Int J Adv Manuf Technol (2017) 89:1915–1934
DOI 10.1007/s00170-016-9162-7

ORIGINAL ARTICLE

Design optimization for minimum technological parameters when dry turning of AISI D3 steel using Taguchi method

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Received: 18 April 2016 / Accepted: 11 July 2016 / Published online: 4 August 2016

Abstract The development in the manufacturing flied requires the continuous optimization using various methods. In order to minimize some technological output (such as surface roughness, tangential force, specific cutting force, and cutting power) characterizing material machinability, it is intended in the present paper to perform an optimizing approach of cutting parameters based on Taguchi method. Selected input cutting parameters are major cutting edge angle, cutting insert nose radius, cutting speed, feed rate, and depth of cut. The tests were performed on AISI D3 steel using mixed ceramic inserts under dry cutting conditions. A Taguchi L_{18} orthogonal array is used to design the optimization experiment. The analysis of variance (ANOVA) is exploited to evaluate the foremost effects on the output parameters. The results indicate that both feed rate and cutting insert nose radius are the mainly influencing factors on surface roughness while both tangential force and specific cutting force are affected principally by depth of cut followed by feed rate. The most significant parameter affecting cutting power is depth of cut followed by cutting speed and feed rate. Regression equations are formulated for estimating predicted values of technological parameters. Optimal cutting parameters are determined using the signal-to-noise (S/N) ratio which was calculated for the precited technological output according to the "the smaller-the-better" approach. Based on the confirmation experiments and laboratory results, it is concluded that the Taguchi method is successfully adapted to describe the optimization of cutting parameters (inputs) for improved technological ones (output).

Keywords Optimization · Taguchi method · S/N ratio · ANOVA · AISI D3 steel · Mixed ceramic insert

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Nomenclature

ANOVA	Analysis of variance
ap	Depth of cut (mm)
CNC	Computerized numerical control
Cont %	Contribution ratio (%)
DF	Degrees of freedom
f	Feed rate (mm/rev)
Fz	Tangential force (N)
Ks	Specific cutting force (MPa)
MS	Mean squares
OA	Orthogonal array
Pc	Cutting power (W)
Ra	Arithmetic mean roughness (μm)
r	Nose radius of cutting insert (mm)
RSM	Response surface methodology
SS	Sum of squares

S/N	Signal-to-noise ratio
Vc	Cutting speed (m/min)
α	Clearance angle (°)
γ	Rake angle (°)
λ	Inclination angle (°)
χr	Major cutting edge angle (°)

1 Introduction

In industry, manufacturing processes are planned and improved in order to achieve higher accuracy levels and lower costs in shorter times. As a consequence, selection of optimal cutting parameters via optimization techniques in order to design economic experimental plans and obtain reliable results becomes an important task. Among optimization techniques, the Taguchi method is a powerful and consistent tool for the design of high-quality systems as it provides a simple, efficient, and systematic approach to optimize output such as performance, quality, and cost [1, 2]. The method is adequate in setting the design parameters and reducing the sensitivity of the system performance associated to its deviation sources. Moreover, the methodology is valuable when the design parameters are qualitative and discrete. In recent years, the rapid growth of interest in the Taguchi method has led to numerous applications of the method in a many industrial processes [1].

Several researchers have adopted the use of the Taguchi method with the aim of optimizing the cutting process parameters based on reduce design experiments.

Yang and Tarng applied the Taguchi technique for determining optimum cutting parameters when turning S45C steel bars using tungsten carbide cutting tools [2]. Cutting speed (*Vc*), feed rate (*f*), and depth of cut (*ap*) were selected as input parameters. Signal-to-noise (S/N) ratio and ANOVA analysis were employed to determine the effect of the cutting parameters on both tool life and surface quality leading to the selection and the affirmation of the optimum cutting parameters.

Similarly, Asiltürk and Akkus [3] selected the optimum cutting conditions to get the lowest surface roughness in hard turning of AISI 4140. The study used a coated carbide cutting tool with the L_9 OA in a CNC turning machine. Optimal cutting parameters were determined using Taguchi method based on the S/N ratio which was calculated for roughness (*Ra* and *Rz*) according to the approach "the-smaller-is-the-better."

Taguchi method was also applied by Thamizhmanii et al. [4] to obtain the optimal value of surface roughness under optimum cutting condition when turning SCM 440 alloy steel. It was found that the causes of poor surface finish were machine tool vibrations and tool chattering whose effects were ignored for analysis. The authors concluded that depth of cut has significant role to play in producing acceptable surface roughness followed by feed rate and cutting speed. According to this study, a depth of cut of within the range 1 to 1.5 mm is recommended to get lowest surface roughness.

In a research for an adequate cutting regime, Bouzid et al. [5] determined minimum surface roughness which corresponds to maximum material removal rate in turning of X20Cr13 steel with mono- and multi-objective optimizations. Turning experiments were carried out using a coated carbide cutting tool (CVD) based on the L_{16} OA of Taguchi. They used only the answers in the optimization study as objective function. Mono-objective optimization results were obtained considering Taguchi's S/N ratio whereas multi-objective optimization results were sought using grey relational analysis. As a result, optimal cutting parameters were determined through both mono- and multi-objective optimizations.

The aim of the study authored by Selvaraj et al. [6] is to optimize dry turning parameters of two different grades of nitrogen alloyed duplex stainless steel using Taguchi method. The results revealed that the feed rate is the more significant parameter which influences both surface roughness and cutting force. The cutting speed was identified as the more significant parameter when tool wear is considered.

Bhattacharya et al. [7] studied the effects of cutting parameters on surface roughness and power consumption by using Taguchi method. They employed a combined technique using orthogonal array and analysis of variance to investigate the contribution and effects of cutting speed, feed rate, and depth of cut on three criterions of surface roughness and power consumption. ANOVA results proved that the most significant factor affecting both surface roughness and power consumption is the cutting speed, while the other parameters did not substantially affect the responses.

An attempt was made by Gaitonde et al. [8] to analyze the effects of depth of cut and turning time on machinability aspects. These considered aspects were machining force, power, specific cutting force, surface roughness, and tool wear. The study was carried on high chromium AISI D2 cold work tool steel using conventional and wiper ceramic inserts. Authors found from the parametric analysis that the power increases with increase in feed rate, while the specific cutting force decreases, whereas the requirement of machining force is low at low values of feed rate and machining time. Also, they found thought the response surface analysis that the surface roughness can be reduced at lower values of feed rate and machining time with higher values of cutting speed, while the maximum tool wear occurs at Vc = 150 m/min for all values of feed rate.

For the same material, Davim and Figueira [9] investigated the machinability of AISI D2 tool steel using experimental and statistical techniques. Hard turning operations were performed on material having hardness of 60 HRC. The tests were conducted by using cutting speed, feed rate, and time as entry parameters, and analysis was done based on the responses. The influence of cutting parameters under flank wear, specific cutting force, and surface roughness on machinability evaluation in turning with conventional and wiper ceramic insert tools using ANOVA is presented. They found that with wiper ceramics inserts, machined surfaces with *Ra* <0.8 μm were achievable. Consequently, surface qualities (dimensional accuracy) in a workpiece of mechanical precision, IT <7, are possible.

The same authors [10] used ceramic cutting tools, composed approximately with (70 %) of Al_2O_3 and (30 %) of TiC, in surface finish operations on the same material (cold work tool steel AISI D2) heat treated to a hardness of 60 HRC. They adopted a plan of experiments, based on orthogonal arrays in turning with prefixed cutting parameters in tool steel workpieces. The results of the tests found by authors showed that with an appropriate cutting parameters choice is possible to obtain a surface roughness (*Ra* < 0.8 μm) that allows to eliminate cylindrical grinding operations.

The study of Neseli et al. [11] focused on the effect of tool geometry parameters on the surface roughness obtained in turning of AISI 1040 steel using response surface methodology (RSM). They developed a prediction model related to average *Ra* based on experimental data. The results indicated that the tool nose radius was the dominant factor on the measured surface roughness.

In another aspect, Yücel and Günay [12] presented a study aimed at modeling and optimizing the cutting conditions for the resulting cutting force (*Fc*) and average *Ra* while machining a high-alloy white cast iron (Ni-hard) based on Taguchi's L_{18} orthogonal array. Cutting tool material, cutting speed, feed rate, and depth of cut were chosen as the cutting conditions (control factors). The-smaller-the-better performance characteristic was applied in order to obtain the optimal cutting conditions. The effects of the cutting conditions on machining output variables were evaluated by the analysis of variance. The results showed that the depth of cut and feed rate were the most significant factors on *Fc* and *Ra*, respectively. Besides that, the optimal cutting conditions were established at the different levels for measured cutting forces and observed surface roughness.

Al-Ahmari [13] developed empirical models for surface roughness and cutting forces during turning operation. The process parameters considered in this study were speed, feed rate, depth of cut, and nose radius in order to develop a machinability model. Additionally, RSM and neural networks (NN) were employed to assess the model.

Aouici et al. [14] investigated the machinability of cold work hard tool steel AISI D3 heat-treated (60 HRC) with a TiN-doped ceramic cutting tool (SNGA120408) containing approximately 30 % of TiC. The responses were estimated based on a (3^3) full factorial experimental design, where the quadratic effects were also determined. The desired optimum was set for minimum levels of surface roughness, cutting force, specific cutting force, and consumed power using RSM and the desirability function approach.

Singh and Dureja [15] compared Taguchi method and RSM for optimizing tool flank wear and surface roughness during the finish operation of AISI D3 steel. A Taguchi L_9 orthogonal array has been applied for experimental design. The confirmation experiments carried out at optimal combination of parameters given by Taguchi analysis predicted the response factors with less than 5 % error. In addition to the desirability function module, RSM was applied to determine the optimal cutting parameters minimizing tool wear and *Ra* and to compare them with optimal cutting parameters found by Taguchi analysis. The optimization results provided by desirability function are found quite close to the optimal solutions provided by Taguchi method.

Hanafi et al. [16] optimized cutting parameters in machining of PEEK-CF30 using TiN tools under dry conditions, to achieve minimum power consumption and the best surface quality. Taguchi optimization and grey relational theory were used in the optimization process.

The aim of the work reported in Asiltürk and Neseli [17] was to model the surface roughness in turning of AISI 304 austenitic stainless steel under dry conditions, using the RSM. An orthogonal array was applied to study the influence of cutting parameters (cutting speed, feed rate, and depth of cut) on the surface roughness.

The work of Bhushan [18] presents experimental investigations into the effects of cutting speed, feed rate, depth of cut, and nose radius in CNC turning of 7075 Al alloy SiC composite. The cutting parameters were optimized by multi-response considerations namely power consumption and tool life. RSM and desirability analysis were used to found out the optimum values of cutting parameters that minimize power consumption and maximize tool life.

Fratila and Caizar [19] minimized the cutting power and the surface roughness during milling of $AlMg_3$. Taguchi optimization methodology was applied to evaluate the outcome of the parameters related to the operation.

Bouchelaghem et al. [20] proposed statistical models based on the RSM, correlating the cutting parameters together with surface roughness cutting forces and tool life in turning of AISI D3 steel.

In the present work, cutting parameters such as major cutting edge angle (χr), cutting insert nose radius (r), cutting speed (Vc), feed rate (f), and depth of cut (ap) are optimized in order to determine the levels of the cutting parameters that lead to minimum technological parameters in terms of surface roughness (*Ra*), tangential force (*Fz*), specific cutting force (*Ks*), and cutting power (*Pc*). The case of dry turning AISI D3 steel with Al_2O_3 (70 %) + TiC (30 %) mixed ceramic inserts was studied. Taguchi's parameter design approach has been used to accomplish this objective. Furthermore, a statistical analysis (ANOVA) of S/N ratio for *Ra*, *Fz*, *Ks*, and *Pc* is performed to see which cutting parameters are statistically significant, the effect of all cutting parameters and their interactions are confirmed by Pareto chart and 3D surface graphs based on S/N ratios of technological output. The relationship between the responses and cutting parameters with their interactions was established by regression analysis to formulate mathematical models.

2 Taguchi method

The Taguchi method is a powerful problem-solving technique for improving process performance and productivity. It allows finding answers for problems which need to reduce for instance, scrap rates, rework costs, and manufacturing costs due to excessive variability in processes. Taguchi [21] advocates the use of orthogonal array designs to assign the chosen factors for the experiment. The most commonly used orthogonal array designs are L_8 (i.e., eight experimental trials), L_{16}, and L_{18}. The power of the Taguchi method is that it integrates statistical methods into the engineering process.

Bendell et al. [1] and Rowlands et al. [22] reported successful applications of the Taguchi method in the automotive, plastics, semiconductors, metal fabrication, and foundry industries. Taguchi method also allows controlling the variations caused by the uncontrollable factors which are not taken into consideration at conventional design of experiment [23, 24]. Taguchi converts the objective function values into S/N ratio to measure the performance characteristics of the control factors. S/N ratio is defined as the desired signal ratio for the undesired random noise value and shows the quality characteristics of the experimental data [25, 26]. Whenever the characteristic is continuous, the S/N ratios are usually divided into three categories given by the following equations [27]:

$$\text{Nominal is the best}: S/N = 10\log\left(\frac{\overline{y}}{s_y^2}\right) \quad (1)$$

$$\text{The-larger-is-the better(maximize)}: S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (2)$$

$$\text{The-smaller-is-the better(minimize)}: S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \quad (3)$$

where $\overline{y}$ is the average of observed data, s_y^2 is the variance of y, n is the number of observations, and y_i is the observed data.

To achieve desirable product quality by design, Taguchi suggests a three-stage process (Fig. 1): system design, parameter design, and tolerance design. System design is the conceptualization and synthesis of a product or process to be used. The system design stage is where new ideas, concepts, and knowledge in the areas of science and technology are utilized by the design team to determine the right combination of

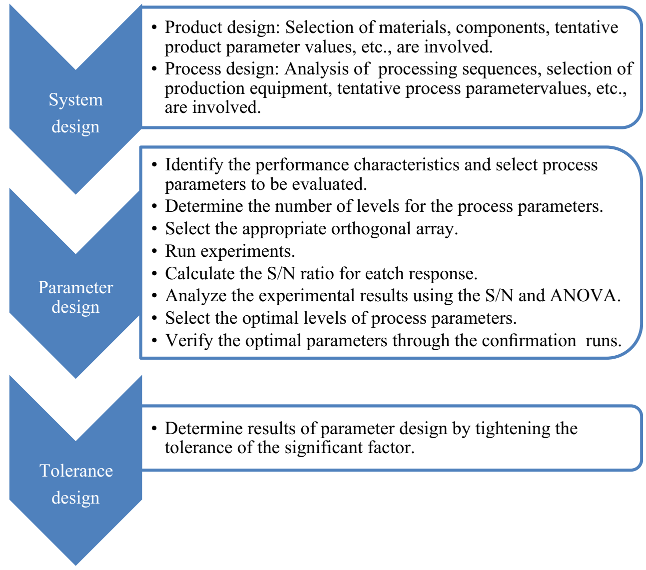


Fig. 1 Taguchi design procedure

materials, parts, processes, and design factors that will satisfy functional and economical specifications. To achieve an increase in quality at this level requires innovation, and therefore, improvements are not always made. In parameter design, the system variables are experimentally analyzed to determine how the product or process reacts to uncontrollable “noise” in the system; parameter design is the main thrust of Taguchi’s approach. Parameter design is related to finding the appropriate design factor levels to make the system less sensitive to variations in uncontrollable noise factors, i.e., to make the system robust. In this way the product performs better, reducing the loss to the customer. The final step in Taguchi’s robust design approach is tolerance design; tolerance design occurs when the tolerances for the products or process are established to minimize the sum of the manufacturing and lifetime costs of the product or process. In the tolerance design stage, tolerances of factors that have the largest influence on variation are adjusted only if after the parameter design stage, the target values of quality have not yet been achieved. Most engineers tend to associate quality with better tolerances, but tightening the tolerances increases the cost of the product or process because it requires better materials, components, or machinery to achieve the tighter tolerances. Taguchi’s parameter design approach allows for improving the quality without requiring better materials or parts and makes it possible to improve quality and decrease (or at least maintain the same) cost.

3 Turning process experiments

3.1 Workpiece material, cutting insert, and tool holders

In this study, a conventional lathe of the check company “TOS TRENCIN” SN40 model, with 6.6-kW spindle power was

Table 1 Mechanical and physical properties of work piece (AISI D3)

Density (g/cm^3)	Modulus of elasticity (MPA)	Thermal conductivity (W/m °C)
7.7	21.10	20

used for carrying out the turning operations in dry conditions on round bars of steel having 70 mm in diameter and 400 mm in length. The workpiece material used was a high alloy steel AISI D3, (DIN 1.2080, JIS SKD1, GB Cr12, AFNOR Z200Cr12). It is a tool steel with high chromium minimum risk of deformation and alteration of dimensions to thermal treatments, and it has excellent wear resistance. Mechanical and physical properties of AISI D3 steel and its chemical composition are given in Tables 1 and 2, respectively.

Among the more important applications of AISI D3 steel are the following [28]:

Blanking, stamping, cold forming dies and punches for long runs, lamination dies, bending, forming, and seaming rolls; cold trimmer dies or rolls, burnishing dies or rolls, plug gages, drawing dies for bars or wire, slitting cutters, lathe centers subject to severe wear.

All operations of turning were made by three mixed ceramic inserts CC650 were manufacturing by Sandvik Coromant and its chemical composition is as follow (Al_2O_3 (70 %) + TiC (30 %)). Each insert is characterized by a nose radius $r = 0.8$, 0.12, and 0.16 mm and ISO geometric designations SNGA120408T01020, SNGA120412T01020, and SNGA120416T01020, respectively. These last are removable, of square form with mechanical fixing by center hole, and each one of them has eight edges of cut. They are mainly recommended for finish machining hardened steels and refractory superalloys, requiring good wear resistance associated with good thermal properties. Two tool holders are used in this experimental study designated by ISO as PSDNN 2525 M12 and PSBNR 2525 M12, respectively. Their geometry of the active part, as shown in Fig. 2, is the same for the following angles: clearance angle (α) = 6°, rake angle (γ) = −6°, and cutting edge inclination angle (λ) = −6°, but it is different to the major cutting edge angle (χr) = 45° and 75°, respectively.

3.2 Experimental design and cutting conditions

The full factorial experimental design for the factors (*Vc*, *f*, *ap*, *r*) which varies at three levels (3^4) and the factor (χr) which

Table 2 Chemical composition of work piece (AISI D3)

Carbon (C)	Manganese (Mn)	silicon (Si)	Chrome (Cr)	Tungsten (W)
2 %	0.30 %	0.25 %	12 %	0.70 %

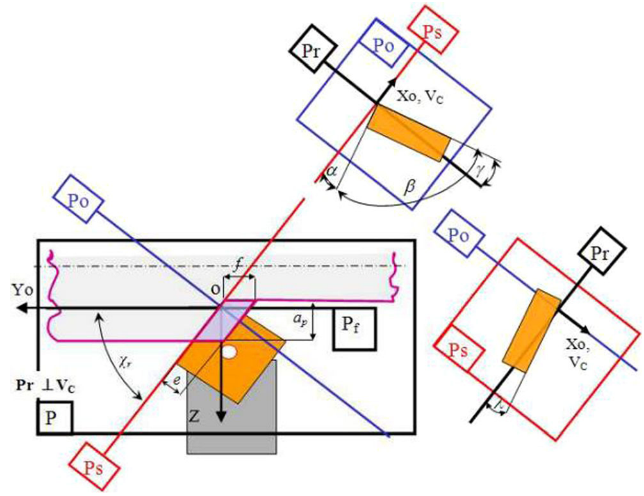


Fig. 2 Illustration of cutting tool geometry

varies at two levels (2^1) involves ($3^4 \times 2^1$) = 162 experimental runs. The number of experimental runs increases with increase of process parameters which is time consuming and costly. In order to simplify the above problem, Dr. Genichi Taguchi proposed a special design orthogonal array (OA) to study the entire parameter space with small number of experiments only. The proposed methodology saves not only time as well as cost substantially. For this, to study the impact of different cutting parameters (*Vc*, *f*, *ap*) and tool geometry (χr, *r*) on technological parameters (*Ra*, *Fz*, *Ks*, and *Pc*), we chose a mixed factorial plan reduces of Taguchi L_{18} as an experimental design for five factors. The levels of the parameters were selected as recommended by the cutting tool manufacturer intervals. The parameters to be studied and the attribution of the levels respectively are shown in Table 3.

3.3 Apparatus of measurement

3.3.1 Surface roughness measurement

The criterion measures of the surface roughness (arithmetic mean roughness *Ra*) are obtained instantly after each pass roughing by means of a Mitutoyo Surftest SJ-201 roughness meter. It consists of a diamond point (probe), with a radius of 5 μm moving linearly on the machined surface. The length examined is 4 mm with a cutoff of 0.8 mm, and the measured

Table 3 Process parameters and their levels

Factor	Symbol	Unit	Level 1	Level 2	Level 3
Cutting speed	*Vc*	m/min	220	307	440
Feed rate	*f*	mm/tr	0.08	0.12	0.16
Depth of cut	*ap*	mm	0.15	0.3	0.45
Nose radius	*r*	mm	0.8	1.2	1.6
Major cutting edge angle	χr	°	45	75	–

values of *Ra* are within the range 0.05–40 μm. To prevent errors and recovery for more precision, roughness measurement was performed directly on the workpiece without dismounting it from the lathe. The measurements were repeated three times along three workpiece feed rate directions also placed at 120° (Fig. 3). The result is considered the average of these values for each cutting condition. To properly characterize the surface roughness of the workpiece, several

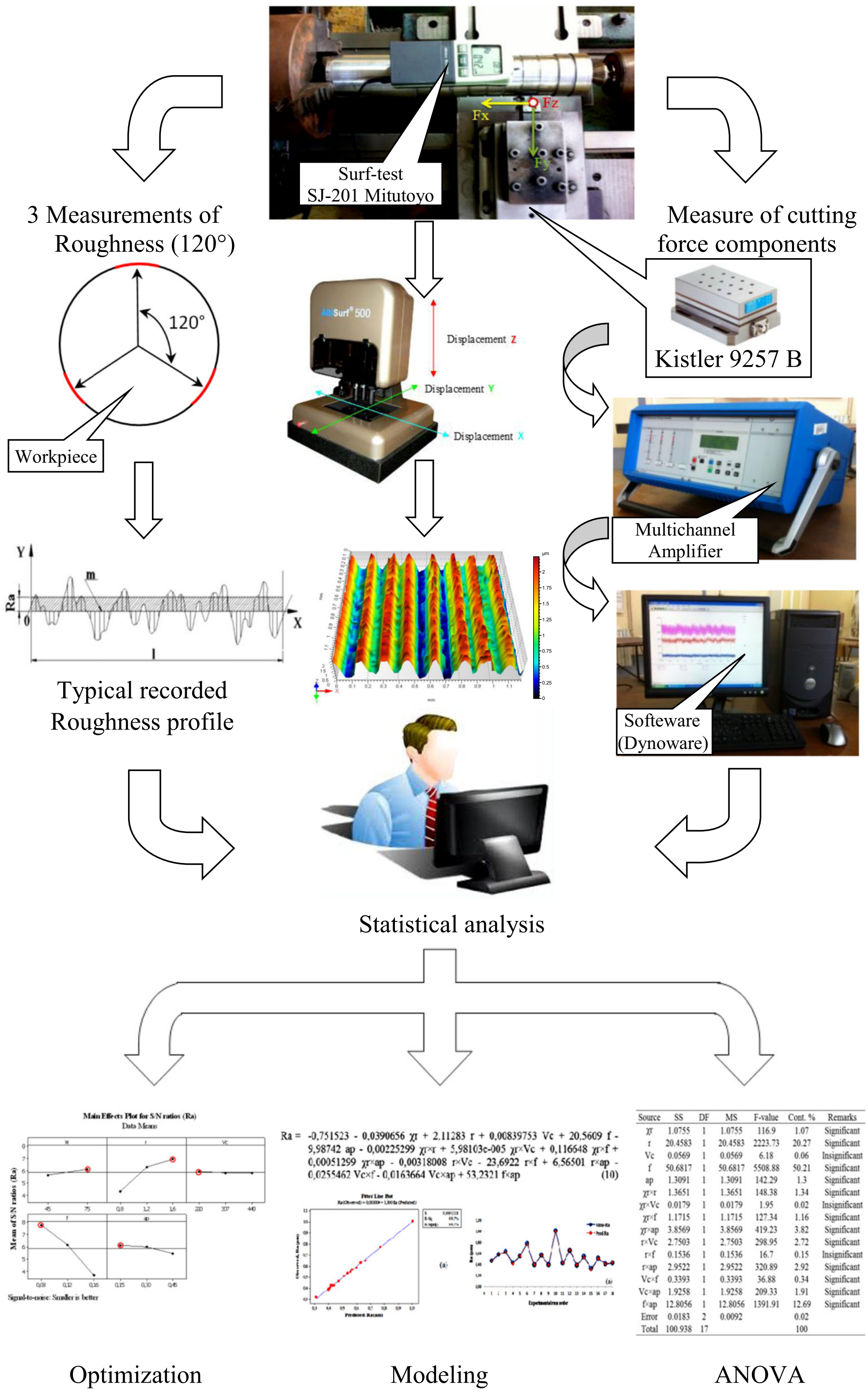


Fig. 3 Schematic diagram of the experimental setup

measurements were made using a 3D with optical platform of metrology modular Altisurf 500.

3.3.2 Tangential force measurement

The Fz, schematically shown in Fig. 3, was recorded using a standard quartz dynamometer (Kistler 9257B) allowing measurements from −5 to 5 KN. The tool is mounted on the platform, which is itself fixed on the cross slide of the machine tool with the aid of the fixing plate. The platform consists of four quartz sensors. The forces acting on the plate during the cutting are converted into electrical charges which are then amplified by the charge amplifier (Kistler 5019B130). These amplified signals are the acquired by the PC through the acquisition card (A = D2855A3) installed especially on the central control unit latter. Software (DynoWare 2825A1-1) analyzes and processes these signals and the force produced during the turning processes directly expressed in three components.

3.3.3 Formula of specific cutting force and cutting power

To determine the energy consumed during the machining operation, the cutting power Pc (W) related to the cutting force Fz is often measured. Another common magnitude used to quantify the work provided is to calculate the specific cutting force (or cutting pressure) in turning (MPa). These values can be defined as the energy required to removing a certain amount of matter in the form of chips. These aspects of machinability such as Ks and Pc are calculated with the obtained results by tangential force using the following equations:

$$Ks = \frac{Fz}{S} = \frac{Fz}{f \times ap} \tag{4}$$

$$Pc = \frac{Fz \times Vc}{60} \tag{5}$$

where Ks is the specific cutting force (MPa), Fz is the tangential force (N), S is the shear plane area (mm^2), Pc is the cutting power (W), f is the feed rate (mm/rev), ap is the depth of cut (mm), and Vc is the cutting speed (m/min).

4 Experimental results and data analysis

The experimental results of (Ra, Fz, Ks, and Pc) with their computed S/N ratio are presented in Table 4. These results of (Ra, Fz) were obtained as a result of various combinations of levels of cutting parameters based on mixed factorial plan reduced of Taguchi L_{18}. The results of (Ks, Pc) were calculated with the obtained results by tangential force using the Eqs. 4 and 5. The-smaller-is-the-better characteristics (Eq. 3) [27] are used to calculate the S/N ratio for each response that aims to minimize the surface roughness, tangential force, specific cutting force, and cutting power, respectively.

Table 4 Experimental results for surface roughness, tangential force, specific cutting force, and cutting power

Trail no.	Machining parameters					Response parameters							
	χr (°)	r (mm)	Vc (m/min)	f (mm/rev)	ap (mm)	Ra (μm)	S/N (dB)	Fz (N)	S/N (dB)	Ks (MPa)	S/N (dB)	Pc (W)	S/N (dB)
1	45	0.8	220	0.08	0.15	0.47	6.56	53.6	−34.58	4466.67	−72.99	196.53	−45.87
2	45	0.8	307	0.12	0.3	0.59	4.63	131.5	−42.38	3652.78	−71.25	672.84	−56.56
3	45	0.8	440	0.16	0.45	0.63	3.97	231.15	−47.28	3210.42	−70.13	1695.10	−64.58
4	45	1.2	220	0.08	0.3	0.43	7.26	88.33	−38.92	3680.42	−71.32	323.88	−50.21
5	45	1.2	307	0.12	0.45	0.55	5.14	173.82	−44.8	3218.89	−70.15	889.38	−58.98
6	45	1.2	440	0.16	0.15	0.78	2.20	93.2	−39.39	3883.33	−71.78	683.47	−56.69
7	45	1.6	220	0.12	0.15	0.39	8.10	70.66	−36.98	3925.56	−71.88	259.09	−48.27
8	45	1.6	307	0.16	0.3	0.57	4.83	161.01	−44.14	3354.38	−70.51	823.83	−58.32
9	45	1.6	440	0.08	0.45	0.40	8.03	138.61	−42.84	3850.28	−71.71	1016.47	−60.14
10	75	0.8	220	0.16	0.45	1.01	−0.09	201.04	−46.07	2792.22	−68.92	737.15	−57.35
11	75	0.8	307	0.08	0.15	0.43	7.40	64.4	−36.18	5366.67	−74.59	329.51	−50.36
12	75	0.8	440	0.12	0.3	0.65	3.70	112	−40.98	3111.11	−69.86	821.33	−58.29
13	75	1.2	220	0.12	0.45	0.39	8.18	171.9	−44.71	3183.33	−70.06	630.30	−55.99
14	75	1.2	307	0.16	0.15	0.54	5.35	99.21	−39.93	4133.75	−72.33	507.62	−54.11
15	75	1.2	440	0.08	0.3	0.33	9.72	87.3	−38.82	3637.50	−71.22	640.20	−56.13
16	75	1.6	220	0.16	0.3	0.51	5.79	176.2	−44.92	3670.83	−71.30	646.07	−56.21
17	75	1.6	307	0.08	0.45	0.41	7.74	139.8	−42.91	3883.33	−71.78	715.31	−57.09
18	75	1.6	440	0.12	0.15	0.43	7.33	87.71	−38.86	4872.78	−73.76	643.21	−56.17

4.1 Analysis of variance (ANOVA)

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested.

This analysis allows testing the significance of all main factors (χr, r, Vc, f, ap) and their interactions in order of influence on the responses by comparing the mean square against an estimate of the experimental errors at specific confidence levels. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. First, the total sum of squared deviations SS_T from the total mean S/N ratio η_m can be calculated as follows [29]:

$$SS_T = \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \tag{6}$$

where n is the number of experiments in the orthogonal array and η_i is the mean S/N ratio for the ith experiment.

The total sum of squared deviations SS_T is decomposed into two sources: the sum of squared deviations SS_d due to each design parameter and the sum of squared error SS_e.

$$SS_T = SS_d + SS_e \tag{7}$$

Statistically, there is a tool called an F test, named after Fisher [30], to see which design parameters have a significant effect on the quality characteristic. In the analysis, the F ratio is a ratio of the mean square error to the residual error and is traditionally used to determine the significance of a factor.

This analysis was carried out for a level of significance of 5 %, i.e., for a 95 % level of confidence. The last column of the table shows the “percent” contribution (Cont. %) of each factor and interaction as the total variation, indicating its influence on the result.

The results of ANOVA for S/N (Ra) are shown in Table 5. It is observed that the feed rate comes in first position of influencing on the quality of surface with a contribution of 50.21 %, because during the feed rate of cutting tool on along of workpiece in turning process, the tool shape generate helicoid furrows on surface of workpiece. These furrows are deeper and broader as the feed rate increases; therefore, the surface quality decreases. The second influential machining parameter is the nose radius of the tool with an impact of 22.19 %. A popular established model [31] to estimate the surface roughness, with a tool having none zero nose radius, is

$$Ra = \frac{f^2}{32 \times r} \tag{8}$$

where Ra is the average surface roughness (μm), f is the feed rate (mm/rev), and r is the cutting tool nose radius (mm).

Table 5 Analysis of variance for S/N (Ra)

Source	SS	DF	MS	F value	Cont. %	Remarks
χr	1.0755	1	1.0755	116.9	1.07	Significant
r	20.4583	1	20.4583	2223.73	20.27	Significant
Vc	0.0569	1	0.0569	6.18	0.06	Insignificant
f	50.6817	1	50.6817	5508.88	50.21	Significant
ap	1.3091	1	1.3091	142.29	1.3	Significant
$\chi r \times r$	1.3651	1	1.3651	148.38	1.34	Significant
$\chi r \times Vc$	0.0179	1	0.0179	1.95	0.02	Insignificant
$\chi r \times f$	1.1715	1	1.1715	127.34	1.16	Significant
$\chi r \times ap$	3.8569	1	3.8569	419.23	3.82	Significant
$r \times Vc$	2.7503	1	2.7503	298.95	2.72	Significant
$r \times f$	0.1536	1	0.1536	16.7	0.15	Insignificant
$r \times ap$	2.9522	1	2.9522	320.89	2.92	Significant
$Vc \times f$	0.3393	1	0.3393	36.88	0.34	Significant
$Vc \times ap$	1.9258	1	1.9258	209.33	1.91	Significant
$f \times ap$	12.8056	1	12.8056	1391.91	12.69	Significant
Error	0.0183	2	0.0092		0.02	
Total	100.938	17			100	

According to Eq. 8, the increase in tool nose radius decreases surface roughness.

Figure 4 shows a representative example of 3D image of turned surface envisioned by means of optical platform of metrology modular Altisurf 500 with isometric view. It is clearly seen in Fig. 4 the influence of both feed rate and nose radius on surface roughness. The use of large feed rate results a worst surface roughness because at large feed rate, the distance between peaks and valleys of the feed marks is much more important. Whereas the use of large nose radius improve the surface roughness by the crushing of the asperities. When the nose radius of cutting tool increases, as the contact languor between the beak of the tool and the machined surface is increased, leading to crushing of the asperities and traces of advance of the tool as shown in Fig. 4.

Similarly, Dilbag and Venkateswara [32] and Ashvin and Nanavati [33] found that the feed rate is the main factor followed by tool nose radius affecting the surface roughness. The interaction $f \times ap$ comes in third position with an effect of 12.69 % on quality of surface, the same interaction significance found by Aslan et al. [34] when turning hardened AISI 4140 steel with Al_2O_3 + TiCN mixed ceramic tool. The factors (χr, Vc, ap) and the other interactions are having a slight effect on quality of surface.

It is obvious from the results of ANOVA for S/N (Fz) that the depth of cut is the dominant factor affecting tangential force Fz (Table 6). Its contribution is 60.9 %. The second factor influencing Fz is the feed rate. Its contribution is 19.5 %. The results found are a good agreement with the previous researcher’s works Yücel and Günay [12] and

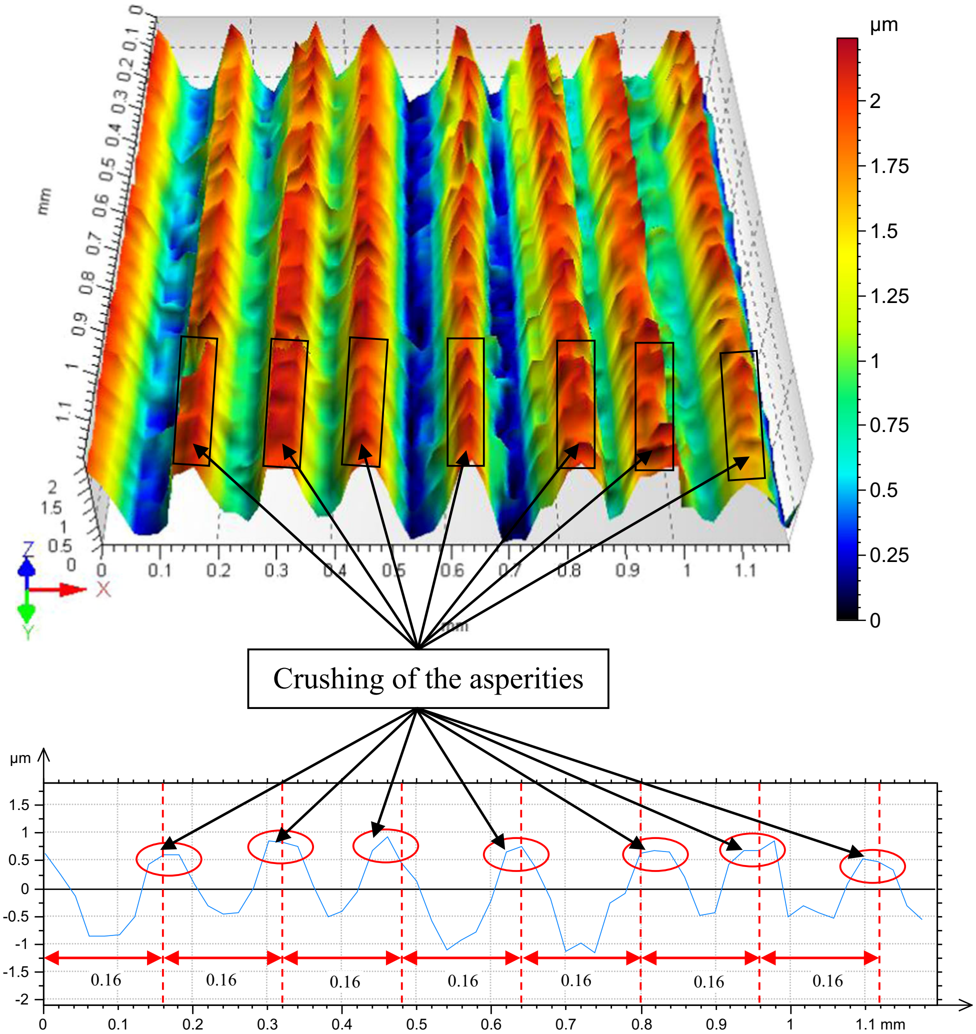


Fig. 4 Example of 2D profile and 3D topography of turned surface: $\chi r = 75°$, $r = 1.6$ mm, $Vc = 220$ m/min, $f = 0.16$ mm/rev, and $ap = 0.15$ mm

Table 6 Analysis of variance for S/N (*Fz*)

Source	SS	DF	MS	*F* value	Cont. %	Remarks
χr	2.683	1	2.683	1.69	1.55	Insignificant
r	14.708	1	14.708	9.24	8.5	Insignificant
Vc	1.94	1	1.94	1.22	1.12	Insignificant
f	33.734	1	33.734	21.19	19.5	Significant
ap	105.344	1	105.344	66.17	60.9	Significant
$\chi r \times r$	0.003	1	0.003	0.00	0.00	Insignificant
$\chi r \times Vc$	5.209	1	5.209	3.27	3.01	Insignificant
$\chi r \times f$	0.05	1	0.05	0.03	0.03	Insignificant
$\chi r \times ap$	2.375	1	2.375	1.49	1.37	Insignificant
$r \times Vc$	0.95	1	0.95	0.6	0.55	Insignificant
$r \times f$	0.036	1	0.036	0.02	0.02	Insignificant
$r \times ap$	0.158	1	0.158	0.1	0.09	Insignificant
$Vc \times f$	0.896	1	0.896	0.56	0.52	Insignificant
$Vc \times ap$	1.178	1	1.178	0.74	0.68	Insignificant
$f \times ap$	0.519	1	0.519	0.33	0.3	Insignificant
Error	3.185	2	1.592		1.84	
Total	172.969	17			100	

Bouchelaghem et al. [20]. The tangential cutting force increases as the depth of cut and feed rate are increased due to the increase of the cutting area. As for the nose radius, its contribution is 8.5 %.

The results given by ANOVA for S/N (*Ks*) presented in Table 7 shows that the factors *ap* and *f* are the most significant with the respective contribution (51.91, 18.27) %. However, a qualitative comparison can be made; for example, Aouici et al. [14] found that depth of cut and feed rate are the important factors affecting specific cutting force. The interaction $\chi r \times Vc$ present a statistical significance with contribution (10.3 %).

From Table 8, which represents ANOVA for S/N (*Pc*), it is observed that the depth of cut (44.22 %) is the most significant parameter followed by cutting speed (34.14 %). However, the feed rate has the least effect (18.33 %) in controlling the cutting power. A similar result was obtained by Hanafi et al. [16] revealing that depth of cut is the most influencing parameter followed by cutting speed and feed rate on cutting power. The other factors and all interactions do not present any significant contribution on the *Pc*.

Table 7 Analysis of variance for S/N (*Ks*)

Source	SS	DF	MS	*F* value	Cont. %	Remarks
χr	0.2374	1	0.2374	1.45	0.69	Insignificant
r	0.8428	1	0.8428	5.14	2.46	Insignificant
Vc	0.1965	1	0.1965	1.2	0.58	Insignificant
f	6.2395	1	6.2395	38.05	18.27	Significant
ap	17.7205	1	17.7205	108.05	51.91	Significant
$\chi r \times r$	1.1699	1	1.1699	7.13	3.42	Insignificant
$\chi r \times Vc$	3.5155	1	3.5155	21.44	10.3	Significant
$\chi r \times f$	0.0586	1	0.0586	0.36	0.17	Insignificant
$\chi r \times ap$	2.5705	1	2.5705	15.67	7.53	Insignificant
$r \times Vc$	0.4836	1	0.4836	2.95	1.42	Insignificant
$r \times f$	0.1708	1	0.1708	1.04	0.5	Insignificant
$r \times ap$	0.0231	1	0.0231	0.14	0.07	Insignificant
$Vc \times f$	0.0312	1	0.0312	0.19	0.09	Insignificant
$Vc \times ap$	0.2548	1	0.2548	1.55	0.75	Insignificant
$f \times ap$	0.2964	1	0.2964	1.81	0.87	Insignificant
Error	0.3281	2	0.164		0.96	
Total	34.1393	17			100	

Pareto analysis is a simple technique for prioritizing problem solving. It is based on the Pareto principle also known as 80/20 rule which in general means that 80 % of problems may be caused by as few as 20 % of causes [35]. To confirm the results obtained by ANOVA analysis for S/N of technological parameters, a Pareto chart is integrated (Fig. 5). The aim of this chart is to rank in descending order the influence of the cutting parameters and their interactions on the *Ra*, *Fz*, *Ks*, and *Pc*. The effects of factors and their interactions on the responses are standardized for a better comparison. The standardized values called *F* value in this chart are obtained by dividing the mean squares of each factor by the error of mean squares. The more standardized the effect, the higher the factor considered influence. If the *F* table values which correspond to the cutting parameters and their interactions are greater than 18.51; the effects are significant. By against, if the values of *F* table are less than 18.51, the effects are not significant. The confidence interval chosen is 95 % ($\alpha = 0.05$).

Table 8 Analysis of variance for S/N (*Pc*)

Source	SS	DF	MS	*F* value	Cont. %	Remarks
χr	0.237	1	0.237	0.21	0.07	Insignificant
r	0.843	1	0.843	0.76	0.25	Insignificant
Vc	117.156	1	117.156	104.98	34.14	Significant
f	62.887	1	62.887	56.35	18.33	Significant
ap	151.744	1	151.744	135.97	44.22	Significant
$\chi r \times r$	1.17	1	1.17	1.05	0.34	Insignificant
$\chi r \times Vc$	0.069	1	0.069	0.06	0.02	Insignificant
$\chi r \times f$	0.41	1	0.41	0.37	0.12	Insignificant
$\chi r \times ap$	4.533	1	4.533	4.06	1.32	Insignificant
$r \times Vc$	0.014	1	0.014	0.01	0.00	Insignificant
$r \times f$	0.468	1	0.468	0.42	0.14	Insignificant
$r \times ap$	0.323	1	0.323	0.29	0.09	Insignificant
$Vc \times f$	0.387	1	0.387	0.35	0.11	Insignificant
$Vc \times ap$	0.519	1	0.519	0.47	0.15	Insignificant
$f \times ap$	0.13	1	0.13	0.12	0.04	Insignificant
Error	2.233	2	1.116		0.65	
Total	343.124	17			100	

4.2 Interaction effect on responses (3D plots and contours)

In order to check the influence of interactions $f \times ap$ and $\chi r \times Vc$ on the S/N ratio for *Ra* and *Ks*, respectively, graphs of the interactions of factors for each response surface are drawn in Fig. 6a, b. Variables not represented in the figure are held constant (the middle level). Figure 6a shows the 3D response surface for the effect of the interaction of the depth of cut and the feed rate on the surface quality (S/N ratio for *Ra*), maintaining the major cutting edge angle, nose radius of the tool, and the cutting speed to medium level (χr = 60°, r = 1.2 mm, Vc = 330 m/min), respectively. This figure indicates that, for a given depth of cut, the reduction in surface quality is recorded with the increase in the feed rate. It can be seen through this figure that the surface quality is sensitive to the feed rate; an increase of the latter decreases the surface quality. This is in good agreement with the research work published by Bouzid et al. [36] where they observed that the *Ra* rapidly increases with increasing feed rate. However, this decrease in surface quality becomes increasingly small with lower values of the depth of cut.

Figure 6b shows the impact of the major cutting edge angle and the cutting speed on the S/N ratio of the specific cutting force while the nose radius of the tool, the feed rate, and depth of cut are maintained at medium level (r = 1.2 mm, f = 0.12 mm/rev, ap = 0.3 mm). This figure indicates that for the major cutting edge angle (χr = 75°), the increase of the S/N ratio (*Ks*) is notable with the increase of cutting speed. By cons, for the major cutting edge angle (χr = 45°), there was a slight decrease in the S/N ratio (*Ks*) with increasing cutting speed. For low cutting speeds, the S/N ratio (*Ks*) decreases with increase of the major cutting edge angle. By against, for high speeds, it is clear that the S/N (*Ks*) decreases with decreasing the major cutting edge angle.

The contour for the response surface for S/N (*Ra*) is shown in Fig. 7a. It is clear from Fig. 7a that at any particular depth of cut, the best quality of surface is obtainable when the feed rate is somewhere at lower of the feed rate range experimented. Also, at higher depths of cut, better quality of surface is obtainable from 0.3 to 0.45 mm.

Figure 7b displays the contour for the response surface for S/N (*Ks*). Regardless of the category of the quality characteristic in Taguchi method, a greater S/N ratio corresponds to

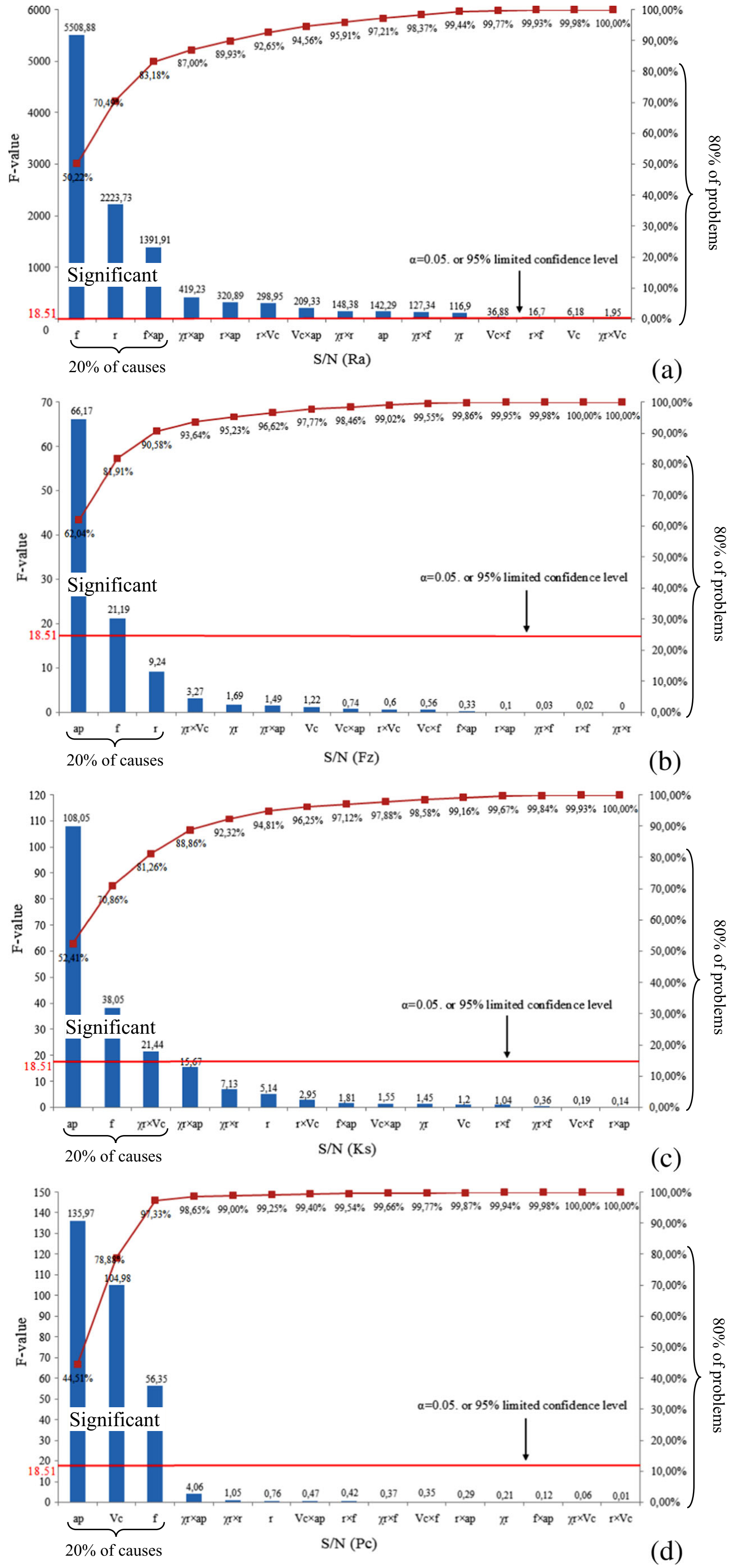
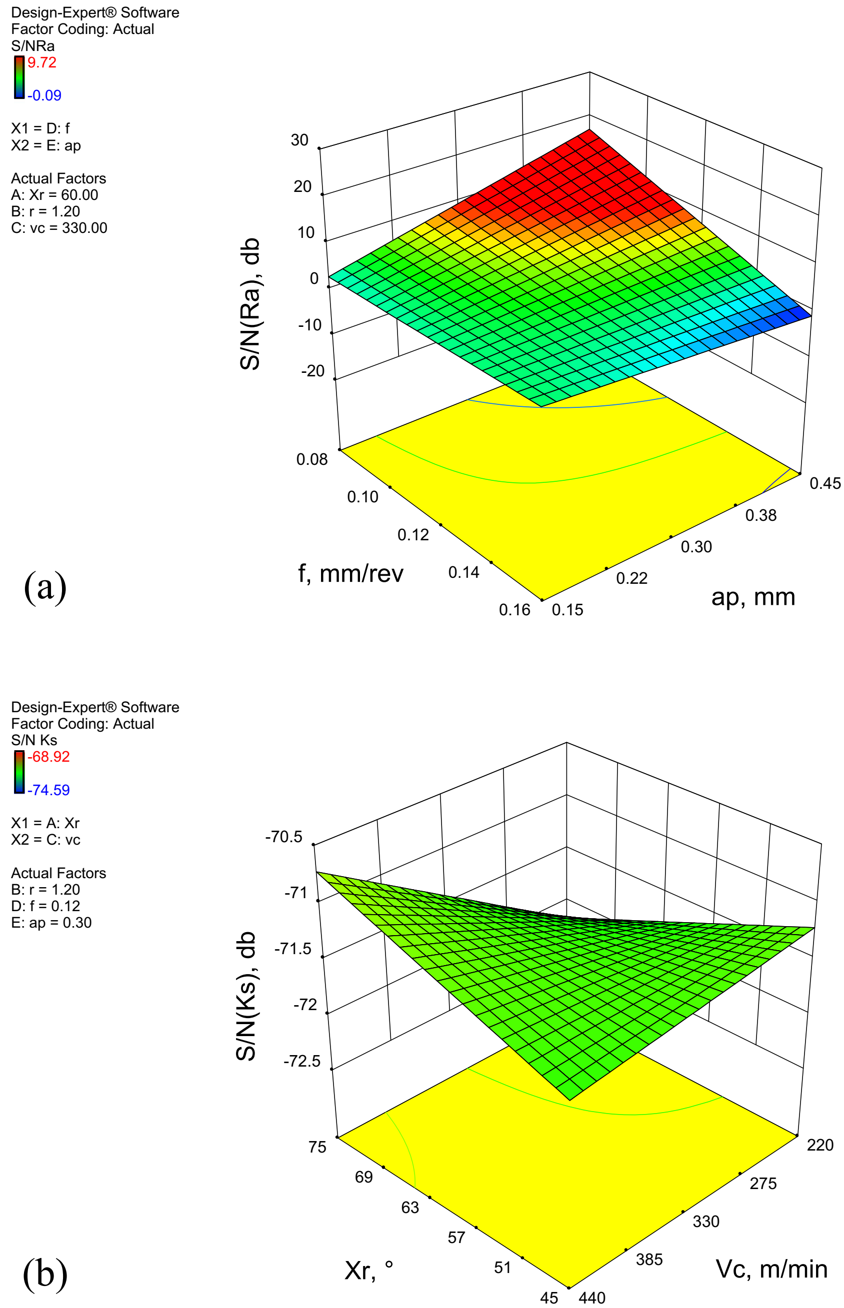


Fig. 5 Pareto chart, for effect cutting parameters on **a** surface roughness, **b** tangential force, **c** specific cutting force, and **d** cutting power

Fig. 6 3D plots for **a** effect of $f \times ap$ on the S/N (Ra), **b** effect of $\chi r \times Vc$ on the S/N (Ks)



better quality characteristics. Therefore, the lowest specific cutting force that corresponds to a greater S/N ratio (Ks) is obtained when both of cutting speed and major cutting edge angle levels are high.

4.3 Regression analysis

Regression analysis is technique for investigating functional relationship between the dependent variable and one or more independent variables. In this study, the dependent variables are Ra, Fz, Ks, and Pc, while the independent variables are χr, r, Vc, f, and ap. The predictive equations for the technological parameters were formulated by linear regression model with interactions given by Eq. 9.

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{ij}^{k} b_{ij} X_i X_j + \varepsilon_i \tag{9}$$

where b_0 is the free term of the regression equation, the coefficients b_1, b_2 … b_k and b_{12}, b_{13}, b_{k-1} are the linear

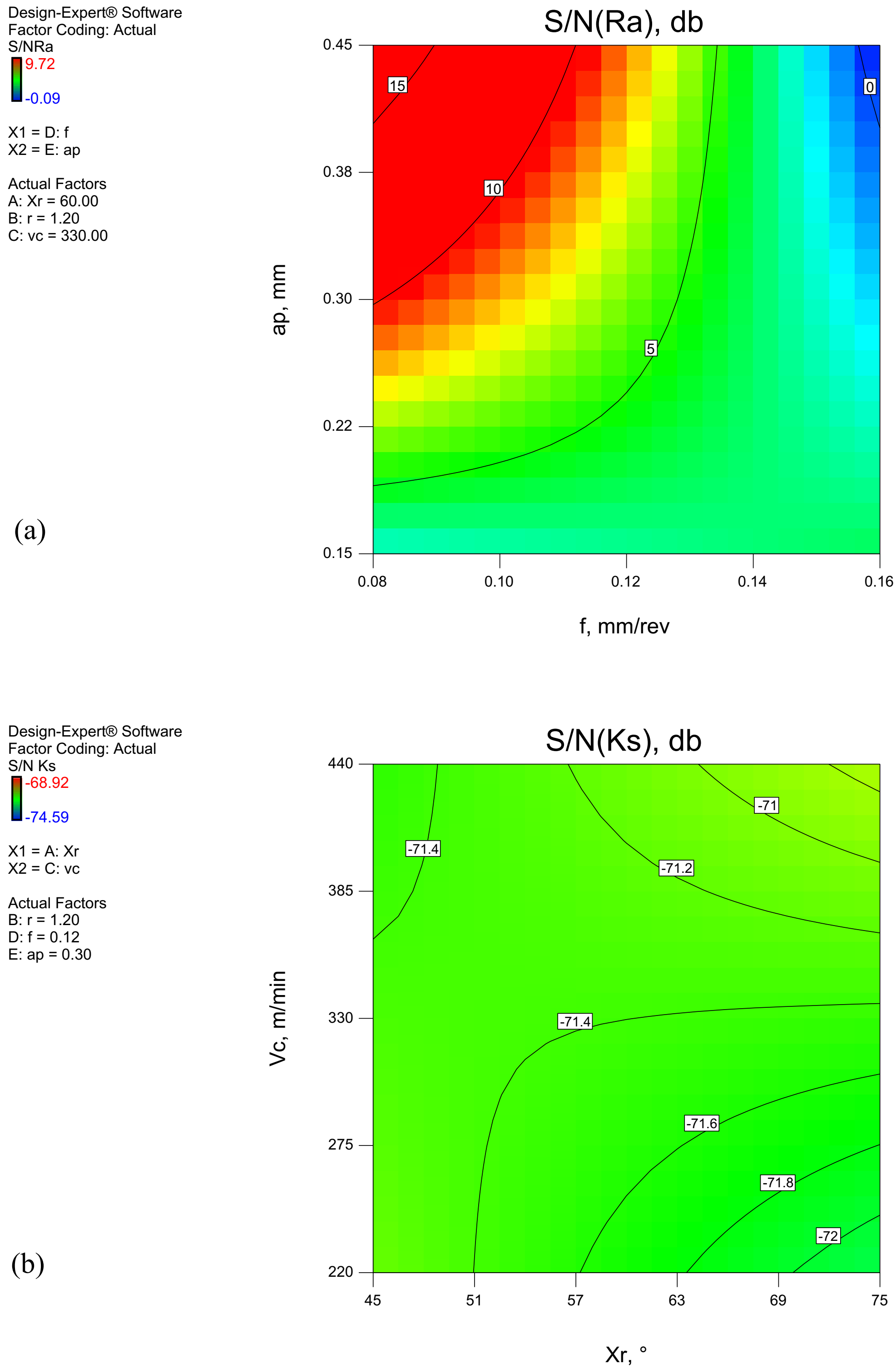


Fig. 7 Contours for the response surface for **a** effect of $f \times ap$ on the S/N (Ra), **b** effect of $\chi r \times Vc$ on the S/N (Ks)

and interacting terms, respectively. X_i represents the input parameters (χr, r, Vc, f, ap), and Y represents the output (surface roughness, tangential force, specific cutting force, and cutting power).

Predictive equations of Ra, Fz, Ks, and Pc in function of cutting parameters (Vc, f, ap) and the tool geometry (χr, r) which were obtained by the linear regression model with interactions are given below by Eqs. 10–13 with respective coefficients of determination R^2 of 99.72, 99.81, 98.67, and 99.82 %. These regression models are useful in predicting the response parameters with respect to the input control parameters.

$$Ra = -0.751523 – 0.0390656\,\chi r + 2.11283\,r + 0.00839753\,Vc + 20.5609\,f – 9.98742\,ap – 0.00225299\,\chi r \times r + 5.98103e{-}005\,\chi r \times Vc + 0.116648\,\chi r \times f + 0.00051299\,\chi r \times ap – 0.00318008\,r \times Vc – 23.6922\,r \times f + 6.56501\,r \times ap – 0.0255462\,Vc \times f – 0.0163664\,Vc \times ap + 53.2321\,f \times ap \quad (10)$$

$$Fz = -47.4569 + 0.634052\,\chi r – 32.4047\,r + 0.299883\,Vc + 452.092\,f – 5.93513\,ap + 1.0859\,\chi r \times r – 0.00269694\,\chi r \times Vc – 2.79961\,\chi r \times f – 2.6456\,\chi r \times ap – 0.0698555\,r \times Vc – 189.798\,r \times f + 98.2247\,r \times ap – 0.439946\,Vc \times f – 0.038708\,Vc \times ap + 2983.77\,f \times ap \quad (11)$$

$$Ks = 1521.5 + 82.6988\,\chi r + 648.574\,r + 6.74166\,Vc + 14572.6\,f – 11469.8\,ap + 17.3155\,\chi r \times r – 0.114641\,\chi r \times Vc – 196.365\,\chi r \times f – 134.196\,\chi r \times ap + 0.794421\,r \times Vc – 26415.7\,r \times f + 6571.84\,r \times ap + 3.69599\,Vc \times f – 8.36022\,Vc \times ap + 72926.3\,f \times ap \quad (12)$$

$$Pc = 98.25 + 8.51575\,\chi r – 193.257\,r – 1.14402\,Vc – 1740.52\,f – 1007.09\,ap + 5.70617\,\chi r \times r – 0.0157304\,\chi r \times Vc – 37.1442\,\chi r \times f – 18.1753\,\chi r \times ap + 0.134651\,r \times Vc – 776.369\,r \times f – 40.8738\,r \times ap + 15.3665\,Vc \times f + 6.68678\,Vc \times ap + 13983.2\,f \times ap \quad (13)$$

The criterion, for fitting the best line through the data in simple linear regression, is based on the minimization of the sum of squares of residuals between the measured values of response and the values of response calculated with the regression model. The linear fit is expressed as follows:

$$y = a_0 + a_1 x \quad (14)$$

where y is the value of response and x is the value of variable.

To verify the pertinence of fit for the obtained mathematical models the fitted line plots (Fig. 8) were traced. They suggest that there is an increasing linear relationship between predicted and observed values of technological parameters. They also

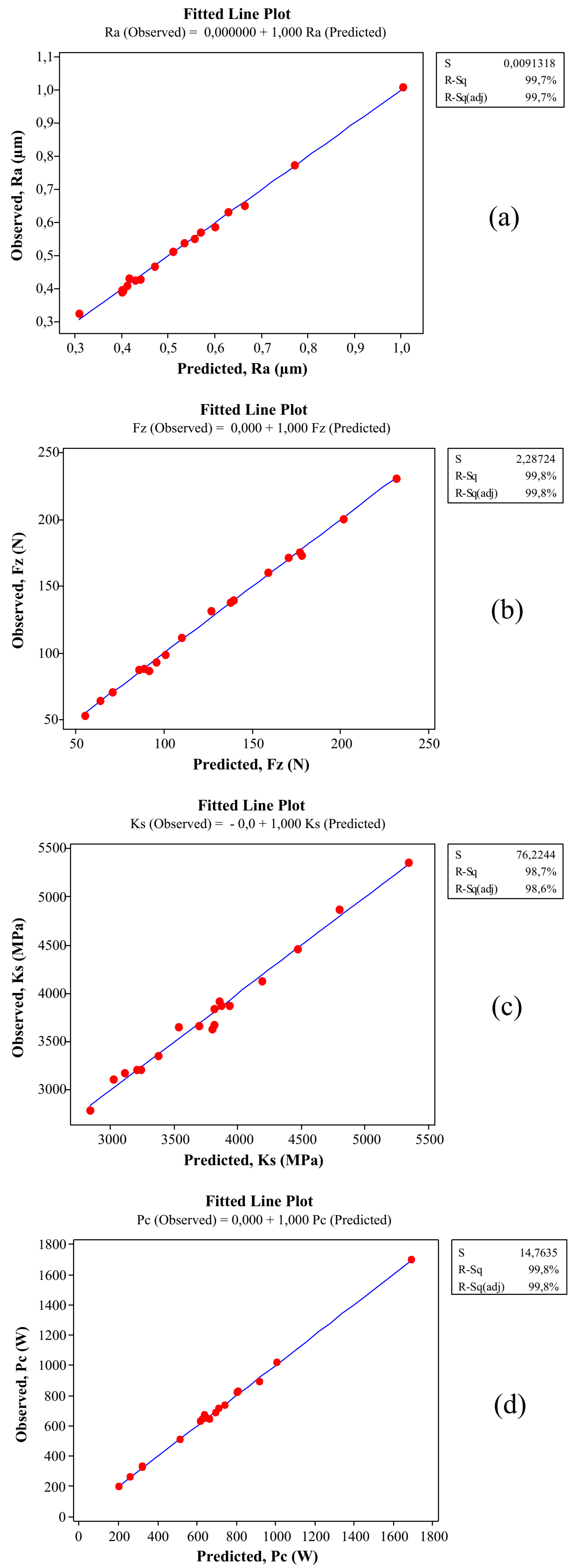


Fig. 8 Relationship between observed and predicted responses values: **a** ▶ surface roughness, **b** tangential force, **c** specific cutting force, and **d** cutting power

suggest that there are no unusual data points in the dataset. And, they illustrate that the variation around the estimated regression line is constant suggesting that the assumption of equal error variances is reasonable.

Figure 9 also shows a comparison between the predicted values of technological parameters (obtained from linear regression model of response equations) and the observed ones. The results of the comparison prove that predicted values of

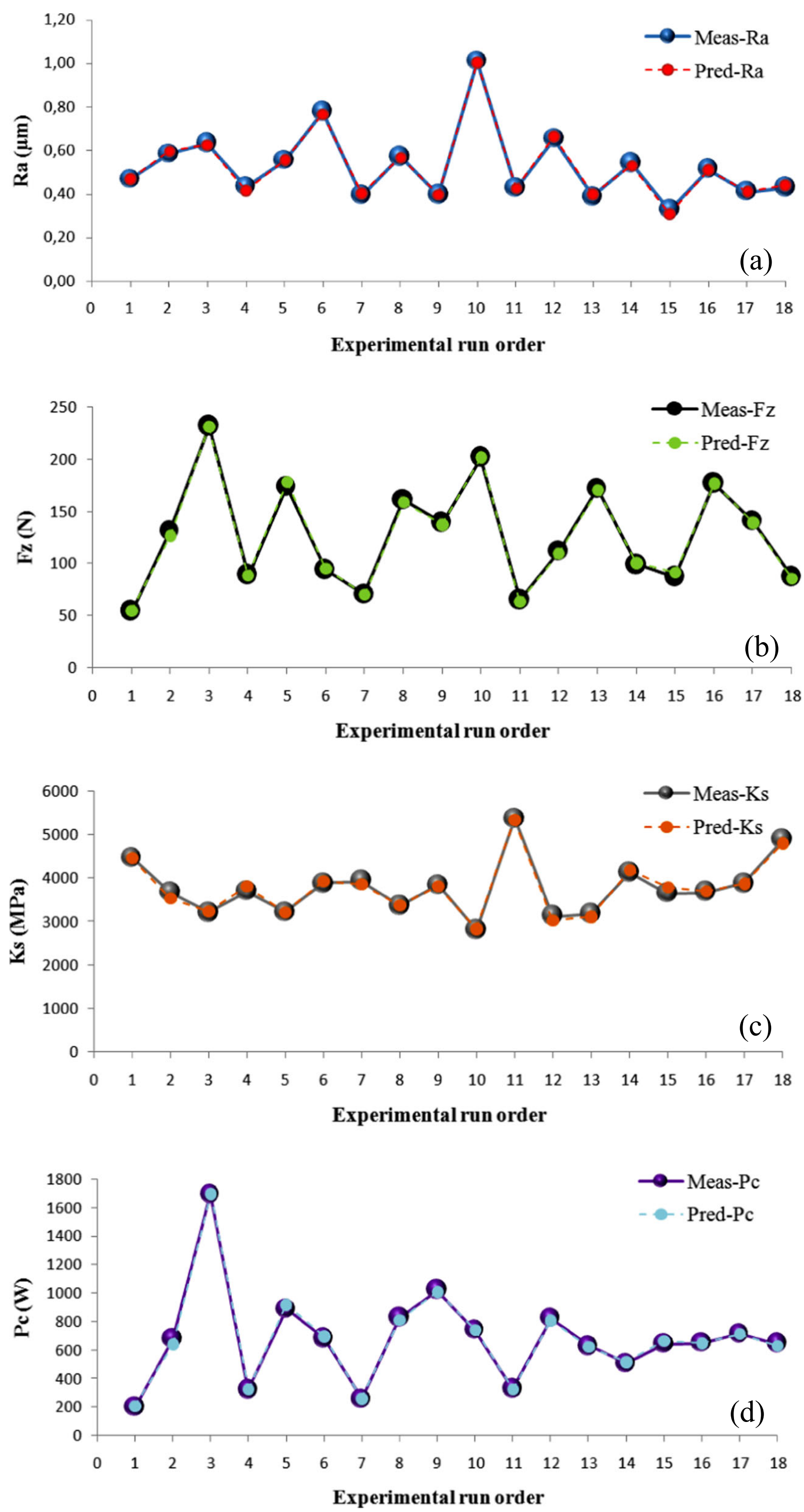


Fig. 9 Measured vs. predicted values of technological parameters: **a** surface roughness, **b** tangential force, **c** specific cutting force, and **d** cutting power

the technological parameters are very close to those readings recorded experimentally (good agreement between predicted and observed values). These figures indicate that the linear regression models are capable of representing the system under the given experimental domain.

4.4 Analysis of the S/N ratio and selection of optimal levels for technological parameters

The control factor that has the strongest influence is determined depending on the value of delta as shown in Table 9 (a, b, c, d). Delta equals the difference between maximum and minimum S/N ratios for a particular control factor. The higher the value of delta, the more influential is the control factor. The control factors and their interactions were sorted in relation to the values of delta. It can be seen in Table 9 (a, b, c, d) that the significance of all main factors (χr, r, Vc, f, ap) are ranking in descending order of influence on the responses (Ra, Fz, Ks, Pc). It can observed clearly that the same ranking in descending order of influence of all main factors on responses are obtained by ANOVA analysis and that confirmed by Pareto chart.

The plots for S/N ratios of responses are shown in Fig. 10. Response graphs show the variation of S/N ratio when the setting of the control factors is changed from one level to another. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio which shows in Table 9 (a, b, c, d) with bold style.

The optimal levels for each control factor can be easily determined from these graphs (Fig. 10) by considering the higher points in accordance with Taguchi's "the-smaller-is-the-better" performance characteristic. All the optimal machining parameters were highlighted in circles in Fig. 10. It suggests that the optimum condition for the minimum surface roughness is the combination of (χr_2, r_3, Vc_1, f_1, ap_1) levels of the respective control factors. The optimum parameters were as follows: major cutting edge angle of 75°, insert radius of 1.6 mm, cutting speed of 220 m/min, feed of 0.08 mm/rev, and depth of cut of 0.15 mm. This implies that in order to reduce the surface roughness, the use of higher insert radius and low both of feed rate and depth of cut is recommended, as indicated also by Meddour et al. [37]. They recommended higher insert radius and low feed rate to obtain better surface finish under dry turning operation when hard turning of AISI 52100 steel with mixed ceramic insert.

Similarly, as the-smaller-is-the-better was selected for tangential force and cutting power, the best level for each control factor was found according to the highest S/N ratio in the levels of that control factor (Fig. 10b, d). According to this,

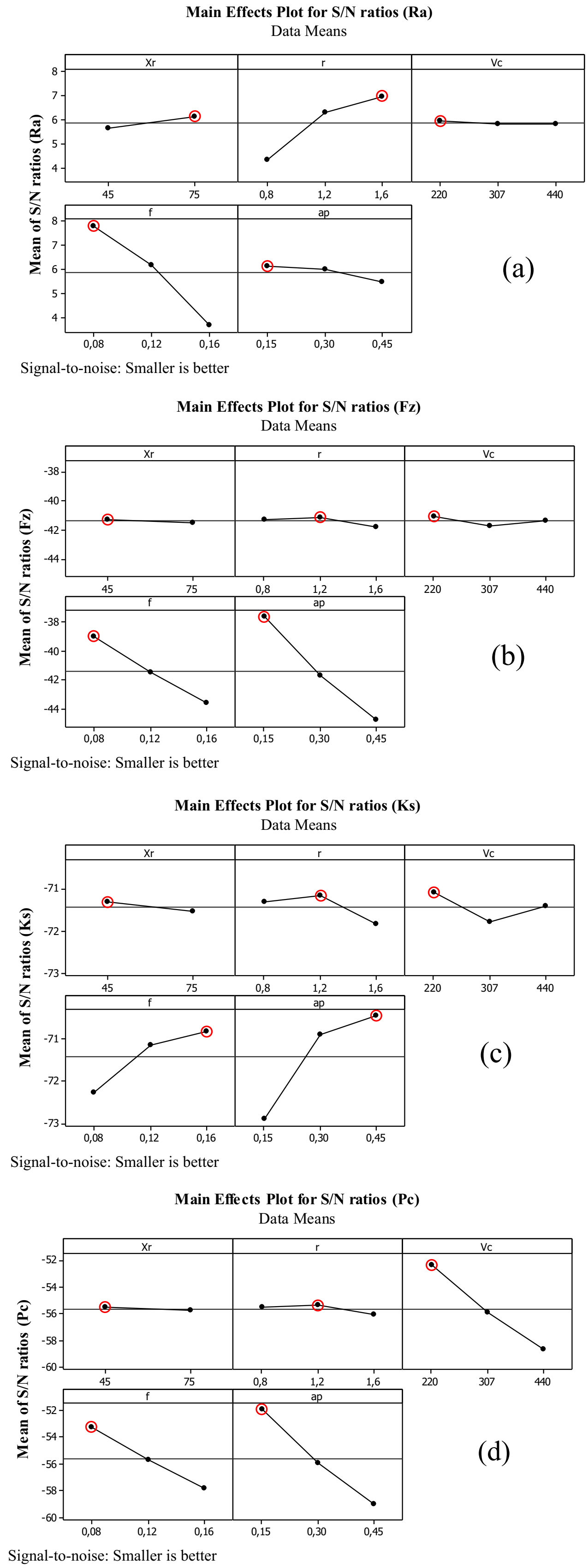


Fig. 10 Main effect plots of S/N for **a** surface roughness, **b** tangential force, **c** specific cutting force, and **d** cutting power

Table 9 S/N response table for (a) surface roughness, (b) tangential force, (c) specific cutting force, and (d) cutting power (the-smaller-is-the-better)

Level	χr	r	Vc	f	ap
(a)					
1	5.636	4.361	**5.968**	**7.786**	**6.157**
2	**6.125**	6.308	5.85	6.181	5.989
3	–	**6.973**	5.823	3.675	5.496
Delta	0.489	2.611	0.145	4.11	0.661
Rank	4	2	5	1	3
(b)					
1	**−41.26**	−41.24	**−41.03**	**−39.04**	**−37.65**
2	−41.49	**−41.09**	−41.72	−41.45	−41.69
3	–	−41.77	−41.36	−43.62	−44.77
Delta	0.23	0.68	0.69	4.58	7.11
Rank	5	4	3	2	1
(c)					
1	**−71.3**	−71.29	**−71.08**	−72.27	−72.89
2	−71.53	**−71.14**	−71.77	−71.16	−70.91
3	–	−71.82	−71.41	**−70.83**	**−70.46**
Delta	0.23	0.68	0.69	1.44	2.43
Rank	5	4	3	2	1
(d)					
1	**−55.51**	−55.5	**−52.32**	**−53.3**	**−51.91**
2	−55.74	**−55.35**	−55.9	−55.71	−55.95
3	–	−56.03	−58.67	−57.88	−59.02
Delta	0.23	0.68	6.35	4.58	7.11
Rank	5	4	2	3	1

the levels and S/N ratios for the factors giving the best Fz and Pc values were specified as χr_1, r_2, Vc_1, f_1, ap_1; in other words, an optimum Fz and Pc values were obtained at a major cutting edge angle of 45°, insert radius of 1.2 mm, cutting speed of 220 m/min, feed of 0.08 mm/rev, and depth of cut of 0.15 mm. For the case of cutting power, its minimum value is obtained at the same levels as the ones required for obtaining the minimum value of cutting power (Vc_1, f_1, ap_1). In the work of Hanafi et al. [16], it is stated that cutting power is minimized when the smallest values of depth of cut, feed rate, and cutting velocity are selected. Same levels were selected by Bouzid et al. [36] and Hessainia et al. [38] for minimizing tangential force.

As seen from Fig. 10c, the S/N (Ks) value increased when the both of feed rate and depth of cut are increased from 0.08 to 0.16 mm/rev and 0.15 to 0.45 mm, respectively. This result shows that the need to choose higher feed rate and depth of cut is revealed to obtain small values of Ks during machining of AISI D3 steel because the feed rate and depth of cut were found in the denominator formula of specific force. Optimal level for each factor that selected for reduce Ks value in machining of AISI D3 steel are determined as χr_1, r_2, Vc_1, f_3, ap_3: major cutting edge angle of 45°, insert radius of 1.2 mm, cutting speed of 220 m/min, feed of 0.16 mm/rev, and depth of cut of 0.45 mm.

4.5 Confirmation tests

Once the optimal level of the design parameters has been selected, the final step is very essential to perform a confirmation experiment for the parameter design, particularly when less numbers of data are utilized for optimization. The purpose of this confirmation experiment is to predict and to verify the improvement of the quality characteristics. Confirmation test was carried out using the optimal level of the design parameters. The estimated S/N ratio η using the optimal level of the design parameters can be calculated as follows [27]:

$$\eta = \eta_m + \sum_{i=1}^{q} \left(\eta_i - \eta_m\right) \tag{15}$$

where η_m is the total mean S/N ratio, η_i is the mean S/N ratio at the optimal level, and q is the number of the main design parameters that affect the quality characteristic.

The estimated S/N ratio using the optimal cutting parameters for technological parameters can then be obtained and the corresponding technological parameters can also be calculated by using Eq. 3.

The results of the validation test for optimal levels of cutting parameters that selected for the minimization of responses such as surface roughness, tangential force, specific cutting force, and cutting power are illustrated in Table 10 (a, b, c, d), respectively. Based on these results, a notable agreement was remarked between the values found experimentally and that calculated by the estimation formula while the S/N ratio of the results found experimentally when using the optimal levels compared to initial testing has been improved with 2.15 dB for the surface roughness, 7.55 dB for the tangential force, 1.56 dB for the specific cutting force, and 10.44 dB for cutting power. According to confirmation runs, the output responses such as Ra, Fz), Ks, and Pc ameliorate approximately 1.28, 2.38, 1.19, and 3.32 times, respectively.

In other words, the experiment results confirm the prior design and analysis for optimizing the cutting parameters. Surface roughness, tangential force, specific cutting force, and cutting power in turning operations are greatly improved through the approach of Taguchi.

5 Conclusions

This study has discussed an application of the Taguchi method for optimizing cutting parameters in the aim to minimize surface roughness, tangential force, specific cutting force, and

Table 10 Results of the confirmation experiment for: (a) surface roughness, (b) tangential force, (c) specific cutting force, and (d) cutting power

	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experiment
(a)			
Level	$\chi r_2, r_2, Vc_2, f_2, ap_2$	$\chi r_2, r_3, Vc_1, f_1, ap_1$	$\chi r_2, r_3, Vc_1, f_1, ap_1$
Surface roughness (μm)	0.50	–	0.39
S/N ratio (dB)	6.02	8.88	8.17
Improvement of S/N ratio	2.15		
(b)			
Level	$\chi r_2, r_2, Vc_2, f_2, ap_2$	$\chi r_1, r_2, Vc_1, f_1, ap_1$	$\chi r_1, r_2, Vc_1, f_1, ap_1$
Tangential force (N)	131.6	–	55.16
S/N ratio (dB)	−42.38	−34.59	−34.83
Improvement of S/N ratio	7.55		
(c)			
Level	$\chi r_2, r_2, Vc_2, f_2, ap_2$	$\chi r_1, r_2, Vc_1, f_3, ap_3$	$\chi r_1, r_2, Vc_1, f_3, ap_3$
Specific force (MPa)	3655.55	–	3049.63
S/N ratio (dB)	−71.25	−69.17	−69.68
Improvement of S/N ratio	1.56		
(d)			
Level	$\chi r_2, r_2, Vc_2, f_2, ap_2$	$\chi r_1, r_2, Vc_1, f_1, ap_1$	$\chi r_1, r_2, Vc_1, f_1, ap_1$
Cutting power (W)	673.35	–	202.25
S/N ratio (dB)	−56.56	−45.91	−46.11
Improvement of S/N ratio	10.44		

cutting power in dry turning on AISI D3 steel. The important findings are mentioned in the following specific conclusions:

1. The use of mixed orthogonal array of Taguchi to reduce the cutting experiments for determining the optimal cutting parameters is reported.
2. Based on the ANOVA analysis of S/N ratio for surface roughness, it is found that the feed rate is the most effective parameter affecting the surface roughness followed by nose radius and the interaction ($f \times ap$) with contributions of 50.21, 20.27, and 12.69 %, respectively.
3. Tangential force is highly affected by depth of cut. Its contribution is about 60.9 %, followed by feed rate with contribution of 19.5 %.
4. Depth of cut has the highest influence on specific cutting force to perform the machining operation with a contribution of 51.91 % followed by feed rate of 18.27 % and the contribution of 10.3 % for the interaction ($\chi r \times Vc$).
5. The results given by ANOVA for S/N (Pc) shows that the controllable factors (depth of cut and cutting speed) are the most significant with the respective contribution (44.22, 34.14) %. The feed rate presents a statistical significance with contribution 18.33 %.
6. The results obtained by ANOVA analysis for S/N of technological parameters were confirmed by a Pareto chart and analysis of the S/N ratio, and the effect of interactions on the responses were verified by 3D plots and contours.
7. The 3D topographical maps of the machined surface obtained by optical platform of metrology modular are of great importance in the investigation of the surface roughness by showing the crushing of the asperities using a big cutting insert nose radius (r = 1.6 mm).
8. The mathematical models elaborated for Ra, Fz, Ks, and Pc are very reliable, and they represent an important industrial interest, since they help to make predictions within the range of the actual experimentation.
9. Based on the Taguchi optimization approach, the optimal cutting parameters for minimizing (Ra) are found to be as follows: χr = 75°, r = 1.6 mm, Vc = 220 m/min, f = 0.08 mm/rev, and ap = 0.15 mm. Similarly, an optimum of Fz and Pc value was obtained at χr = 45°, r = 1.2 mm, Vc = 220 m/min, f = 0.08 mm/rev, and ap = 0.15 mm. Optimal level for each factor that selected for reduce Ks value are determined as χr = 45°, r = 1.2 mm, Vc = 220 m/min, f = 0.16 mm/rev, and ap = 0.45 mm. The optimized responses found by the use of optimal levels for each response are Ra = 0.39 μm, Fz = 55.16 N, Ks = 3049.63 MPa, and Pc = 202.25 W.
10. The results of the confirmation test prove that the performance characteristics of the turning process such as surface roughness, tangential force, specific cutting force, and cutting power are improved through the optimal combination of the cutting parameters obtained from the Taguchi optimization method.

Acknowledgments This work was achieved in the laboratory LMS (Guelma University, Algeria) in collaboration with LaMCoS (INSA-Lyon, France). The authors would like to thank the Algerian Ministry of Higher Education and Scientific Research (MESRS) and the Delegated Ministry for Scientific Research (MDRS) for granting financial support through CNEPRU Research Project, code J0301520140021 (May 8th 1945 University, Guelma).

References

1. Bendell A, Disney J, Pridmore WA (1989) Taguchi methods: applications in world industry, IFS Publications, Bedford
2. Yang WH, Tarng YS (1998) Design optimization of cutting parameters for turning operations based on the Taguchi method. J Mater Process Technol 84:122–129
3. Asiltürk I, Akkus H (2011) Determining the effect of cutting parameters on surface roughness in hard turning using the Taguchi method. Measurement 44:1697–1704
4. Thamizhmanii S, Saparudin S, Hasan S (2007) Analysis of surface roughness by turning process using Taguchi method. Ach Mater Manuf Eng 20(1–20):503–505
5. Bouzid L, Boutabba S, Yallese MA, Belhadi S, Girardin F (2014) Simultaneous optimization of surface roughness and material removal rate for turning of X20Cr13 stainless steel. Int J Adv Manuf Technol 74(1–4):879–891
6. Selvaraj DP, Chandramohanb P, Mohanraj M (2014) Optimization of surface roughness, cutting force and tool wear of nitrogen alloyed duplex stainless steel in a dry turning process using Taguchi method. Measurement 49:205–215
7. Bhattacharya A, Das S, Majumder P, Batish A (2009) Estimating the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA. Prod Eng Res Dev 3:31–40
8. Gaitonde VN, Karnik SR, Figueira L, Davim JP (2009) Analysis of machinability during hard turning of cold work tool steel (type: AISI D2). Mater Manuf Process Taylor Francis 24(12):1373–1382
9. Davim JP, Figueira L (2007) Comparative evaluation of conventional and wiper ceramic tools on cutting forces, surface roughness, and tool wear in hard turning AISI D2 steel. J Eng Manuf 221:625–633
10. Davim JP, Figueira L (2007) Machinability evaluation in hard turning of cold work tool steel (D2) with ceramic tools using statistical techniques. Mater Des 28:1186–1191
11. Neseli S, Yaldız S, Türkes E (2011) Optimization of tool geometry parameters for turning operations based on the response surface methodology. Measurement 44(3):580–587
12. Yücel E, Günay M (2012) Modelling and optimization of the cutting conditions in hard turning of high-alloy white cast iron (Ni-Hard). J Mech Eng Sci 227(10):2280–2290
13. Al-Ahmari AM (2007) Predictive machinability models for a selected hard material in turning operations. J Mater Process Technol 190:305–311
14. Aouici H, Bouchelaghem H, Yallese MA, Elbah M, Fnides B (2014) Machinability investigation in hard turning of AISI D3 cold work steel with ceramic tool using response surface methodology. Int J Adv Manuf Technol 73:1775–1788
15. Singh R, Dureja JS (2014) Comparing Taguchi method and RSM for optimizing flank wear and surface roughness during hard turning of AISI D3 steel. Proceedings of the International Conference on Research and Innovations in Mechanical Engineering, India, pp 139–152
16. Hanafi I, Khamlichi A, Mata Cabrera F, Almansa E, Jabbouri A (2012) Optimization of cutting conditions for sustainable machining of PEEK-CF30 using TiN tools. J Clean Prod 33: 1–9
17. Asiltürk I, Neseli S (2011) Multi response optimisation of CNC turning parameters via Taguchi method-based response surface analysis. Measurement 45:785–794
18. Bhushan RK (2013) Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites. J Clean Prod 39:242–254
19. Fratila D, Caizar C (2011) Application of Taguchi method to selection of optimal lubrication and cutting conditions in face milling of $AlMg_3$. J Clean Prod 19:640–645
20. Bouchelaghem H, Yallese MA, Mabrouki T, Amirat A, Rigal JF (2010) Experimental investigation and performance analysis of CBN insert in hard turning of cold work tool steel (D3). Mach Scie Technol Int J 14:471–501
21. Taguchi G (1986) Introduction to quality engineering. Asian Productivity Organisation, Tokyo
22. Rowlands H, Antony J, Knowles G (2000) An application of experimental design for process optimization. TQM Mag 12(2):78–83
23. Zhang JZ, Chen JC, Kirby ED (2007) Surface roughness optimization in an end-milling operation using the Taguchi design method. J Mater Process Technol 184:233–239
24. Gologlu C, Sakarya N (2008) The effects of cutter path strategies on surface roughness of pocket milling of 1.2738 steel based on Taguchi method. J Mater Process Technol 206:7–15
25. Kurt M, Bagci E, Kaynak Y (2009) Application of Taguchi methods in the optimization of cutting parameters for surface finish and hole diameter accuracy in dry drilling progress. Int J Adv Manuf Technol 40:458–469
26. Günay M, Kaçal A, Turgut Y (2011) Optimization of machining parameters in milling of Ti–6Al–4 V alloy using Taguchi method. E-J New World Sci Acad Eng Sci 6(1): 428–440
27. Nalbant M, Gökkaya H, Sur G (2007) Application of Taguchi method in the optimization of cutting parameters for surface roughness in turning. Mater Des 28:1379–1385
28. Yallese MA, Rigal JF, Chaoui K, Boulanouar L (2005) The effects of cutting conditions on mixed ceramic and cubic boron nitride tool wear and on surface roughness during machining of X200Cr12 steel (60 HRC). J Eng Manuf 219(1):35–55
29. Lindman HR (1992) Analysis of variance in experimental design. Springer-Verlag, New York
30. Ross PJ (1996) Taguchi techniques for quality engineering, International edn. McGraw-Hill, Singapore
31. Yallese MA, Boulanouar L, Chaoui K (2004) Usinage de l'acier 100Cr6 trempé par un outil en nitrure de bore cubique. Méc Ind 5(4):355–368
32. Dilbag SP, Venkateswara RA (2007) Surface roughness prediction model for hard turning process. J Adv Manuf Technol 32:1115–1124
33. Makadia AJ, Nanavati JI (2013) Optimisation of machining parameters for turning operations based on response surface methodology. Measurement 46:1521–1529
34. Aslan E, Camuscu N, Birgoren B (2007) Design optimization of cutting parameters when turning hardened AISI 4140 steel (63 HRC) with Al_2O_3 + TiCN mixed ceramic tool. Mater Design 28: 1618–1622
35. Karuppusami G, Gandhinathan R (2006) Pareto analysis of critical success factors of total quality management: a literature review and analysis. TQM Mag 18(4):372–385

36. Bouzid L, Yallese MA, Chaoui K, Mabrouki T, Boulanouar L (2015) Mathematical modeling for turning on AISI 420 stainless steel using surface response methodology. Proc IMechE Part B: J Eng Manuf 229(1):45–61
37. Meddour I, Yallese MA, Khattabi R, Elbah M, Boulanour L (2015) Investigating and modeling of cutting forces and surface roughness when hard turning of AISI 52100 steel with mixed ceramic tool: cutting conditions optimization. Int J Adv Manuf Technol 77(5): 1387–1399
38. Hessainia Z, Yallese MA, Bouzid L, Mabrouki T (2015) On the application of response surface methodology for predicting and optimizing surface roughness and cutting forces in hard turning by PVD coated insert. Int J Ind Eng Comput 6:267–284