Springer

KSME

Journal of Mechanical Science and Technology 26 (11) (2012) 3605~3616
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-012-0853-1

Analysis and prediction of tool wear, surface roughness and cutting forces in hard turning with CBN tool †

Samir Khamel[1,2,*], Nouredine Ouelaa[2] and Khaider Bouacha[1,2]

[1]*Department of Industrial Maintenance, Mohamed Chérif Messaadia University, P.O. Box 1553, Souk Ahras 41000, Algeria*
[2]*Laboratory of Mechanics and Structures (LMS), 8 May 1945 University, P.O. Box 401, Guelma 24000, Algeria*

(Manuscript Received November 23, 2011; Revised April 21, 2012; Accepted July 3, 2012)

Abstract

The main of the present study is to investigate the effects of process parameters (cutting speed, feed rate and depth of cut) on performance characteristics (tool life, surface roughness and cutting forces) in finish hard turning of AISI 52100 bearing steel with CBN tool. The cutting forces and surface roughness are measured at the end of useful tool life. The combined effects of the process parameters on performance characteristics are investigated using ANOVA. The composite desirability optimization technique associated with the RSM quadratic models is used as multi-objective optimization approach. The results show that feed rate and cutting speed strongly influence surface roughness and tool life. However, the depth of cut exhibits maximum influence on cutting forces. The proposed experimental and statistical approaches bring reliable methodologies to model, to optimize and to improve the hard turning process. They can be extended efficiently to study other machining processes.

Keywords: ANOVA; CBN tool; Hard turning; RSM

1. Introduction

In recent years, hard turning of steel parts that are often hardened above 46 HRC [1] became very popular technique in manufacturing of gears, shafts, bearings, cams, forgings, dies and molds. In order to withstand the very high mechanical and thermal loads of the workpiece and cutting materials with improved performances, such as ultrafine grain cemented carbides, cermets, ceramics, cubic boron nitrides (CBN), polycrystalline cubic boron nitride (PCBN) and polycrystalline diamonds, have been developed and applied [2, 3]. Hard turning is a developing technology that offers many potential benefits compared to grinding, which remains the standard finishing process for critical hardened steel surfaces [3, 4]. Some decisive factors leading to this manufacturing trend are: substantial reduction of manufacturing costs, decrease of production time, achievement of comparable surface finish and reduction or elimination of environmentally harmful cooling media [4-8].

During finish hard turning operation, complex and mutual interactions are created between tool and workpiece at the contact surface. Consequently, significant cutting forces and extreme tribological conditions developing at dry severe friction and high contact interface temperatures (workpiece-tool and tool-chip) are recorded causing or tend towards the acceleration of tool wear and sometimes breakage of the tool.

As a result, the precisions on the finished workpiece dimensions as so as the surface roughness are altered or the material mechanical characteristics are modified. To increase the implementation of this technology, questions about the ability of this process to produce surfaces that meet surface finish and integrity requirements must be answered. Namely that the potential economic benefits of hard turning can be offset by rapid tool wear or premature tool failure if the brittle cutting tools required for hard turning are not used properly. The economics of the process must be justified, which requires a better understanding of the phenomena which intervene during the hard turning operation. Machined surface characteristics are important in determining the functional performance such as fatigue strength, corrosion resistance and tribological properties of machined components. The quality of surfaces of machined components is determined by the surface finish and integrity obtained after machining. High surface roughness values, hence poor surface finish, decrease the fatigue life of machined components. It is therefore clear that control of the machined surface is essential [9] and it can be achieved, among other factors, by the evaluation of the cutting forces.

*Corresponding author. Tel.: +213793407644, Fax.: +21337227857
E-mail address: samirkhamel@yahoo.fr
† Recommended by Associate Editor Song Min Yoo

Indeed, the study of cutting forces is critically important in turning operations because cutting forces correlate strongly with cutting performance such as surface accuracy, tool wear, tool breakage, cutting temperature self-excited and forced vibrations, etc. Knowledge of the cutting forces is needed for estimation of power requirements and for the design of machine tool elements, tool-holders and fixtures, adequately rigid and free from vibration. In turning, there are many factors affecting the cutting process behaviour such as tool variables, workpiece variables and cutting conditions. Tool variables consist of tool material, cutting edge geometry (clearance angle, cutting edge inclination angle, nose radius, rake angle...), tool vibration, etc., while workpiece variables comprise material, mechanical properties (hardness...), chemicals and physicals properties, etc. Furthermore, cutting conditions include cutting speed, feed rate and depth of cut. The selection of optimal process parameters is usually a difficult work, however, is a very important issue for the machining process control in order to achieve improved product quality, high productivity and low cost. The optimization techniques of machining parameters through experimental methods and mathematical and statistical models have grown substantially over time to achieve a common goal of improving higher machining process efficiency.

However, due to the complex nature of the machining processes, where several different and contradictory objectives must be simultaneously optimized, the single objective optimization approaches do not permit to find the global optimal cutting conditions value which satisfies all the performance characteristics; hence the multi-objective optimization has become an increasingly important and demanding task. Indeed, it offers greatest amount of information in order to make a decision on selecting cutting parameters in machining process.

Finish hard turning differs from conventional turning of softer materials in several key ways. Because the material is harder, specific cutting forces (force per unit, chip cross-section area) are larger than in conventional turning. Studies carried out by König et al. [10] showed that cutting force was 50% larger and feed and thrust forces were 100% larger when turning AISI 52100 ball bearing steel of hardness 63 HRC as compared to turning the same material having hardness 32 HRC. Moreover, it is mentioned in the case of hardened steel machining that the larger negative is the insert rake angle, the higher is the thrust force [10, 11]. In this context, Chen [12] has reported when investigating experimentally the machining of hardened steel (45-55 HRC) with CBN insert that the radial thrust cutting force was the largest among the three cutting force components. However, according to Nakayama et al. [13] cutting forces in hard material machining are not necessarily higher compared with those of soft materials. A high shear angle and the formation of saw-toothed chips due to poor ductility reduce the forces despite the high strength of hard material. Also, the smaller is the depth of cut, as compared to nose radius of the tool; the lower is the cutting forces. The surface finish produced by CBN tools was compatible with the results of grinding. More precisely, Davim and Figueira [14] found that with an appropriate choice of cutting parameters it is possible to obtain a surface roughness with Ra < 0.8 µm. This implies that hard machining is an alternative competitive process, which allows eliminating cylindrical grinding operation solutions. Nevertheless, it was affected by cutting speed, tool wear and the plastic behaviour of the workpiece material. Moreover, the cutting forces as the surface roughness are also influenced by the insert cutting edge geometry as it was mentioned by Özel et al. [15]. In their experimental research work, Benga and Abrão [16] investigated the effect of cutting speed and feed rate on surface roughness and tool life using three-level factorial design (3^2) on machining of hardened AISI 52100 bearing steel (62-64 HRC) using ceramic and CBN tools. The 3D response surface plots are used as single objective optimization approach to find optimum values of process parameters. They found that feed rate is the most significant factor affecting surface finish and cutting speed has very little influence on surface finish for both ceramic and CBN cutting tool. Likewise, based on response surface methodology (RSM), Lalwani et al. [17] investigate the effect cutting speed, feed rate and depth of cut on the feed force, thrust force, cutting force and surface roughness in finish hard turning of MDN250 (50 HRC) steel using coated ceramic tool. The results show that cutting forces and surface roughness do not vary much with experimental cutting speed in the range of 55-93 m/min.

Within the framework of the comprehension of the phenomena occurring during an operation of hard machining, a great number of studies were carried out on many materials. Bouacha et al. [1] studied the application of response surface methodology to describe and optimize the performance of CBN tools when turning AISI 52100 steel (64HRC). The factors investigated were cutting speed, feed and depth of cut. The response variables were surface roughness and cutting force. They found that Response surface methodology provides a large quantity of information with a small amount of experimentation and the quadratic model obtained was very adequate. In addition, Choudhury and El-Baradie [18] found that response surface methodology coupled with the factorial design of experiments were useful techniques for tool life testing. Relatively smaller number of designed experiments is required to generate much useful information that could be used to develop the predicting equation for tool life. In another work, Choudhury and El-Baradie [19] used response surface methodology for assessing machinability of Inconel 718. They found that the dual response contours of tool life and surface roughness are very useful in assessing the maximum attainable tool life for the same surface finish. Suresh et al. [20] have developed a surface roughness model for turning mild steel using a response surface methodology. Surface roughness prediction model has also been optimized by using genetic algorithms. In the same way, Oktem et al. [21] developed a mathematical model based on response surface methodology and optimized cutting condition for surface roughness using genetic algorithm. The first order and second order mathematical model, in terms of machining parameters tool geometry (radial rake angle and nose radius) and cutting conditions (cutting speed and feed rate) on machining performance was developed based on Taguchi's experimental design method. In their research, Hasçalık and Çaydaş [22] have investigated the effect and optimization of machining parameters on tool life in a turning operation. They concluded that tool life is affected strongly by the cutting speed, whereas the feed rate and depth of cut have a significant statistical influence. Also, Oraby and Hayhurst [23] developed models for tool wear and tool life determination using nonlinear regression analysis techniques in terms of the variation of a ratio of force components acting at the tool tip. Tamizharasan et al. [24] predicted the tool wear, tool life, quality of surface turned and amount of material removed in hard turning by conducting experiments under different machining conditions. Gaitonde et al. [7] carried out experimental investigations on machining of high chromium AISI D2 cold work tool steel with CC650, CC650WG and GC6050WH ceramic inserts under different values of depth of cut and machining time. The influence of depth of cut and machining time on machinability aspects (machining force, power, specific cutting force, surface roughness and tool wear) were analyzed using second order mathematical models. They concluded that the CC650WG wiper insert performs better with reference to surface roughness and tool wear, while the CC650 conventional insert is useful in reducing the machining force, power and specific cutting force. In other work, Gaitonde et al. [8] proposed the response surface methodology-based mathematical models for modeling and analyzing the effects of process parameters (cutting speed, feed rate and machining time) on machinability aspects (machining force, power, specific cutting force, surface roughness and tool wear) during turning of high chromium AISI D2 cold work tool steel using CC650WG wiper ceramic inserts. As well, Al-Ahmari [25] has developed different empirical models for tool life when turning austenitic AISI 302 with carbide inserts. Process parameters (cutting speed, feed rate, depth of cut and tool nose radius) were used as inputs to the developed machinability models. He used response surface methodology. The two model building methods (RA, and RSM) are compared and evaluated using descriptive statistics and hypothesis testing. They have statistically satisfactory goodness of fit from the modeling point of view. It has been found that the RSM models are better than RA models for predicting tool life. By conducting experiments on machining AISI D2 steel at hardness 60 HRC with ceramic cutting tools, Quiza et al. [26] concluded that the multilayer perceptron neural network model has shown better capability to make accurate predictions of tool wear under the conditions studied (cutting speed, feed rate and cutting time) then the statistical regression model.

In the present study, an attempt has been made to investigate the effect of process parameters (cutting speed, feed rate and depth of cut) on the performance characteristics (tool life, surface roughness and cutting forces) in finish hard turning of AISI 52100 bearing steel hardened at 60HRC with CBN tool. In this research, a L27 Taguchi standard orthogonal array is adopted as the experimental design. Both of cutting forces and surface roughness are measured at the end of useful tool life which corresponds to VB = 0.3mm. The combined effects of the process parameters on performance characteristics are investigated while employing the analysis of variance (ANOVA). The relationship between process parameters and performance characteristics through the response surface methodology (RSM) are modeled. The composite desirability optimization technique associated with the quadratic models of RSM is used as multi-objective optimization approach to find optimum values of process parameters that optimize simultaneously the performance characteristics.

2. Experimental procedure

The experimental work was divided into two series: The main aim of the first experiments series was the quantification of tool wear evolution as a function of cutting time for different process parameters combinations. This was carried out in accordance with long-duration wear tests as stated by standard ISO 3685 [27].

The purpose behind the second experiments series was to investigate the effects of process parameters on tool life, surface roughness and cutting forces, then to establish a correlation between them using the response surface methodology (RSM).

2.1 Means and materials

The experiments were realized in dry straight turning operation using lathe type SN 40 with 6.6 KW spindle power and AISI 52100 bearing steel as workpiece material with round bars form (41 mm diameter and 300 mm length) and with the following chemical composition: 1.05% C; 1.41% Cr; 0.38% Mn; 0.21% Si; 0.02% Mo; 0.03% Al; 0.28% Cu; 0.02% P; 0.02% Sn; 0.21% Ni and 0.01% V. After quenching treatment at 850°C followed by tempering at 250°C, an average workpiece hardness of 60 HRC was obtained. The coated CBN tool employed is the CBN7020 from Sandvik Company [28] it's grade is a low CBN content material with a ceramic phase added (TiN). The insert ISO designation is SNGA12 04 08 T01020. It was clamped onto a tool holder (ISO designation PSBNR2525K12). Combination of the insert and the tool holder resulted in negative rake angle

Table 1. Cutting parameters and their levels.

Level	Cutting speed Vc (m/min)	Feed rate f (mm/rev)	depth of cut ap (mm)
1	100	0.08	0.2
2	140	0.12	0.4
3	200	0.16	0.6

γ = -6°, clearance angle α = 6°, negative cutting edge inclination angle λ = -6° and cutting edge angle χr = 75°. Tool wear follow-up was achieved by using an optical Hund (W-AD) microscope (precision of 0.001 mm). A Kistler 9257B force dynamometer was used to measure cutting forces in three mutually perpendicular directions. The surface roughness criteria measurements (arithmetic average roughness Ra) for each cutting condition were obtained from a Surftest 301 Mitutoyo roughnessmeter. The cut-off and traverse lengths for each measurement were taken as 0.8 and 4 mm, respectively. The measurements were repeated three times out of three generatrices equally positioned at 120°. The considered result is an average of these values for a given machining pass.

2.2 Experimental design

In this work, an L27 Taguchi standard orthogonal array corresponding to response measurements is adopted as the experimental designs. The parameter levels were chosen within the intervals recommended by the cutting tool manufacturer [28]. The L27 table contains 27 rows corresponding to the number of tests (26 degrees of freedom) with 13 columns at three levels. The first column of the table was assigned to the cutting velocity (Vc), the second to the feed rate (f), the fifth to the depth of cut (ap) and the remaining were assigned the interactions [29]. The parameters to be studied and the attribution of the respective levels are indicated in Table 1.

3. Results and discussion

3.1 Tool wear

The flank wear was measured for different inserts in connection to cutting time and for different combinations of cutting parameters. The tool wear zone occurs mostly in the tool nose radius corner on the flank side. Fig. 1 illustrates a typical flank wear versus cutting time behavior obtained during finish hard turning of AISI 52100 bearing steel for six different combinations of low and high cutting parameters levels.

In the present work, all the experimental conditions investigated, the flank wear value monotonically increases with cutting time. We find the classical process of tool wear which followed three stages: rapid, gradual and catastrophic wear. Increase in cutting parameters in addition to high resistance of metal removal because of their high shear

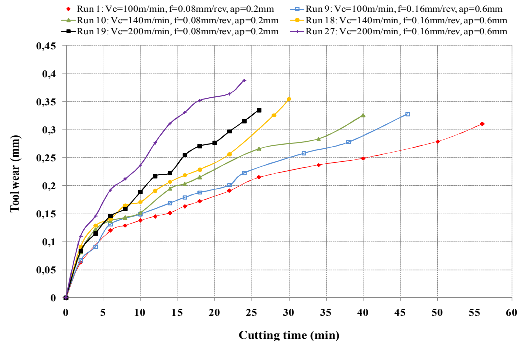


Fig. 1. CBN tool wear results when hard turning of AISI 52100 bearing steel.

strength (60HRC) indicates that the interaction of process energies, including temperature, increases generally, which accelerate tool wear the consequent reduction in tool life. For high values of cutting speed and feed rate, the time of tool failure is reached rapidly. Flank wear was rapid at higher cutting speeds and feed rates, especially when cutting under dry condition. Increased flank wear was observed with the increase in cutting speed. This makes the contact area at chip-tool interface smaller, which consequently caused a concentration of high temperature very close to the cutting edge.

Although the cutting tool-workpiece interface undergone a significant heating during the process of cutting, CBN particles were held rigidly and effectively in place by the TiN matrix. Furthermore, the CBN-TiN coating has a low content of CBN particles, and thus, a low thermal conductivity. Therefore, quite possibly, the heat produced at the interface is partially transferred to the workpiece and chips, thereby retaining the integrity of the TiN binding phases. Notch wear, which usually degrades the surface finish, was not observed for the used CBN-TiN coated cutting inserts (Fig. 2).

3.2 Flank wear shape

The severe forces taken by the tool's rake and flank face cause cutting tool wear. These loads are accentuated by thermal phenomena, especially, in the high cutting speed (200 m/min). The type of wear depends on the nature of the tool, machined materiel, cutting conditions and the type of cutting. Fig. 2 shows the tool wear of CBN tool at rake and flank face.

The wear pattern on the flank indicates abrasive wear resulting from rubbing of the tool cutting edge and flank with workpiece material during cutting. The examination of the worn surfaces shows many grooves on the flank surface. These grooves are mainly due to the ultra-hard carbide particles which contained in hardened AISI 52100 steel (chromium-carbide: $M_7C_3$and M_3C [30, 31]. The abrasion may also be due to the loose CBN particles since they are easily released as free abrasive particles.

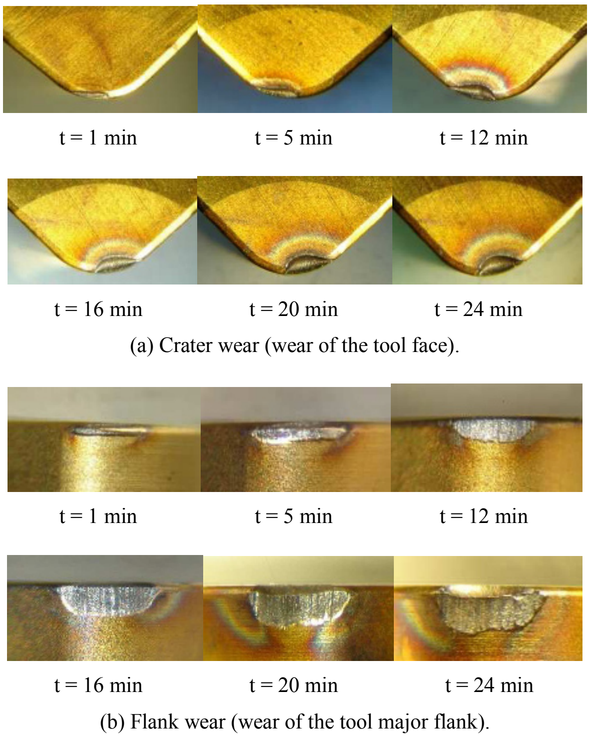


Fig. 2. CBN tool wear for run: Vc = 200 m/min, f = 0.08 mm/rev, ap = 0.2 mm.

3.3 Study of tool life, surface roughness and cutting forces using RSM method

3.3.1 Selection of tool life criterion

Tool life differs based on the wear criterion selected. For finish hard turning, surface roughness is critical. According to standard ISO 3685 [27], the time at which the tool ceases to produce a workpiece of desired surface quality usually determines the end of useful tool life. To this end, when Ra reached the value of 1.6 µm (the surface roughness as set by conventional grinding processes), the test was assumed to be finished. If such criterion was not satisfied, the tests were assumed to be finished when a flank wear of 0.3 mm is achieved. Using L27 Taguchi standard orthogonal array, the experimental results are given in Table 2 which shows all values of tool life, surface roughness and cutting forces. Both of cutting forces and surface roughness are measured at the end of useful tool life which corresponds to VB of 0.3 mm. Up to this value of wear, CBN tools maintain their good cutting ability, the increase of cutting force is insignificant and the surface roughness does not increase considerably.

The tool life was obtained in the range of 13.2-54.11 min. The surface roughness (Ra) was obtained in the range of 0.5 µm to 1.15 µm. The feed force, cutting force and thrust force were obtained in the range of 50.875-179.014 N, 70.628-314.496 N and 111.177-403.842 N, respectively. Furthermore, thrust force is about 1.5-2.5 and 1.2-2 higher than feed force and cutting force respectively.

Table 2. Experimental results for cutting force components, surface roughness and tool life.

Vc (m/min)	f (mm/rev)	ap (mm)	Fa (N)	Fc (N)	Fp (N)	Ra (µm)	T (min)
100	0.08	0.2	72.371	107.535	162.536	0.60	54.11
100	0.08	0.4	96.126	132.501	227.783	0.59	52.94
100	0.08	0.6	127.25	213.216	313.203	0.68	49.78
100	0.12	0.2	74.976	118.945	185.788	0.88	50.27
100	0.12	0.4	98.779	146.475	243.03	0.89	48.61
100	0.12	0.6	144.355	200.216	332.966	0.91	46.94
100	0.16	0.2	126.756	166.573	201.03	0.98	45.44
100	0.16	0.4	152.962	199.566	287.672	1.00	40.78
100	0.16	0.6	179.014	314.496	403.842	1.15	42.00
140	0.08	0.2	65.469	97.105	139.755	0.55	36.70
140	0.08	0.4	90.708	118.908	203.316	0.56	35.04
140	0.08	0.6	125.783	170.813	249.761	0.54	32.38
140	0.12	0.2	65.429	70.628	139.61	0.66	34.87
140	0.12	0.4	94.265	135.487	213.254	0.67	33.21
140	0.12	0.6	126.643	192.747	247.67	0.68	30.54
140	0.16	0.2	79.746	113.417	156.896	0.88	31.04
140	0.16	0.4	116.103	175.885	247.04	0.87	29.38
140	0.16	0.6	159.917	205.511	304.345	0.88	26.00
200	0.08	0.2	55.73	71.716	111.177	0.50	22.11
200	0.08	0.4	88.949	116.404	162.099	0.52	21.44
200	0.08	0.6	122.415	167.314	208.545	0.53	20.78
200	0.12	0.2	50.875	82.62	121.064	0.65	20.27
200	0.12	0.4	79.812	110.111	182.09	0.63	19.61
200	0.12	0.6	111.746	177.923	216.855	0.66	18.94
200	0.16	0.2	75.277	98.546	130.84	0.74	16.44
200	0.16	0.4	109.151	161.842	204.953	0.75	15.78
200	0.16	0.6	127.696	213.013	269.555	0.79	13.20

3.3.2 Response surface method (RSM)

The experimental results are used to establish the quadratic model of cutting forces (Fa, Fc and Fp), tool life (T) and surface roughness (Ra). This model can be written as follows:

$$Y = a_0 + \sum_{i=1}^{3} a_i X_i + \sum_{i=1}^{3} a_{ii} X_i^2 + \sum_{i<j}^{3} a_{ij} X_i X_j \quad (1)$$

where Y is the desired response: cutting force components (Fa, Fc and Fp), surface roughness (Ra) and tool life (T), a_0 is constant, a_j, a_{ii} and a_{ij} represent the coefficients of linear, quadratic and cross product terms, respectively. X_i reveals the coded variables that correspond to the studied cutting parameters. Using this quadratic model of the response function in this study was not only to investigate over the entire factor space, but also to locate the region of being desired target where the response approaches its optimum or near optimal value.

The tests for significance of the regression and individual model coefficients were performed to verify the goodness of fit for the obtained model. The analysis of variance was applied to summarize these tests, which is used for identifying the factors significantly affecting the performance measures. The results of the ANOVA with the response measurements (cutting forces, surface roughness and tool

Table 3. Analysis of variance for cutting force components, surface roughness and tool life.

Term	DF	Seq SS	Adj SS	Adj MS	*F*	*P*	PC%
(a) Analysis of variance for Fa							
Vc	1	3368.2	265.1	265.1	6.04	0.023	11.81
f	1	4412.4	361.0	361.0	8.22	0.009	15.48
ap	1	17309.8	17309.8	17309.8	394.1	0.000	60.72
*f*f*	1	1427.7	1427.7	1427.7	32.51	0.000	5.01
*Vc*f*	1	1067.4	1067.4	1067.4	24.30	0.000	3.74
Erreur	21	922.4	922.4	43.9			3.24
Total	26	28507.9					100
(b) Analysis of variance for Fc							
Vc	1	8091	2591	2591	8.49	0.008	10.34
f	1	11417	1635	1635	5.36	0.031	14.60
ap	1	47860	47860	47860	156.91	0.000	61.19
*Vc*Vc*	1	1848	1848	1848	6.06	0.023	2.36
*f*f*	1	2591	2591	2591	8.49	0.008	3.31
Erreur	21	6405	6405	305			8.19
Total	26	78214					100
(c) Analysis of variance for Fp							
Vc	1	30013	2137	2137	14.71	0.001	23.28
f	1	10177	795	795	5.48	0.030	7.89
ap	1	79740	3513	3513	24.19	0.000	61.84
*Vc*Vc*	1	1777	1777	1777	12.24	0.002	1.38
*f*f*	1	894	894	894	6.15	0.023	0.69
*Vc*ap*	1	2159	2159	2159	14.86	0.001	1.67
*f*ap*	1	1429	1429	1429	9.84	0.005	1.11
Erreur	19	2759	2759	145			2.14
Total	26	128947					100
(d) Analysis of variance for T							
Vc	1	3731.61	237.73	237.73	174.65	0.000	89.83
f	1	236.31	43.6	43.60	32.03	0.000	5.69
ap	1	52.33	52.33	52.33	38.44	0.000	1.26
*Vc*Vc*	1	98.94	98.94	98.94	72.69	0.000	2.38
*Vc*f*	1	6.50	6.50	6.50	4.78	0.040	0.16
Erreur	21	28.58	28.58	1.36			0.69
Total	26	4154.28					100
(e) Analysis of variance for Ra							
Vc	1	0.19987	0.03342	0.03342	22.09	0.000	23.99
f	1	0.53389	0.10532	0.10532	69.59	0.000	64.09
ap	1	0.01125	0.01125	0.01125	7.43	0.013	1.35
*Vc*Vc*	1	0.03874	0.03874	0.03874	25.60	0.000	4.65
*Vc*f*	1	0.0175	0.01750	0.01750	11.57	0.003	2.10
Erreur	21	0.03178	0.03178	0.00151			3.81
Total	26	0.83303					100

life) are shown in Table 3. This analysis was carried out for a significance level of a = 0.05, i.e. for a confidence level of 95%. Table 3 show the P-values, that is, the realized significance levels, associated with the F-tests for each term of variation. The terms with a P-value less than 0.05 are considered to have a statistically significant contribution to the performance measures and the obtained models are considered to be statistically significant. It demonstrates that the terms chosen in the model have significant effects on the responses. Also, the last column of the table shows the percent contribution of each source to the total variation indicating the degree of influence on the result.

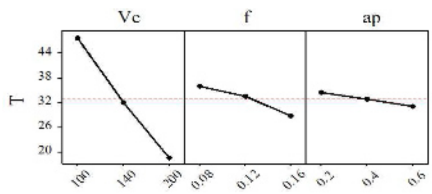
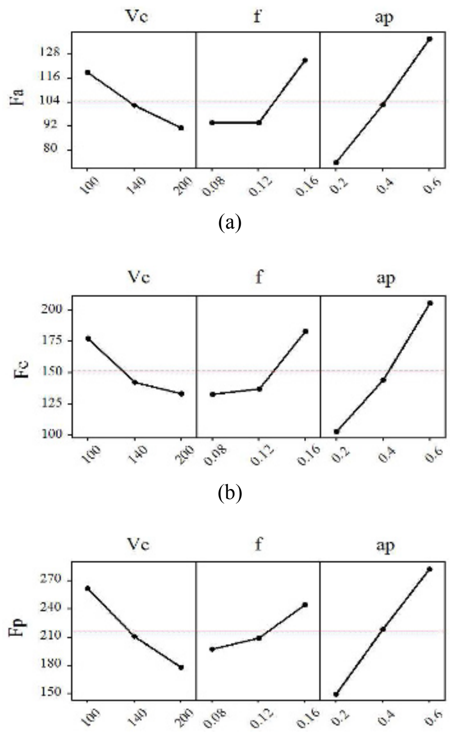


Fig. 3. Main effect plots for average tool life (T).



(c)

Fig. 4. Main effect plots for average cutting force components: (a) Fa; (b) Fc; (c) Fp.

The other important coefficient is the determination coefficients R^2, which defined as the ratio of the explained variation to the total variation and it is a measure of the degree of fit. When R^2 approaches to unity, the better the response model fits the actual data. Additionally, plots of normal probability, main effects and 3D response surface corresponding to each ANOVA analysis were constructed. These plots are used to investigate the influences of cutting parameters on response measurements, and are illustrated in Figs. 3-5.

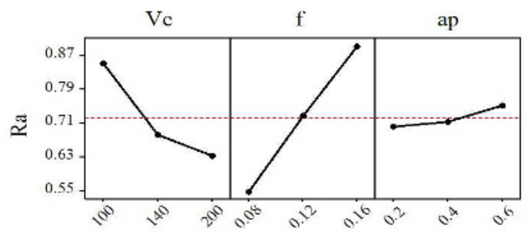


Fig. 5. Main effect plots for average surface roughness (Ra).

By selecting the significant terms, the resulting ANOVA table for reduced model is shown in Table 3. This one shows that the model is significant and cutting speed (Vc), feed rate (f) and depth of cut (ap) are the principal significant factors (terms) in the models. All other terms (interaction terms) have weakest influences or are insignificant. The percentage contribution of factors and their interaction is also shown in Table 3.

Table 3(d) shows that the cutting speed is the dominant contributor to the tool life (T), accounting for 89.83% of total variability, whereas feed rate and its interaction with cutting speed have modest influence which accounts for 5.69% and 0.16% of the total variability. Depth of cut has much lower levels of contribution 1.26%.

Fig. 3 shows a decreasing of the tool life with increasing of cutting speed, to reach a minimal value of 13.2 min at the cutting speed 200 m/min (f = 0.16 mm/rev, ap = 0.6 mm).

The most significant factor on the cutting force components is depth of cut (ap) which explain until a 61.84% contribution of the total variability (Table 3(a), (b) and (c)). The next largest contribution on feed force and cutting force comes from the feed rate with the contribution 15.48% and 14.60% respectively, whereas cutting speed accounts for 11.81% and 10.34 of the total variability. This indicates that cutting speed has little influence on feed force and cutting force. However, for thrust force, Vc is in second position with a contribution 23.28% of the total variability.

The effect plots in Fig. 4 indicate that the cutting force components (Fa, Fc and Fp) are significantly affected by depth of cut, feed rate and cutting speed. These graphs indicate that as feed rate and depth of cut increase, the cutting components also increase. Because as the depth of cut and the feed rate increases, the tool- chip interface area increases which leads to increase in components. However, the effect of feed rate on cutting forces was significant for feed rates higher than 0.12 mm/rev, whereas cutting forces slightly change at lower feed rates.

The cutting forces values were almost identical for feed rates of 0.08-0.12 mm/rev. The cutting speed has decreasing control on cutting forces components (Fa, Fc and Fp). The increase in cutting speed leads to high cutting temperature, particularly, in the shear zone and hence softening of the workpiece material (reduction of the yield strength of the work material), reducing of chip thickness and tool chip contact length and as a result, the cutting force shows a decreasing trend [32-35].

From Table 3 it can be seen that the Vc, f, ap and the products Vc^2, Vc*f are significant terms on Arithmetic Average of Absolute Roughness Ra. The most significant factor on Ra is feed rate (f), which explains 64.09% contribution of the total variation. The next largest contribution on Ra comes from the cutting speed Vc with 23.99%.

In Fig. 5 the main effects for average surface roughness (Ra) are plotted. It is clearly observed that the feed rate (f) strongly affects surface roughness parameters. Feed rate has an increasing effect. That was expected; because it is well known that the theoretical geometrical surface roughness is primarily a function of the feed for a given nose radius and changes with the square of the feed rate value. The cutting speed has an important and decreasing effect. Surface roughness is improved by increasing cutting speed, though the improvement was very limited at higher cutting speed (140-200 m/min). Producing a better surface finish at higher cutting speed is well known in metal cutting. The conventional explanations are related to built-up-edge (BUE). That is, the formation of BUE is favored in a certain range of cutting speed. By increasing cutting speed beyond this region, BUE is eliminated and as a result, the surface finish is improved. During present experiments, where hardened steel was machined, the cutting speeds were higher than those favoring BUE formation. Indeed BUE was not observed (even at the lowest speed of 56.5 m/min). Therefore, the phenomenon needs further explanation. According to Liu [32], Chen [12] and Bouacha [1], the deformation velocity influences the properties of metals. The higher the velocity, the less significant the plastic behaviour is. The lateral plastic flow of the workpiece material along the cutting edge direction may increase the peak-to-valley height of the surface irregularity. If the material presents less plasticity by increasing cutting speed and hence deformation velocity, the surface finish can be improved as a result of less significant lateral plastic flow and thus less additional increase in the peak-to-valley height of the machined surface roughness. Furthermore, at low cutting speed, grooves are developed on the tool wear face. The large the development of the grooves, the more significant deterioration of the surface finish is. When such cutting edge is engaged with a workpiece, the defects will in part be copied on to the newly generated surface.

In any event it is likely that the surface will be rough. With an increase in cutting speed the grooves will gradually be reduced, thus the cutting edge and tool wear face will become smoother, as will the workpiece surface.

For the depth of cut (ap), influence value is that smallest and it has much lower levels of contribution 1.35%. This does not present a statistical significance on surface roughness. However, low depth of cut should be used in order to reduce the tendency to chatter.

The depth of cut (ap) has little direct influence on the surface roughness, however, with increases in ap, above nose radius of tool values (0.8 mm), chatter may result causing degradation of the workpiece surface. Therefore, if the tool-work system is not very rigid, such as in cutting slender parts, very fine depth of cut should be employed to avoid chatter. In this way very good surface finishes can be obtained.

For all machining tests, the Ra values observed were in the range of 0.50-1.15 µm, indicating that CBN tool is able to produce parts with surfaces equivalent to those resulting from grinding and other finishing processes. It is also interesting to note that when f = 0.08 mm/rev, average surface roughness values become less sensitive to changes in Vc and ap, not exceeding 0.68 µm in the worst case (Vc = 100 m/min, ap = 0.6 mm). Instead of specifying optimal levels for all the three factors, setting only the feed rate to 0.08 mm/rev would be a robust alternative, which would produce reliable and low surface roughness values even when the two other factors are not controlled.

The Anderson-Darling test and normal probability plots of the residuals versus the predicted response for the cutting force components (Fa, Fc and Fp), surface roughness (Ra) and tool life (T) are plotted in Fig. 6. The data closely follows the straight line. The null hypothesis is that the data distribution law is normal and the alternative hypothesis is that it is non-normal. Using the P-value (0.143-0.598) which is greater than alpha of 0.05 (level of significance), so we cannot reject the null hypothesis (i.e., the data follow a normal distribution). The plots and the normality tests results assume that the data follow a normal distribution. This implies that the models proposed are adequate.

3.3.2.1 Cutting forces, surface roughness and tool life quadratic models

The initial analysis of the responses obtained from RSM includes all parameters and their interactions. The models are reduced by eliminating terms with no significant effect on the responses. Through the backward elimination process, the final quadratic models of response equation in terms of actual factors are presented as follows:

$$Fa = 81.35 + 0.2904 \cdot Vc - 1235.4 \cdot f + 155.053 \cdot ap + 9641 \cdot f^2 - 4.6845 \cdot Vc \cdot f \quad (2)$$

R^2 = 96.8%, R^2 (ajus) = 96.0%

$$Fc = 363.89 - 2.6529 \cdot Vc - 2488 \cdot f + 257.82 \cdot ap + 0.007361 \cdot Vc^2 + 12988 \cdot f^2 \quad (3)$$

R^2= 91.8%, R^2 (ajus) = 89.9%

$$Fp = 374.34 - 2.4669 \cdot Vc - 1781.9 \cdot f + 364.54 \cdot ap + 0.007219 \cdot Vc^2 + 7628 \cdot f^2 - 1.3324 \cdot Vc \cdot ap + 1363.9 \cdot f \cdot ap \quad (4)$$

R^2= 97.9%, R^2 (ajus) = 97.1%

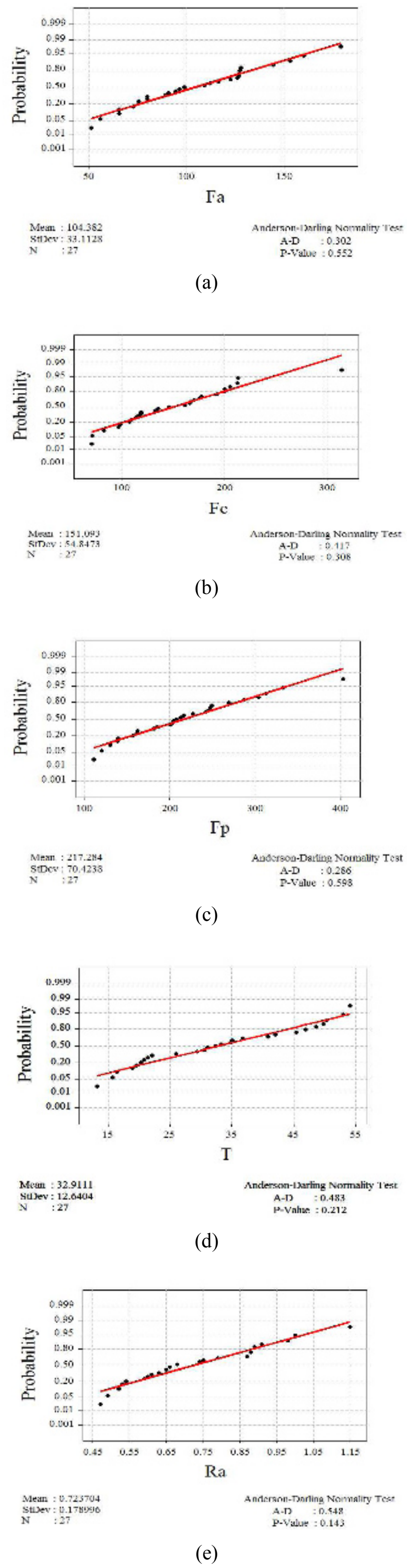
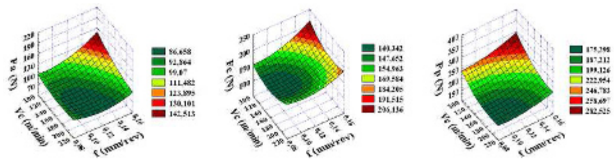
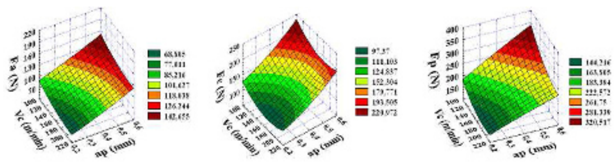


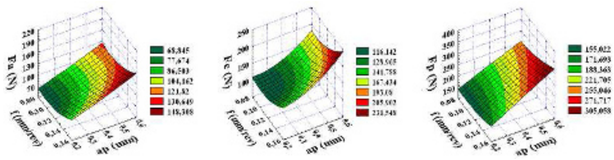
Fig. 6. Normal probability plots of cutting force components, tool life and surface roughness.



(a)



(b)



(c)

Fig. 7. Estimated response surface of cutting force components versus Vc, f and ap.

$$Ra = 0.8469 - 0.010035 \cdot Vc + 7.0877 \cdot f + 0.125 \cdot ap + 0.000034 \cdot Vc^2 - 0.018969 \cdot Vc \cdot f \quad (5)$$

R^2 = 96.2%, R^2 (ajus) = 95.3%

$$T = 131.799 - 0.84629 \cdot Vc - 144.21 \cdot f - 8.525 \cdot ap + 0.001703 \cdot Vc^2 + 0.3656 \cdot Vc \cdot f \quad (6)$$

R^2= 99.3%, R^2 (ajus) = 99.1%

These equations give the expected value of cutting forces, tool life and surface roughness for any combination of factor levels given that the levels are within the ranges in Table 1. The R^2-values (91.8% - 99.3%) for the regression equations are very high enough to obtain reliable estimates.

3.3.2.2 3D responses surface plots

Fig. 7(a) presents the influences of cutting speed (Vc) and feed rate (f) on the cutting force components, while the depth of cut (ap) is kept at the middle level. Fig. 7(b) shows the estimated response surface in relation to the cutting speed (Vc) and depth of cut (ap), while feed rate (f) is kept at the middle level. The effects of the feed rate (f) and depth of cut (ap) on the cutting force components are shown in Fig. 7(c), while the cutting speed (Vc) is kept at the middle level.

In Figs. 8 and 9, the estimated response surface of surface roughness and tool life as a function of cutting speed, feed rate and depth of cut, are depicted. For each plot, the variables not represented are held at a constant value (the middle level). These 3D plots confirm the notes observed during the principal effects plots analysis.

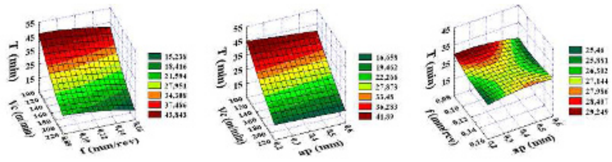


Fig. 8. Estimated response surface of tool life versus Vc, f and ap.

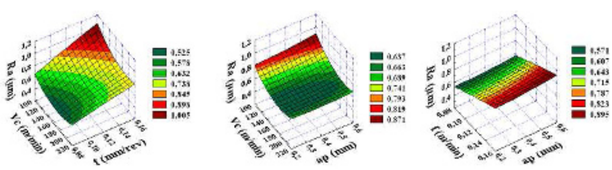


Fig. 9. Estimated response surface of surface roughness versus Vc, f and ap.

3.3.3 Comparison between experimental and predicted results

Fig. 10 shows cutting force components (Fa, Fc and Fp), surface roughness (Ra) and tool life (T) values obtained by experimentation and values predicted by response surface models. It is obvious that the predicted values are very close to the experimental readings. It is seen that there is a strong relationship between the predictor variables and response variables, which is confirmed by the results of Table 4.

3.3.4 Response optimization

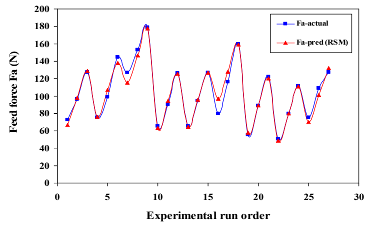
One of the main goals of this experimental study is to find optimal cutting parameters in order to obtain the highest tool life value, the desired value of the machined surface roughness and the lowest cutting forces during the hard turning process.

The use of response surface optimization helps to identify the combination of input variable settings that jointly optimize the cutting force components, tool life and surface roughness during the hard turning process. Joint optimization must satisfy the requirements for all the responses in the set. Optimization achievement is measured by the composite desirability (D_c) which is the weighted geometric mean of the individual desirability's (D_i) for the responses on a range from zero to one. One represents the ideal case. Zero indicates that one or more responses are outside acceptable limits.

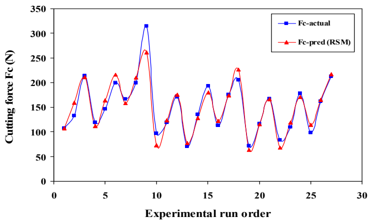
Table 5 shows the RSM optimization results for the cutting force components and surface roughness. The optimum cutting parameters obtained in Table 5 are found to be cutting speed of 168 m/min, feed rate of 0.08 mm/rev and cutting depth of 0.22 mm. The optimized cutting force components are Fa = 61.4520N, Fc = 78.6066N and Fp = 126.6144N. In addition, the optimized tool life and surface roughness parameter are: T = 28.4729 min and Ra = 0.4944 µm.

4. Conclusions

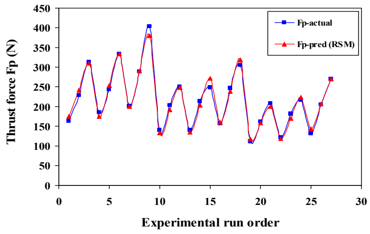
In the present study, an attempt has been made to investi-



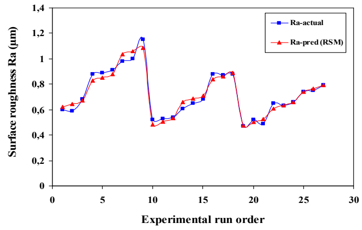
(a)



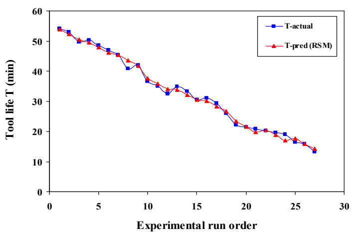
(b)



(c)



(d)



(e)

Fig. 10. Actual and predicted values of: (a) Fa; (b) Fc; (c) Fp; (d) Ra; (e) T.

gate the effect of process parameters (cutting speed, feed rate and depth of cut) on the performance characteristics (tool life, surface roughness and cutting forces) in finish hard turning of AISI 52100 bearing steel hardened at 60HRC with CBN tool.

The combined effects of the process parameters on performance characteristics are investigated while employing

Table 4. The RSM models comparison for the cutting force components, surface roughness and tool life.

		R^2	AE			MSE	MAPE
			Min	Max	Mean		
RSM	Fa	96.8	0.209	17.485	4.026333333	34.16165507	4.153012598
	Fc	91.8	0.367	53.094	10.98240741	102.1971596	7.738152315
	Fp	97.9	0.124	24.108	7.857962963	102.1971596	3.815041224
	Ra	96.2	0.00009	0.06404	0.027788889	0.001177055	3.85719232
	T	99.3	0.1067	2.7886	0.838725926	1.05866	3.030520898

Table 5. Response optimization for cutting forces (Fa, Fc and Fp), surface roughness (Ra) and tool life (T).

Output	Goal	Optimum combination			Lower	Target	Upper	Predicted response	D_i
		Vc m/min	f mm/rev	ap mm					
Fa (N)	Min.	168	0.08	0.22	50.875	62	179.014	61.4520	1
Fc (N)	Min.	168	0.08	0.22	70.628	85	314.496	78.6066	1
Fp (N)	Min.	168	0.08	0.22	111.177	130	403.842	126.6144	1
Ra (µm)	Min.	168	0.08	0.22	0.50	0.51	1.15	0.4944	1
T (min)	Max.	168	0.08	0.22	13.2	20	54.11	28.4729	1
Composite desirability = 1									

the analysis of variance (ANOVA). The relationship between process parameters and performance characteristics through the response surface methodology (RSM) are modeled. The composite desirability optimization technique associated with the quadratic models of RSM is used as multi-objective optimization approach to find optimum values of process parameters that optimize simultaneously the performance characteristics. From the results found in this study, the following conclusions were drawn:

(1) The results delivered from ANOVA analysis and conducting validation experiments have proved that the quadratic models allow predicting response measurements values with a 95% confident interval and high determination coefficient (> 91%) within the limits of the factors studied.

(2) From the tool life models, it is found that an increase of cutting speed, feed rate and depth of cut by 100%, will lead to reduction of tool life by 59.14%, 16.02% and 2.16%, respectively.

(3) The surface roughness is highly affected by feed rate, which explains until 64.09% of the total variation, where increasing feed rate will increase the surface roughness values. The cutting speed has a negative effect (23.99%), whereas the effect of depth of cut is negligible (1.35%).

(4) Cutting forces show an increasing trend with the increase in feed rate and depth of cut on the other hand they

show a decreasing trend with cutting speed. The depth of cut exhibits maximum influence on cutting force components (Fa, Fc, Fp) compared to the feed rate and cutting speed. It explains till 60.72%, 61.19% and 61.84% of the total variation, respectively.

(5) When finish cutting of hardened steel, the thrust force became the largest among the three cutting force components and was the most sensitive to the changes of machining parameters.

(6) Simultaneous optimization of the performance characteristics (tool life, surface roughness and cutting forces) when hard turning of AISI 52100 bearing steel with CBN tool was achieved with a cutting speed Vc = 168 m/min, feed rate f = 0.08 mm/rev and depth of cut ap = 0.22 mm.

(7) The proposed experimental and statistical approaches bring a reliable methodology to optimize and to improve the hard turning process. Also, they can be extended efficiently to study other machining processes.

Acknowledgment

This work was achieved in the Laboratory of Mechanics and Structures (LMS), 8 May 1945 University, Guelma, Algeria. It is a pleasure for us, to express our great gratitude to all colleagues who helped us to realize this work.

Nomenclature

Vc	: Cutting speed (m/min)
f	: Feed rate (mm/rev)
t	: Cutting time (min)
ap	: Depth of cut (mm)
α	: Clearance angle (°)
χ_r	: Cutting edge angle (°)
γ	: Rake angle (°)
λ	: Cutting edge inclination angle (°)
Ra	: Arithmetic average of absolute roughness (μm)
HRC	: Rockwell hardness
X_i	: Coded machining parameters
a_j	: Coefficients of linear terms
a_{ii}	: Quadratic terms
a_{ij}	: Cross product terms
VB	: Tool wear (mm)
ANOVA	: Analysis of variance
RSM	: Response surface method
D.F.	: Degrees of freedom
Seq SS	: Sequential sum of squares
Adj SS	: Adjusted sum of squares
Adj MS	: Adjusted mean squares
PC%	: Percentage contribution ratio (%)
R^2	: Determination coefficient
MSE	: Mean squared error
MAPE	: Mean absolute percentage error
AE	: Absolute error
D_i	: Individual desirability
D_c	: Composite desirability

References

[1] K. Bouacha, M. A. Yallese, T. Mabrouki and J. F. Rigal, Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool, *International Journal of Refractory Metals & Hard Materials,* 28 (2010) 349-361.

[2] G. Poulachon, A. Moisan and I. S. Jawahir, Tool-wear mechanisms in hard turning with polycrystalline cubic boron nitride tools, *Wear,* 250 (2001) 576-586.

[3] J. P. Davim (Ed.), Machining of Hard Materials, *Springer,* 2011.

[4] H. K. Tönshoff, C. Arendt and R. Ben Amor, Cutting of hardened steel, *Annals of the CIRP,* 49 (2) (2000) 547-566.

[5] W. König, A. Berktold and K. F. Koch, Turning versus grinding - a comparison of surface integrity aspects and attainable accuracies, *Annals of the CIRP*, 42 (1) (1993) 39-43.

[6] F. Klocke, E. Brinksmeier and K. Weinert, Capability profile of hard cutting and grinding processes, *Annals of the CIRP*, 54 (2) (2005) 557-580.

[7] V. N. Gaitonde, S. R. Karnik, L. Figueira and J. P. Davim, Machinability investigations in hard turning of AISI D2 cold work tool steel with conventional and wiper ceramic inserts, *International Journal of Refractory Metals & Hard Materials,* 27 (4) (2009) 754-763.

[8] V. N. Gaitonde, S. R. Karnik, L. Figueira and J. P. Davim, Analysis of machinability during hard turning of cold work tool steel (type:AISI D2), *Materials and Manufacturing Processes,* 24 (12) (2009) 1373-1382.

[9] V. S. Sharma, S. Dhiman, R. Sehgal and S. K. Sharma, Estimation of cutting forces and surface roughness for hard turning using neural networks, *Journal of Intelligent Manufacturing*, 19 (4) (2008) 473-83.

[10] W. König, R. Komanduri, H. K. Tönshoff and G. Ackershott, Machining of hard materials, *Annals of the CIRP,* 33 (2) (1984) 417-428.

[11] Z. C. Lin and D. Y. Chen, A study of cuttting with CBN tool, *Journal of Materials Processing Technology*, 49 (1995) 149-164.

[12] W. Chen, Cutting forces and surface finish when machining medium hardness steel using CBN tools, *International Journal of Machine Tools and Manufacture*, 40 (3) (2000) 455-66.

[13] K. Nakayama, M. Arai and T. Kanda, Machining characteristics of hard materials, *Annals of the CIRP,* 37 (1) (1988) 89-92.

[14] J. P. Davim and L. Figueira, Machinability evaluation in hard turning of cold work tool steel (D2) with ceramic tools using statistical techniques, *Materials and Design*, 28 (2007) 1186-91.

[15] T. Özel, T. K. Hsu and E. Zeren, Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened

AISI H13 steel, *International Journal of Advanced Manufacturing Technology*, 25 (3-4) (2005) 262-9.
[16] G. C. Benga and A. M. Abrão, Turning of hardened 100Cr6 bearing steel with ceramic and PCBN cutting tools, *Journal of Materials Processing Technology*, 143-144 (2003) 237-41.
[17] D. I. Lalwani, N. K. Mehta and P. K. Jain, Experimental investigations of cutting parameters influence on cutting forces and surface roughness in finish hard turning of MDN250 steel, *Journal of Materials Processing Technology*, 206 (1-3) (2008) 167-179.
[18] I. A. Choudhury and M. A. El-Baradie, Tool-life prediction model by design of experiments for turning high strength steel (290 BHN), *J. Mater. Process, Technol.* (1998) 319-326.
[19] I. A. Choudhury and M. A. El-Baradie, Machinability assessment of Inconel 718 by factorial design of experiment coupled with response surface methodology, *J. Mater. Process. Technol.* 95 (1999) 30-39.
[20] N. S. K. Reddy and P. V. Rao, Selection of optimum tool geometry and cutting conditions using a surface roughness prediction model for end milling, *Int. J. Adv. Manuf. Technol*. 26 (2005) 1202-1210.
[21] H. Oktem, T. Erzurumlu and H. Kurtaran, Application of response surface methodology in the optimization of cutting conditions for surface roughness, *J. Mater. Process. Technol.* 170 (2005) 11-16.
[22] A. Hasçalık and U. Çaydaş, Optimization of turning parameters for surface roughness and tool life based on the Taguchi method, *Int. J. Adv. Manuf. Technol.* 9-10 (2008) 896-903.
[23] S. E. Oraby and D. R. Hayhurst, Tool life determination based on the measurement of wear and tool force ratio variation, *Int. J. Mach. Tools Manuf.* 44 (2004) 1261-1269.
[24] T. Tamizharasan, T. Selvaraj and A. Noorul Haq, Analysis of tool wear and surface finish in hard turning, *International Journal of Advanced Manufacturing Technology*, 28 (2006) 671-679.
[25] A. M. A. Al-Ahmari, Predictive machinability models for a selected hard material in turning operations, *J. Mater. Process. Technol.* 190 (2007) 305-311.
[26] R. Quiza, L. Figueira and J. P. Davim, Comparing statistical models and artificial neural networks on predicting the tool wear in hard machining D2 AISI steel, *International Journal of Advanced Manufacturing Technology*, 37 (7-8) (2008) 641-648.
[27] ISO 3685, Tool life testing with single-point turning tools, *ISO Standard,* 3685 (1993) (E).
[28] Sandvik Coromant, Main catalogue, *The official website of the Sandvik. Coromant*: http://www.coromant.sandvik.com (2006) [accessed 10.04.2007].
[29] G. Taguchi and S. Konishi, Taguchi methods, orthogonal arrays and linear graphs, tools for quality engineering, *American Supplier Institute* (1987) 35-38.
[30] G. Poulachon, B. P. Bandyopadhyay, I. S. Jawahir, S. Pheulpin and E. Seguin, Wear behavior of CBN tools while turning various hardened steels, *Wear,* 256 (2004) 302-310 P306.
[31] N. Narukati and Y. Yamane, Tool wear and cutting temperature of CBN tools in machining of hardened steels, *Annals of the CIRP*, 28 (1) (1979) 23-28.
[32] H. Liu, Mechanics of Materials, *The People's Education Press*, (1979).
[33] K. V. B. S. K. Kumar and S. K. Choudhury, Investigation of tool wear and cutting force in cryogenic machining using design of experiments, *Journal of Materials Processing Technology*, 203 (2008) 95-101.
[34] D. E. Dimla Sr., The impact of cutting conditions on cutting forces and vibration signals in turning with plane face geometry inserts, *Journal of Materials Processing Technology* (155-156) (2004) 1708-1715.
[35] E. G. Ng, D. K. Aspinwall, D. Brazil and J. Monaghan, Modelling of temperature and forces when orthogonally machining hardened steel, *International Journal of Machine Tools & Manufacture,* 39 (1999) 885-903.

Samir khamel is a member in Laboratory of Mechanics and Structures (LMS) of Guelma University and teacher in Mohamed Chérif Messaadia University, Souk Ahras, Algeria. His research interests are material science domain, optimization methodologies, hard turning, vibration, engineering materials and technology.