0.0001	37.68	Significant
f	1	3.8398	3.8398	136.68	< 0.0001	21.67	Significant
ap	1	0.2385	0.2385	8.49	0.011	1.346	Significant
$Vc \times f$	1	0.0292	0.0292	1.04	0.324	0.165	Insignificant
$Vc \times ap$	1	0.0071	0.0071	0.25	0.622	0.040	Insignificant
$f \times ap$	1	0.0034	0.0034	0.12	0.733	0.019	Insignificant
Vc^2	1	0.2250	0.2250	8.01	0.013	1.269	Significant
f^2	1	0.1510	0.1510	5.37	0.035	0.852	Significant
ap^2	1	0.0021	0.0021	0.08	0.787	0.012	Insignificant
Residual	15	0.4214	0.02809				
Cor total	24	17.7196					

From the analysis of the variance (ANOVA) of the core roughness depth (R_k) (Table 5), it can be observed that the three cutting conditions (Vc, f and ap) significantly affect the output parameter R_k. However, the cutting speed (Vc) is the most important factor influencing the core roughness depth (R_k) with a contribution of 37.65%. The next factor influencing the core roughness depth (R_k) is the feed rate (f) followed by the depth of cut (ap) with contributions of 23.88% and 1.082%, respectively. The product contribution of the feed rate ($f \times f$) is 0.986%. Other terms have a lower contribution to 0.5%.

As shown in Table 6, both speeds (Vc and f) and the product ($Vc \times Vc$) are significant parameters in the reduced valley depth R_{vk}. The cutting speed was found to be the most significant with a percentage contribution of 36.91%, followed by feed rate (19.50%) and the product of the cutting speed ($Vc \times Vc$) with 1.801%. Other non-significant terms have a contribution of less than 1%. Agrawal et al. [29] concluded through 39 hard turning tests of AISI 4340 (69 HRC), that the feed rate followed by the cutting speed and the cutting depth are the parameters significantly affecting the arithmetic mean roughness Ra. As reported by Alok et al. [30], ANOVA analysis of the dry hard turning of AISI 52100 steel with a new HSN^2 coated carbide insert indicates that the cutting speed is the first significant

Table 5.
ANOVA for R_k parameter

Source	DF	SS	MS	F value	P value	$Cont.$ %	Remarks
Model	9	18.2400	2.02666	87.80	< 0.0001	98.14	Significant
Vc	1	6.9985	6.9985	303.21	< 0.0001	37.65	Significant
f	1	4.4392	4.4392	192.33	< 0.0001	23.88	Significant
ap	1	0.2011	0.2011	8.71	0.010	1.082	Significant
$Vc \times f$	1	0.0590	0.0590	2.56	0.131	0.317	Insignificant
$Vc \times ap$	1	0.0526	0.0526	2.28	0.152	0.283	Insignificant
$f \times ap$	1	0.0047	0.0047	0.20	0.657	0.025	Insignificant
Vc^2	1	0.0437	0.0437	1.89	0.189	0.235	Insignificant
f^2	1	0.1833	0.1833	7.94	0.013	0.986	Significant
ap^2	1	0.0068	0.0068	0.30	0.594	0.036	Insignificant
Residual	15	0.3462	0.02308				
Cor total	24	18.5862					

cutting condition on the cutting force with a contribution of 89.13%, followed by the depth of cut (2.57%) and finally the feed rate (2.28%). This tool (HSN^2) is costing about one-tenth of CBN tool.

Table 6.
ANOVA for R_{vk} parameter

Source	DF	SS	MS	F value	P value	$Cont.$ %	Remarks
Model	9	4.04834	0.44982	55.87	< 0.0001	97.10	Significant
Vc	1	1.5387	1.5387	191.14	< 0.0001	36.91	Significant
f	1	0.8130	0.8130	100.99	< 0.0001	19.50	Significant
ap	1	0.0243	0.0243	3.02	0.103	0.583	Insignificant
$Vc \times f$	1	0.0142	0.0142	1.76	0.204	0.340	Insignificant
$Vc \times ap$	1	0.0002	0.0002	0.03	0.873	0.004	Insignificant
$f \times ap$	1	0.0010	0.0010	0.13	0.720	0.024	Insignificant
Vc^2	1	0.0751	0.0751	9.34	0.008	1.801	Significant
f^2	1	0.0144	0.0144	1.79	0.201	0.345	Insignificant
ap^2	1	0.0006	0.0006	0.08	0.787	0.014	Insignificant
Residual	15	0.12076	0.00805				
Cor total	24	4.16910					

3.3. Regression analysis

Regression analysis appeared as a technique to study the functional relationship between the dependent variable and the independent variables (Vc, f and ap) [31]. Based on experimental results, the quadratic regression is used to determine the relationship between the cutting conditions and the three parameters (R_{pk}, R_k and R_{vk}). The coefficient of multiple determinations R^2 measures variation proportion in the data points. If R^2 value is very close to +1 (100%), the equation is considered significant [32].

The model of the reduced peaks height R_{pk} is given by Eq. (7). The determination coefficient of this model is equal to 97.62%.

$$\begin{aligned} R_{pk} &= 1.78980 - 0.0640460Vc + 21.2196f - 0.732955ap \\ &\quad + 0.000340937Vc^2 - 0.0622210Vc \times f + 0.0310595Vc \times ap \\ &\quad - 32.4492f^2 - 8.50436f \times ap + 4.09748ap^2 \\ &\qquad (R^2 = 97.62\%). \end{aligned} \tag{7}$$

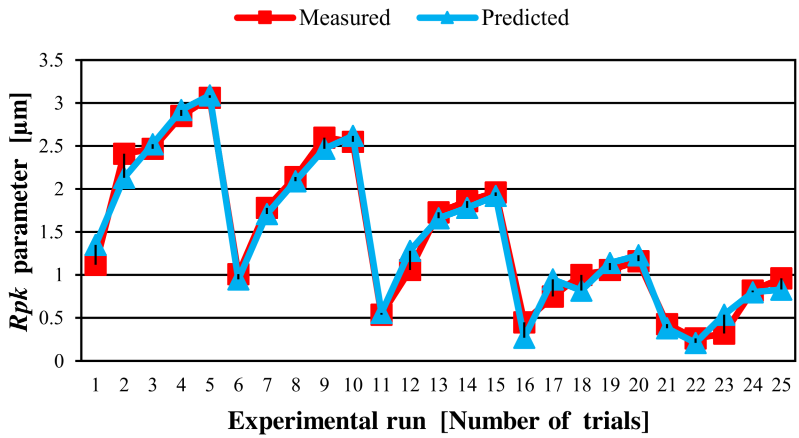
The quadratic regression equation of core roughness depth R_k is given by Eq. (8). The determination coefficient value is 98.14%.

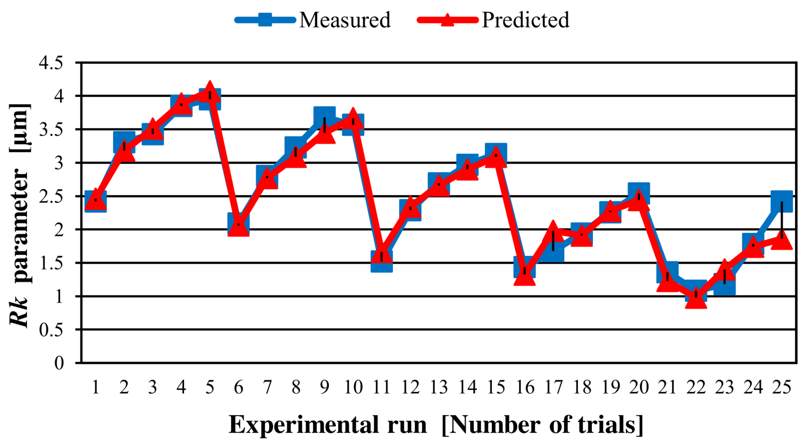
$$\begin{aligned} R_k &= 2.76157 - 0.0484485Vc + 20.5352f - 2.30906ap \\ &\quad + 0.000150177Vc^2 - 0.0884360Vc \times f + 0.0844375Vc \times ap \\ &\quad - 35.7491f^2 + 10.0335f \times ap - 7.35965ap^2 \\ &\qquad (R^2 = 98.14\%). \end{aligned} \tag{8}$$

The quadratic equation of reduced valley depth R_{vk} is given by Eq. (9). The determination coefficient of this model is equal to 97.10%.

$$\begin{aligned} R_{vk} &= 0.836586 - 0.0307799Vc + 9.32216f + 1.75402ap \\ &\quad + 0.000197061Vc^2 - 0.0433723Vc \times f + 0.00537516Vc \times ap \\ &\quad - 10.0318f^2 - 4.77682f \times ap - 2.19134ap^2 \\ &\qquad (R^2 = 97.10\%). \end{aligned} \tag{9}$$

The previous three models of the components of the BAC can be used to predict surface roughness. Fig. 4 shows a comparison between predicted and measured values of the bearing ratio curve components. The results of this study confirm that the actual values are very close to the predicted values. In addition, the three non-linear models are statistically significant with ($P < 0.05$), and hence the validity of the models can be confirmed. These quadratic models could probably contribute to predicting the values of bearing ratio curve parameters in the range of cutting conditions used.





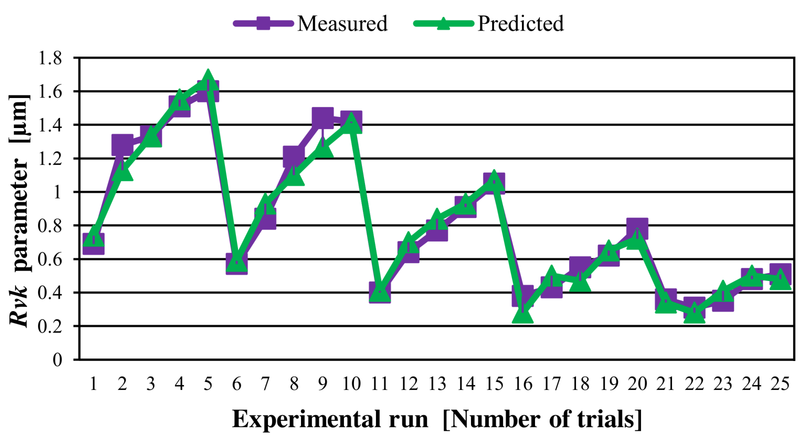
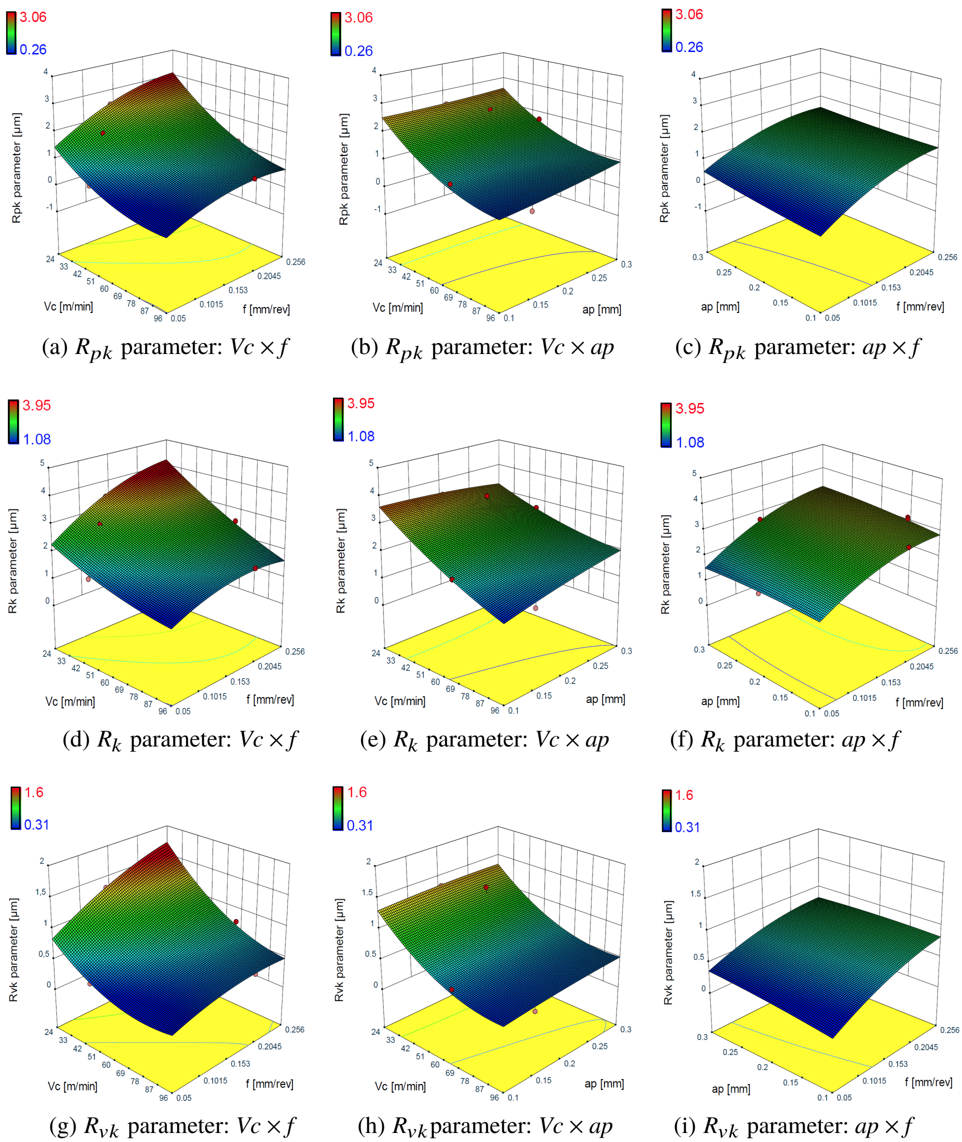


Fig. 4. Comparison between measured and predicted values for the bearing curve components

3.4. Response surface analysis

Fig. 5 shows in 3D response surfaces of three dependent variables (R_{pk}, R_k and R_{vk}) under the effect of interactions of three process variables (Vc, f and ap). So, the possible interactions are: $Vc \times f$, $Vc \times ap$ and $ap \times f$. In the figure and for each interaction, the not shown control factor is kept constant for the intermediate level (Vc = 48 m/min, f = 0.142 mm/rev, ap = 0.20 mm). As shown in this Fig. 5



(a) R_{pk} parameter: $Vc \times f$ (b) R_{pk} parameter: $Vc \times ap$ (c) R_{pk} parameter: $ap \times f$

(d) R_k parameter: $Vc \times f$ (e) R_k parameter: $Vc \times ap$ (f) R_k parameter: $ap \times f$

(g) R_{vk} parameter: $Vc \times f$ (h) R_{vk} parameter: $Vc \times ap$ (i) R_{vk} parameter: $ap \times f$

Fig. 5. 3D response surface obtained for different interactions: left: R_{pk} parameter, middle: R_k parameter, right: R_{vk} parameter

(a, b, d, and g), the slope of cutting speed is greater relative to slope of the two other factors, there by implying that it is the first cutting condition affecting the output parameters. The second significant parameter is the feed rate (f) followed by the depth of cut (ap). Furthermore, the interaction ($Vc \times f$) appears as a significant term for the parameters of Abbott-Firestone curve. These results are in agreement with the work of Alok and Das [33] who found that the cutting speed is the most important parameter influencing the arithmetic mean roughness Ra. According to response surface methodology (RSM) performed by Hessainia et al. [34] during hard turning of AISI 4140 steel (56 HRC), the feed rate and the depth of cut are the two cutting conditions most affecting arithmetic average roughness Ra.

3.5. Optimization

3.5.1. Mono-objective optimization using S/N ratio

In order to analyze the experimental results, the signal-to-noise ratio (S/N) is used because it is the core criterion in the Taguchi method [35]. The signal-to-noise ratio (S/N) optimizes the control factors [36]. These are the variables that can be controlled in a practical and economical way [37]. The purpose of this study is to minimize R_{pk} and R_k parameters while maximizing R_{vk} parameter to improve the quality of bearing area curve (BAC). According to this method, to obtain optimal cutting conditions, the S/N ratio must have a maximum value for the three parameters (R_{pk}, R_k and R_{vk}). The S/N ratio is generally divided into three categories given by the following equations [38, 39]:

Nominal is the best:

$$S/N = 10\log\left(\frac{\bar{y}}{s_y^2}\right). \tag{10}$$

The-smaller-is-the better:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right). \tag{11}$$

The-larger-is-the better:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right). \tag{12}$$

The S/N ratio of both R_{pk} and R_k parameters is calculated using Eq. (11) "The smaller is the better (minimize)". On the other hand, the reduced valley depth R_{vk} was calculated using Eq. (12) "The-larger is the better (maximize)". The experimental results of the parameters of Abbott-Firestone curve and their signal-to-noise (S/N) ratios are shown in Table 3.

By Taguchi design, Table 7 shows the optimal levels of cutting conditions for the optimal values of three parameters of the material ratio curve. These values are graphically represented (Figs. 6–8). From these graphs and Table 7, one can see that optimal cutting conditions are easily determined to minimize the first two BAC parameters and maximize the last one. The best levels correspond to higher S/N ratio values of the three parameters (R_{pk}, R_k and R_{vk}). So, the levels and S/N ratios of the three factors (A: Vc, B: f and C: ap) giving the best values of three parameters (R_{pk}, R_k and R_{vk}) are: for R_{pk} (factor A (level 5, S/N = 6.201),

Table 7.
S/N response table for (a) R_{pk} parameter, (b) R_k parameter, and (c) R_{vk} parameter; (a) and (b): the-smaller-is-the better, (c) the-larger-is-the better

Trail no	A: Vc [m/min]	B: f [mm/rev]	C: ap [mm]
(a)			
1	−7.058	**3.709**	**–0.561**
2	−5.626	0.208	−0.836
3	−2.230	−1.865	−1.415
4	1.527	−4.313	−1.784
5	**6.201**	−4.925	−2.589
Delta	13.259	8.634	2.028
Rank	1	2	3
(b)			
1	−10.484	**–4.711**	**–6.922**
2	−9.580	−6.342	−7.046
3	−7.759	−7.336	−7.278
4	−5.722	−8.914	−7.529
5	**–3.035**	−9.277	−7.804
Delta	7.449	4.566	0.882
Rank	1	2	3
(c)			
1	**1.812**	−6.668	−3.272
2	0.294	−4.150	−3.117
3	−2.900	−2.489	−3.105
4	−5.447	−0.919	−2.578
5	−8.077	**–0.090**	**–2.245**
Delta	9.889	6.577	1.027
Rank	1	2	3

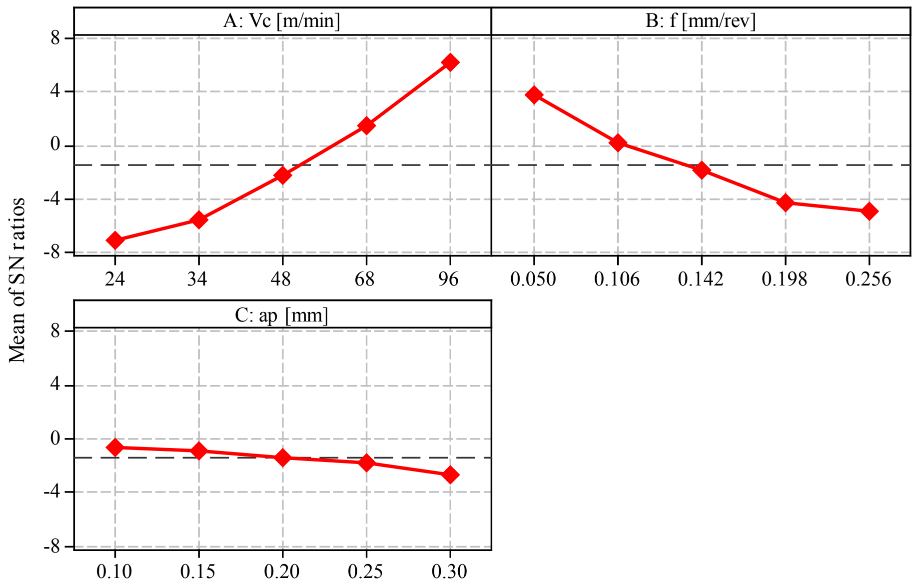


Fig. 6. Impact of cutting conditions on S/N ratio for R_{pk} parameter

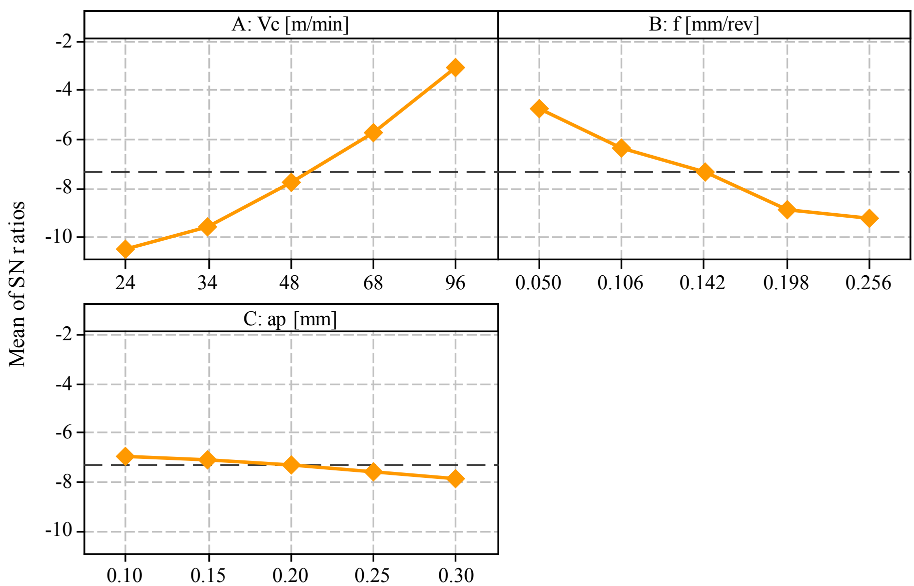


Fig. 7. Impact of cutting conditions on S/N ratio for R_k parameter

factor B (level 1, $S/N = 3.709$) and factor C (level 1, $S/N = -0.561$)), for R_k (factor A (level 5, $S/N = -3.035$), factor B (level 1, $S/N = -4.711$) and factor C (level 1, $S/N = -6.922$)), and for R_{vk} (factor A (level 1, $S/N = 1.812$), factor B (level 5, $S/N = -0.090$) and factor C (level 5, $S/N = -2.245$)). Indeed, we can see that the slope of the cutting speed (Vc) is greater than the slope of the feed rate and the depth of cut (lower slope) (Figs. 6–8). These figures show that the cutting speed has the most significant effect whereas the depth of cut has the least significant one. In this context, the optimal values for R_{pk}, R_k and R_{vk} parameters of the bearing ratio curve are obtained for a cutting speed of 96 m/min (A5), a feed rate of 0.106 mm/rev (B2) and a depth of cut 0.10 mm (C1) because the value of R_{vk} = 0.31 µm is a large value for supplying, circulating and storing the oil during engine running. As a matter of comparison, Meddour et al. [23] found that both S_k and S_{pk} surface parameters decrease with increasing cutting speed when turning AISI 4140 steel hardened to 60 HRC. Khellouki et al. [40] showed that if working on AISI 52100 bearing steel hardened to 62 HRC, the core roughness depth R_k drops from 0.9 µm for hard turning to 0.38 µm for belt finishing.

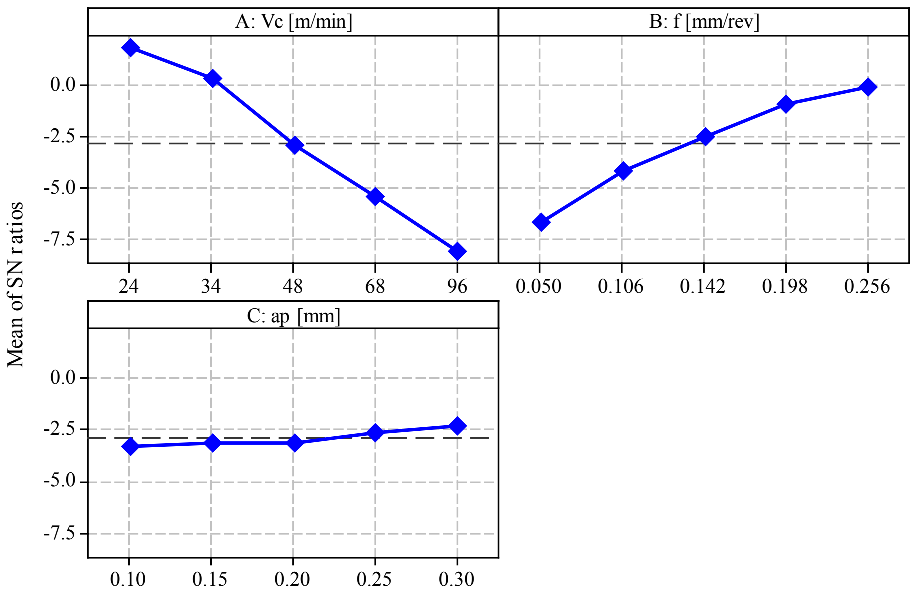


Fig. 8. Impact of cutting conditions on S/N ratio for R_{vk} parameter

3.5.2. Multi-objective optimization using DF

In this section, the main purpose of digital optimization is to find the optimum values of the machining conditions of 16MC5 hard turning steel to produce the lowest value of the bearing ratio curve parameters (R_{pk} and R_k) and the highest value of the other parameter (R_{vk}). The desirability function (DF) is employed to optimize the output parameters. The goal of cutting conditions and the response parameters, and their upper and lower limits are illustrated in Table 8. Tables 9–11 summarize the results of optimizing response parameters, using RSM, of the material ratio curve R_{pk}, R_k and R_{vk}, respectively. The contour graph is shown in Fig. 9.

Table 8.
Conditions for optimization of hard turning parameters

Conditions	Goal	Lower limit	Upper limit
Cutting speed, Vc [m/min]	In range	24	96
Feed rate, f [mm/rev]	In range	0.050	0.256
Depth of cut, ap [mm]	In range	0.10	0.30
R_{pk} parameter, [µm]	Minimize	0.26	3.06
R_k parameter, [µm]	Minimize	1.08	3.95
R_{vk} parameter, [µm]	Maximize	0.31	1.6

Table 9.
Response optimization for R_{pk} parameter

Solution no.	Vc [m/min]	f [mm/rev]	ap [mm]	R_{pk} [µm]	Desirability	Remarks
1	95.262	0.053	0.108	0.245	1.000	Selected
2	81.177	0.254	0.100	0.252	1.000	
3	89.042	0.256	0.101	0.117	1.000	
4	95.554	0.252	0.104	0.073	1.000	

Table 10.
Response optimization for R_k parameter

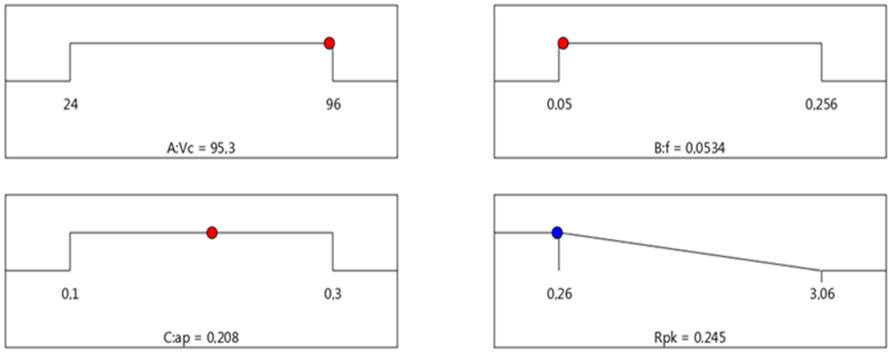
Solution no.	Vc [m/min]	f [mm/rev]	ap [mm]	R_k [µm]	Desirability	Remarks
1	96.000	0.050	0.100	0.479	0.953	Selected
2	96.000	0.050	0.101	0.492	0.950	
3	95.726	0.050	0.100	0.493	0.950	
4	95.936	0.051	0.100	0.501	0.948	

Table 11.
Response optimization for R_{vk} parameter

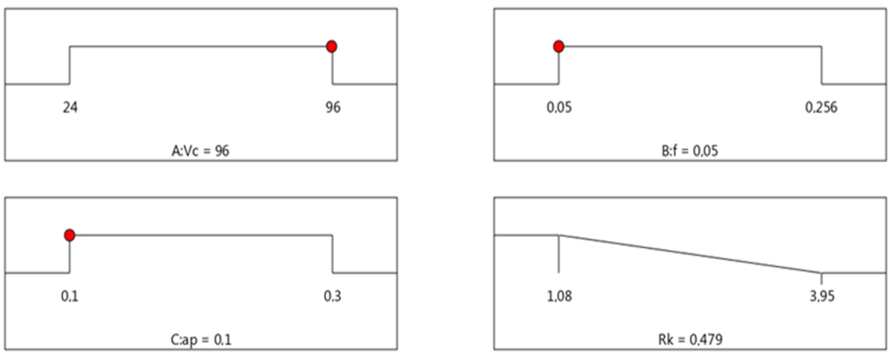
Solution no.	Vc [m/min]	f [mm/rev]	ap [mm]	R_{vk} [µm]	Desirability	Remarks
1	24.000	0.163	0.281	1.646	0.892	Selected
2	24.000	0.163	0.282	1.646	0.892	
3	24.000	0.163	0.282	1.646	0.892	
4	24.000	0.162	0.282	1.645	0.892	

From Tables 9–11 and Fig. 9, the values of the optimal cutting parameters to achieve a better quality of the bearing area curve (BAC) are:

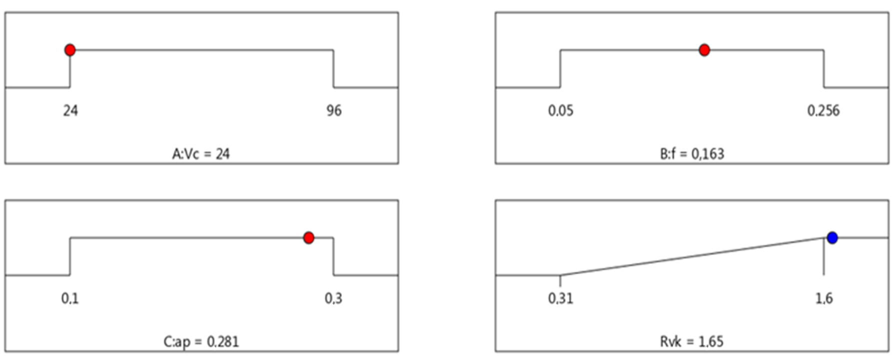
- R_{pk} = 0.24 µm: Vc = 95 m/min, f = 0.05 mm/rev and ap = 0.2 mm,
- R_k = 0.47 µm: Vc = 96 m/min, f = 0.05 mm/rev and ap = 0.1 mm,
- R_{vk} = 1.65 µm: Vc = 24 m/min, f = 0.16 mm/rev and ap = 0.28 mm.



(a) R_{pk} parameter: desirability = 1.000



(b) R_k parameter: desirability = 0.953



(c) R_{vk}parameter: desirability = 0.892

Fig. 9. Desirability function graph for output parameters (R_{pk}, R_k and R_{vk})

So, the optimal cutting regime chosen is: Vc = 96 m/min, f = 0.05 mm/rev and ap = 0.1 mm, since the value of reduced valley depth R_{vk} = 0.31µm is a large value for oil supply, circulation and storage during engine operation.

4. Conclusions

The objective of this work was to study the impact of technological parameters (cutting speed (Vc), feed rate (f) and depth of cut (ap)) during hard turning operation of 16MC5 steel on the Abbott-Firestone curve components (the roughness peaks (R_{pk}), the roughness core (R_k) and the valleys (R_{vk})) and finding the role of each machining parameter. The main conclusions drawn from this study are:

- The S/N report shows that the cutting speed (Vc) is the most fundamental factor affecting the bearing area curve components (R_{pk}, R_k and R_{vk}) whereas the depth of cut (ap) is the least significant.
- The statistical analysis of variance (ANOVA) confirmed that the cutting speed (Vc) has the strongest effect on the three criteria of Abbott curve, followed by feed rate (f). While the depth of cut (ap) is the third significant cutting parameter on the first two parameters (R_{pk} and R_k) and not significant on the reduced valley depth (R_{vk}). The percentage contribution of the cutting speed (Vc) are (37.68%, 37.65%, 36.91%), on the output parameters R_{pk}, R_k and R_{vk}, respectively.
- Comparison of the experimental and estimated results clearly shows that the models resulting from the quadratic regression method give satisfactory results ($R^2(R_{pk}) = 97.62\%$, $R^2(R_k) = 98.14\%$ and $R^2(R_{vk}) = 97.1\%$). Agood agreement has been reached between the two results.
- The mathematical models found represent a considerable interest in mechanics and industry, since they help making predictions.
- The hard machining parameters obtained by the desirability function (DF) method are: cutting speed (96 m/min), feed rate (0.05 mm/rev) and depth of cut (0.1 mm), since the value of $R_{vk} = 0.31$ µm is a great value to supply, circulate and store oil during engine operation, so the engine runs long.
- Under these working conditions, the bearing area curve is improved and this makes it possible to: reduce running-in time, wear rate and oil consumption (the curve is relatively a horizontal line in its intermediate part). Thus, the turned surface approaches the configuration which characterizes a 'plateau' surface. This kind of surface is required for its good bearing properties.

Manuscript received by Editorial Board, December 15, 2019;
final version, March 14, 2020.

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