Advances in Materials Research, *Vol. 7 No. 2 (2018) 137-148*
DOI: https://doi.org/10.12989/amr.2018.7.2.137

Statistical characterisation of end milling of AISI 52100 annealed bearing steel

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(*Received April 6, 2018, Revised March 14, 2019, Accepted March 15, 2019*)

Abstract. The present paper is a contribution in characterising end milling process of AISI 52100 ball bearing steel through statistical analyses of variance (ANOVA). The latter has been performed to identify the effect of the cutting parameters on the machined surface roughness and the cutting tool life. Wear measurements have been carried on multilayer coated carbide inserts and the respective surface roughness has been recorded. Taguchi's technique has been adapted to conduct the design experiments in terms of orthogonal arrays according to the cutting parameters (cutting speed, feed rate and depth of cut), the type of coating (TiN, TiCN, TiAlN) and lubricating condition. Regression analyses have conducted to the development of simplified empirical models that can be effectively used to predict surface roughness and tool wear in the present milling process.

Keywords: statistical analysis (RSM); bearing steel; coating tips, tool life; surface roughness; end milling

1. Introduction

Machining is a process commonly used to cut a piece of raw material into a desired final shape and size using a purpose design tool. The machining accuracy and the surface finish are detrimental in producing a good part providing that should fulfill a required function in an engineering system. The performance of the machining process is commonly characterized by the surface roughness and the tool wear resistant that are both very much dependent on the material to be cut, the cutting material, the cutting parameters the cutting condition and the cutting machine. Characterization of the machining process requires experimentations based on following the evolution of wear tool and the respective surface roughness.

The research of performing tool matching good wear resistance, high mechanical strength and high thermal stability has increased through substrate coating material, coating process and coating material; Da Silva *et al.* (2011) and Ginting and Nouari (2009) in their investigation on surface integrity of titanium alloy under the dry end milling, have investigated the alterations of roughness, lay, defects, microhardness and microstructure. They have concluded that dry end milling can be carried out with uncoated carbide tools as far as cutting condition is limited to finish and/or semi-finish operations. Xu and Geng (2002) have shown that the efficiency of metal cutting process depends on the tribological conditions of specific interaction between the cutting tool and machined material. Alauddin *et al.* (1997) and Kadirgamaa *et al.* (2011) confirm that

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http://www.techno-press.org/?journal=amr&subpage=5 ISSN: 2234-0912 (Print), 2234-179X (Online)

carbide cutting tools are widely used in metal cutting industry for the cutting of various hard materials such as, alloy steels, die steels, high speed steels, bearing steels, white cast iron and graphite cast iron. In the last few decades, carbide tools have known great improvement and development through surface coating in better lubrication at the tool/chip and tool/workpiece interfaces in order to reduce friction, and consequently the temperatures at the cutting edge. Da Silva *et al.* (2011) have stated that the use of coated tools is becoming increasingly demanding among the other tool materials. More than 40% of all cutting tools are coated in modern industry today. The feasibility of dry cutting in the material removal industries has received much attention due to high cost of cutting fluids, at about 17% of the total manufacturing cost. Cutting fluid waste needs to be treated prior to disposal and prolonged exposure is hazardous to the machine operators due to risk of skin cancer and breathing difficulties. Dry cutting is desirable because not only it reduces manufacturing cost but also eliminates all the adverse negative effects associated with the usage of cutting fluids for cooling and lubricating purposes. Da Silva *et al.* (2011) and Solter and Gulpak (2012) showed that a proper combination of cutting conditions is extremely important because this determines surface quality of manufactured parts. The growing demand for higher productivity, product quality and overall economy in manufacturing by machining and grinding, insists high material removal rate and high stability and long life of the cutting tools. But machining and grinding with high cutting velocity, feed rate and depth of cut is inherently associated with generation of large amount of heat and high cutting temperature. Such high cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface integrity of the product by inducing tensile residual stresses, surface and subsurface micro-cracks in addition to rapid oxidation and corrosion. Alauddin (1997), Abou-El-Hossein *et al.* (2007), Suresh *et al.* (2012), Abhang *et al.* (2009) determine how a real object interacts with its environment. Rough surfaces usually wear more quickly and have high friction coefficient than smooth surfaces. Roughness is often a good predictor of the performance of mechanical components, since irregularities in the surface may form nucleation sites for cracks or corrosion. Although roughness is usually undesirable, it is difficult and expensive to control in manufacturing. Decreasing the roughness of surface will usually increase its metal cutting costs exponentially. Surface quality is an important requirement for many machine parts. The purpose of the metal cutting process is not only to shape machined components but also to manufacture them so that they can achieve their functions according to geometric, dimensional and surface considerations. Due to the increasing demand for quality products, manufacturing engineers are faced with the difficult problem of increasing productivity without compromising. Cakir *et al.* (2009) examines the effects of cutting parameters (cutting speed, feed rate and depth of cut) onto the surface roughness through the mathematical model developed by using the data gathered from a series of turning experiments performed. An additional investigation was carried out in order to evaluate the influence of two well-known coating layers onto the surface roughness. Choudhury and El Baradie (1998) and Aslan *et al*. (2006) formulated a mathematical model for flank wear, and concluded the cutting velocity (speed) and the index of diffusion coefficient to be the most significant factors, followed by the feed and depth of cut. Sahin and Motorcu (2005) established first-order and second-order equations (in which the independent variables are logarithmic transformations of speed, feed rate and depth of cut) using response surface methodology in order to predict surface roughness in machining mild steel and reached a conclusion that the main influencing factor on surface roughness is the feed rate. They also deduced from the variance analysis that the interaction terms and square terms for second order model are statistically insignificant. Some works have been done to establish a model between the cutting conditions and surface roughness in milling operations as well. Da Silva *et al.* (2011) and Ginting and Nouari (2009) response that surface methodology is a collection of mathematical and statistical techniques that are useful for modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. RSM also quantifies relationships among one or more measured responses and the vital input parameters. Factorial designs are used widely in experiments involving several factors on a response. The meaning of factorial design is that each complete test or replications of all the possible combinations of the levels of the factors are investigated. Second order model are statistically insignificant. Some works have been done to establish a model between the cutting conditions and surface roughness in milling operations as well. Mansour and Abdalla (2002) created a surface roughness model for the end milling EN32 (a semi-free cutting carbon case hardening steel with improved merchantability). Besides concluding that an increase in either the feed rate or the axial depth of cut increases the surface roughness, whilst an increasing cutting speed decreases the surface roughness; based on the model created, they constructed contours of surface outputs in planes containing cutting speed and feed rate at a certain depth of cut in order to enable the selection of the proper combinations to increase the metal removal rate without sacrificing the quality of the surface finish.quality. Bouacha *et al.* (2010) presented an experimental study of hard turning with CBN tool of AISI 52100 bearing steel, hardened at 64 HRC. The relationship between cutting parameters (cutting speed, feed rate and depth of cut) and machining output variables (surface roughness, cutting forces) through the response surface methodology (RSM) are analysed and modeled. The combined effects of the cutting parameters on machining output variables are investigated while employing the analysis of variance (ANOVA). Aouici *et al.* (2012) Investigated the effects of cutting speed, feed rate, workpiece hardness and depth of cut on surface roughness and cutting force components in the hard turning AISI H11 steel. Mathematical models for surface roughness and cutting force components were developed using the response surface methodology (RSM). cutting force components are influenced principally by the depth of cut and workpiece hardness.

Selaimia *et al.* (2017) have presented an experimental to model the output responses namely; surface roughness (*Ra*), cutting force (Fc), cutting power (Pc), specific cutting force (Ks) and metal removal rate (MRR), during the face milling of the austenitic stainless steel X2CrNi18-9 with coated carbide inserts (GC4040). The results reveal that both of (*Ra*) and (Ks) are mostly influenced by (*fz*). Both of (Fc) and (Pc) are found considerably affected by (*ap*), while (MRR) is influenced by both of (*fz*) and (*ap*).

In the present work the performance of cutting inserts with coatings based on (TiN, TiCN, TiAlN) has been investigated to determine tool life and surface roughness during dry end milling of AISI 52100 bearing ball steel.

Statistical analysis of variance (ANOVA) has been used to conduct a design experiment. The aim of this work is to identify the influence of cutting parameters on output measures and multiple regressions in order to develop empirical models characterising the tool wear and the surface roughness.

2. Experimental procedure

2.1 Workpiece materials

The work piece is a box of 220 mm length and 80x80 mm² cross section made of AISI 52100 ball bearings steel. The corresponding chemical composition is given in Table 1.

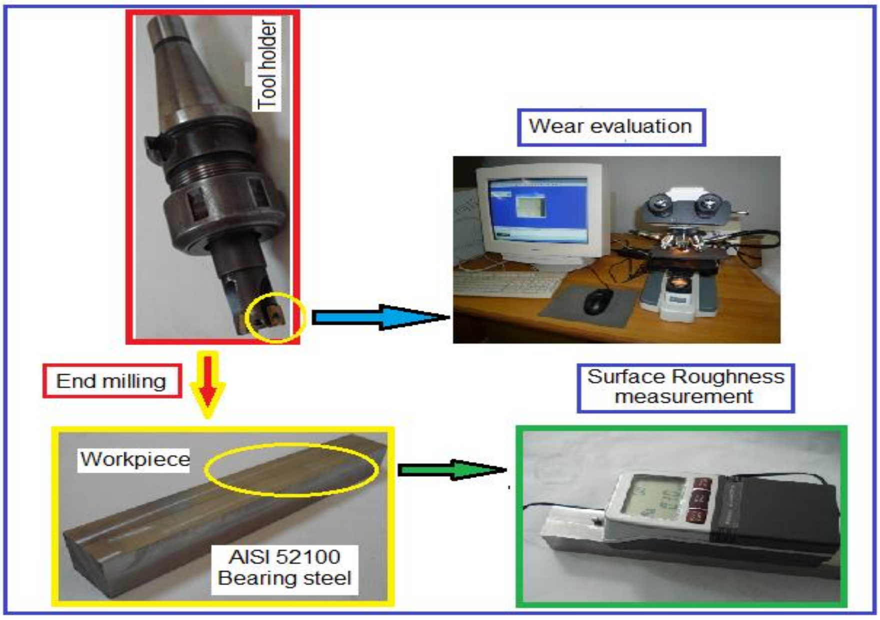

Fig. 1 Tool wear and surface roughness measurement equipments

2.2 Cutting inserts and tool holder geometry

Milling operations have been performed using three multilayer coated carbides (TiN, TiCN, TiAlN) inserts Sandvik Coromant R390 have been investigated. Milling has been carried using a 25 mm mill cutter.

2.3 Wear and roughness tests

Tool wear and surface roughness tests have been carried on a vertical EmcoMILL E350 CNC milling Machine. Measurement of tool flank wear evolution has been followed through cutting time incremental observation using Motic optical microscope until its critical value of 0.3 mm is reached. Respectively, the corresponding roughness value *Ra* is recorded using a portable Mitutoyo Surf Test SJ201.7. Fig 1 shows the layout of the equipment for tool wear and surface roughness investigation during end milling of AISI 52100.

2.4 Planning experiments

Design experiments have been achieved using Taguchi’s technique which consists in analysing the collected data from tool wear and surface roughness measurements. The input parameters are the cutting speed, the feed rate and the depth of cut. The experiments have been conducted using Taguchi27 in terms of orthogonal array in order to involve efficiently several parameters. Table 2 shows the Taguchi27 layout together the measured tool wear and surface roughness. Experimental results have been treated using the analysis of average and the analysis of variance.

The performance of end milling process of AISI 52100 ball bearings steel is achieved according the procedure illustrated in Fig 2.

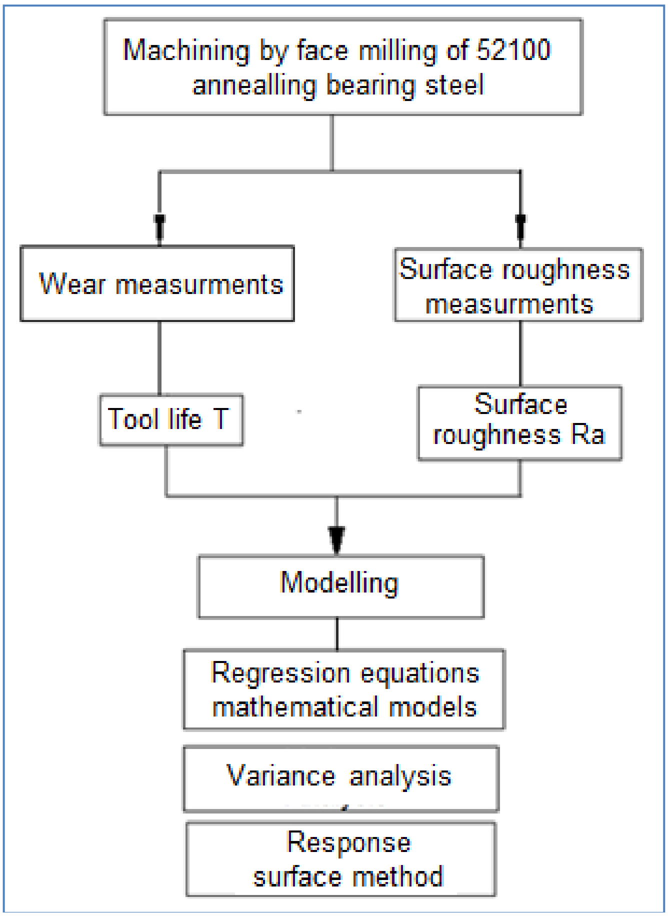

Fig. 2 Schematic illustration of performance analyses of end milling process of steel

Tool life is required to evaluate the performance of cutting inserts during machining. Surface roughness is required to evaluate the surface finish. The mathematical models express the relation between T, *Ra* and the cutting parameters (*Vc*, *fz*, *ap*) during face milling of AISI 52100 steel. Analysis of the variance is used to determine the degree of influence of each parameter. Response surface method defines the trend and the effect of each cutting parameter upon T and *Ra* response parameters.

3. Result and discussion

3.1 Main effect plots for tool life (T)

Fig. 3 gives the main factor plots of *Vc*, *fz* and *ap* for tool life, T. The trend of the plots are almost linear showing that the most significant parameter if *Vc* that causes the tool life to decrease when life *Vc* increases. Meanwhile, when increasing *fz* and *ap*, the tool life remain almost constant. This result is in good agreement with literature.

Table 2 Taguchi table for end milling of AISI 52100 annealed bearing steel using multicoated carbide tool

	Input parameters			Output parameters	
Trial No.	*Vc* m/min	*fz* mm/t	*ap* mm	Tool life (min)	Surface roughness, *Ra* (µm)
1	74	0,02	0,50	**365**	**0.68**
2	74	0,02	0,75	**390**	**0.61**
3	74	0,02	1,00	**340**	**0.90**
4	74	0,05	0,50	**305**	**0.61**
5	74	0,05	0,75	**320**	**0.39**
6	74	0,05	1,00	**310**	**0.73**
7	74	0,10	0,50	**296**	**1.03**
8	74	0,10	0,75	**298**	**1.04**
9	74	0,10	1,00	**297**	**1.05**
10	96	0,02	0,50	**255**	**0.46**
11	96	0,02	0,75	**240**	**0.41**
12	96	0,02	1,00	**218**	**0.43**
13	96	0,05	0,50	**228**	**0.45**
14	96	0,05	0,75	**220**	**0.42**
15	96	0,05	1,00	**209**	**0.45**
16	96	0,10	0,50	**230**	**0.84**
17	96	0,10	0,75	**215**	**1.12**
18	96	0,10	1,00	**215**	**1.07**
19	141	0,02	0,50	**125**	**0.35**
20	141	0,02	0,75	**118**	**0.35**
21	141	0,02	1,00	**105**	**0.44**
22	141	0,05	0,50	**115**	**0.52**
23	141	0,05	0,75	**118**	**0.45**
24	141	0,05	1,00	**100**	**0.42**
25	141	0,10	0,50	**97**	**0.72**
26	141	0,10	0,75	**100**	**0.80**
27	141	0,10	1,00	**90**	**0.73**

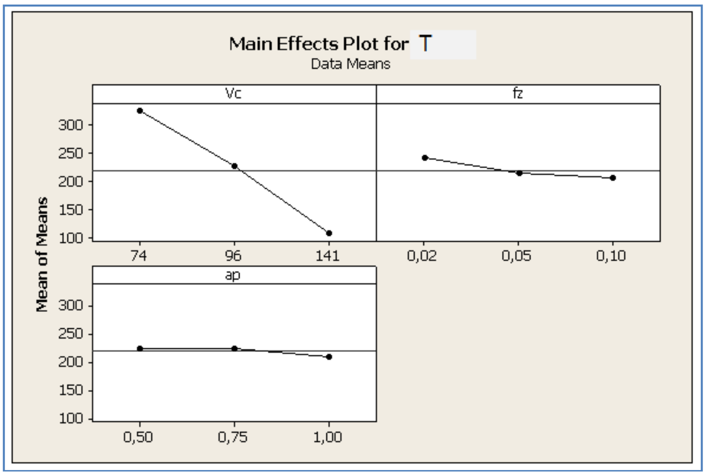

Fig. 3 Main factor plots for tool life T

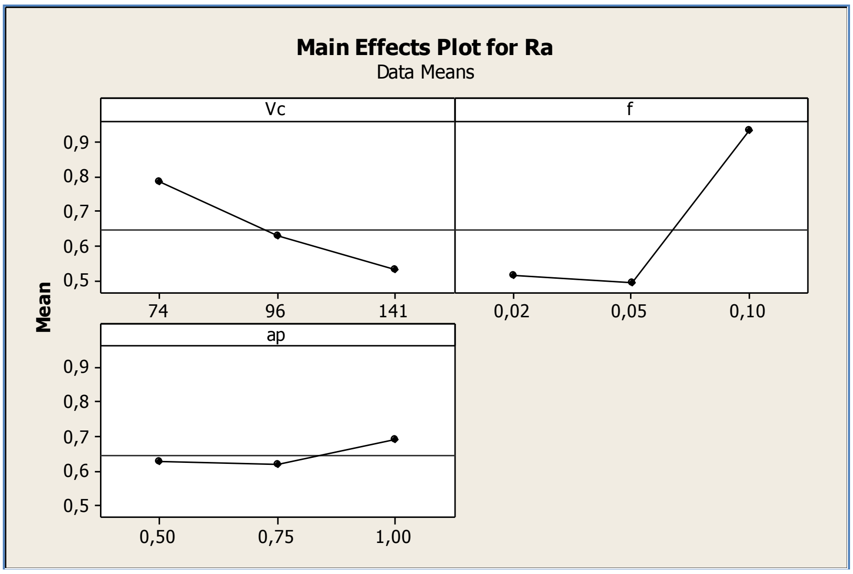

Fig. 4 Main factor plots for *Ra*

Table 3 Analysis of variance for surface roughness, *Ra*

Source	DF	SS	MS	F	P	Remarks
Vc	2	0,288763	0,144381	29,66	0,000	Significant
fz	2	1,108541	0,554270	113,87	0,000	Significant
ap	2	0,026496	0,013248	2,72	0,125	Insignificant
*Vc*fz*	4	0,109259	0,027315	5,61	0,019	Significant
*fz*ap*	4	0,049926	0,012481	2,56	0,120	Insignificant
*Vc*ap*	4	0,051037	0,012759	2,62	0,115	Insignificant
Error	8	0,038941	0,004868			
Total	26	1,672963				

S = 0,0697681
R-Sq =97,67%
R-Sq(adj)= 92,44%

3.2 Main effect plots for surface roughness (Ra)

Fig. 4 illustrates the respective main effect plots for surface roughness. In this case the most significant effect is attributed to *fz* above 0.05mm/t as the mean increased drastically when *fz* double. The cutting speed comes in second position but is still within a linear effect showing that when *Vc* increases, T decreases. With regard to the depth of cut, the effect is not that announced. The present results are in good agreement with literature data suggesting that surface roughness decreases with increasing cutting speed.

Meanwhile, when the feed per tooth increases the roughness increases particularly in (0.05-0.1mm / t) range. There is a slight effect of *Ra* when depth of cut increases in the interval (0.75-1mm).

Table 4 Analysis of variance for tool life, T

Source	DF	SS	MS	F	P	Remarks
Vc	2	212442	106221	2197,68	0,000	Significant
fz	2	6002	3001	62,09	0,000	Significant
ap	2	1321	660	13,66	0,003	Significant
*Vc*fz*	4	3017	754	15,60	0,001	Significant
*fz*ap*	4	577	144	2 ,99	0,088	Insignificant
*Vc*ap*	4	553	138	2,86	0,096	Insignificant
Error	8	387	48			
Total	26	224299				

S = 6, 95222
R-Sq = 99, 83%
R-Sq (adj) = 99,44%

3.3 Analysis of variance

Analysis of variance has been conducted for a significance level of $\alpha=0.05$, and a confident level of 95%. Tables 3, 4, 5 and 6 show the P-values corresponding to the conducted significance levels, associated with the F-tests for each source of variation. The sources with a P-value less than 0.05 are considered to have a statistically significant contribution to the measure performance. Variance analysis confirms the results obtained by the Taguchi method. The contribution in percent of each variable on surface roughness *Ra* is first (65%) for *fz*, then (17%) for *Vc*, and (1.5%) for *ap*. The interactions between these parameters have no significant effect on the roughness. Obviously, the analysis of variance reveals that the most largely dominant contribution for tool life is the cutting speed with a contribution of (94%) in front of *fz* (2.7%) and *ap* (0.58%). In addition, it has revealed that the (*Vc-fz*) interaction has a significant effect on the tool life.

3.4 Tool wear and surface roughness models

From the analysis of variance (ANOVA), regression equations can be determined to develop the engineering models of tool wear and surface roughness. As a result, the corresponding for surface roughness is given in Eq. (1).

$$\boldsymbol{Ra}=0,3039-0,000579Vc+6,042fz+0,4763ap-0,00554Vc.fz-0,003491Vc.ap+0,177fz.ap \quad (1)$$

Applying the significance level of 0.05, then as the effect of *ap*, the interactions (*Vc*,*ap*) and (*fz*,*ap*) is not significant (Table 3), Eq. (3) can reduced into a simplified linear model of surface roughness with a coefficient of correlation of 0.92

$$\boldsymbol{Ra}=0,3039-0,000579Vc+6,042fz-0,00554Vc.fz$$
$$R^2=0,92 \quad (2)$$

The corresponding model for tool wear is given in Eq. (3)

$$\boldsymbol{T}=639,41-3,42Vc-1449fz–42,19ap+6,59Vc.fz-0,1315Vc.ap+467,3fz.ap \quad (3)$$

When removing the non significant effect of of (*Vc.ap*) and (*fz.ap*) as suggested in Table 4, then the simplified linear model for tool wear can be expressed by Eq (4) with a coefficient of correlation of 0.97

$$\mathbf{T}=639{,}41-3{,}42Vc-1449fz-42{,}19ap+6{,}59Vc.fz \qquad (4)$$

$$R^2=0{,}\ 97$$

3.5 Optimization through RSM

The response surface method has been used in order to optimize the effect of the interaction of most significant parameters. In Fig 5, the response surface shows the evolution of the output parameter (T) as a function of the combined averages of parameters *Vc* and *fz* can be extrapolated from the orientation of the surface locating the range of optimal values (*Vc* = 80m / min and *fz* = 0.05 mm / d). In Fig 6 the response surface that shows the evolution of the output parameter (*Ra*) as a function of the combined averages of parameters *Vc* and *fz*. According to the orientation of the surface the range of optimal values are located at (*Vc* = 120 m / min and *fz* = 0.02 mm / d). As a consequence, statistical analysis allows the reduction of number of test and adopts a reduced plan of Taguchi. Thence, the optimised response can be extrapolated from the RSM plots for a maximum value of tool wear resistance, T in the a combination of factor levels presented in Table 7 by setting the low and high limits for the three cutting parameters

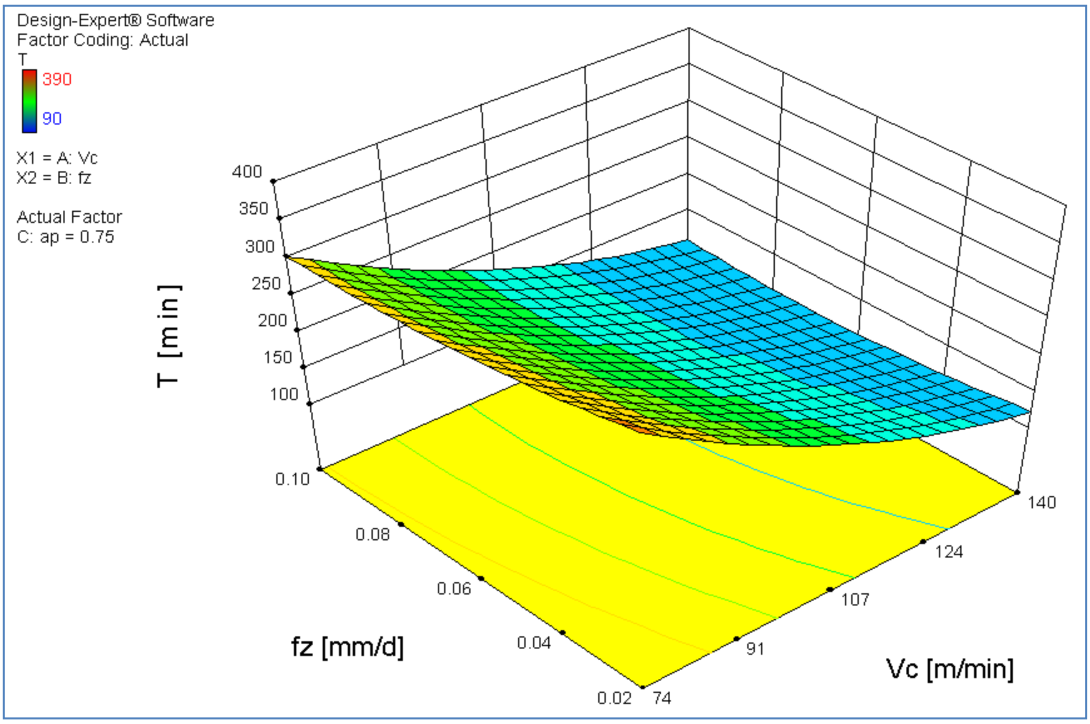

Fig. 5 Surface plot of T versus *Vc*, *fz*

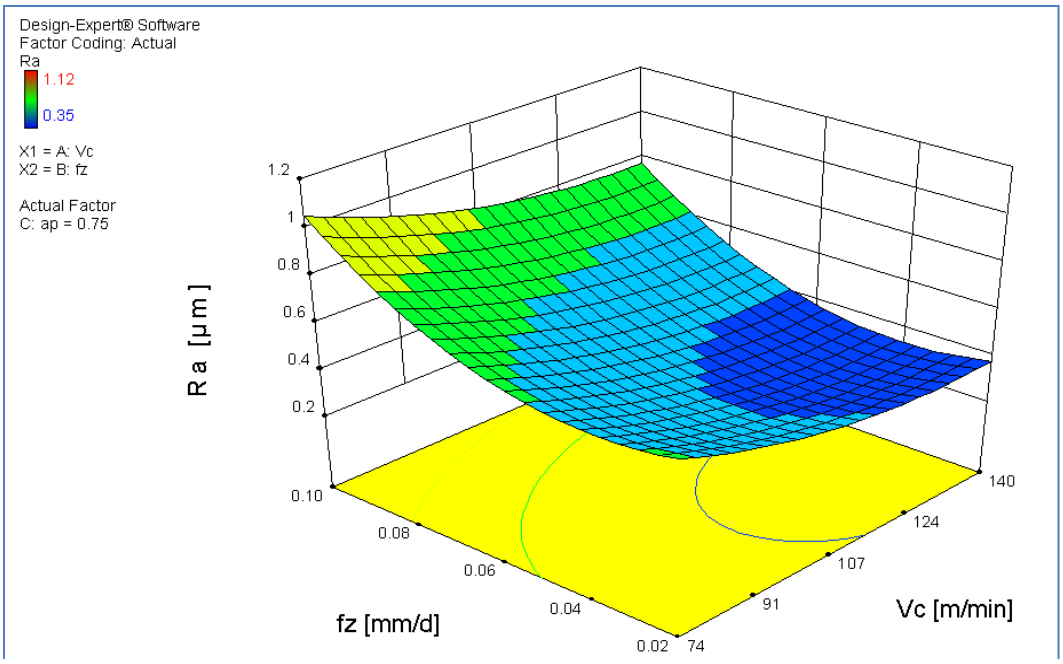

Fig. 6. Surface plot of *Ra* versus *Vc*, *fz*

3.6 Optimization through desirability function

Table 5 Limit values of parameters

		Lower	**Upper**	**Lower**	
Name	Goal	Limit	Limit	Weight	Importance
A:*Vc*	is in range	74	141	1	3
B:*fz*	is in range	0,02	0,1	1	3
C:*ap*	is in range	0,5	1	1	3
Ra	minimize	0,35	1,12	1	3
T	maximize	90	390	1	3

Table 6 Solution of optimum parameters

Solutions							
Number	*Vc*	*fz*	*ap*	*Ra*	T	Desirability	
1	74,000	0,026	0,576	0,552	352,475	0,786	Selected

Table 7 Combination of factor levels for a maximum tool wear

Factor	*Low*	*High*	*Optimum*
Vitesse de coupe *Vc*	74,0	141,0	74,0
Avance	0,02	0,1	0,02
Profondeur de passes	0,5	1,0	0,552996

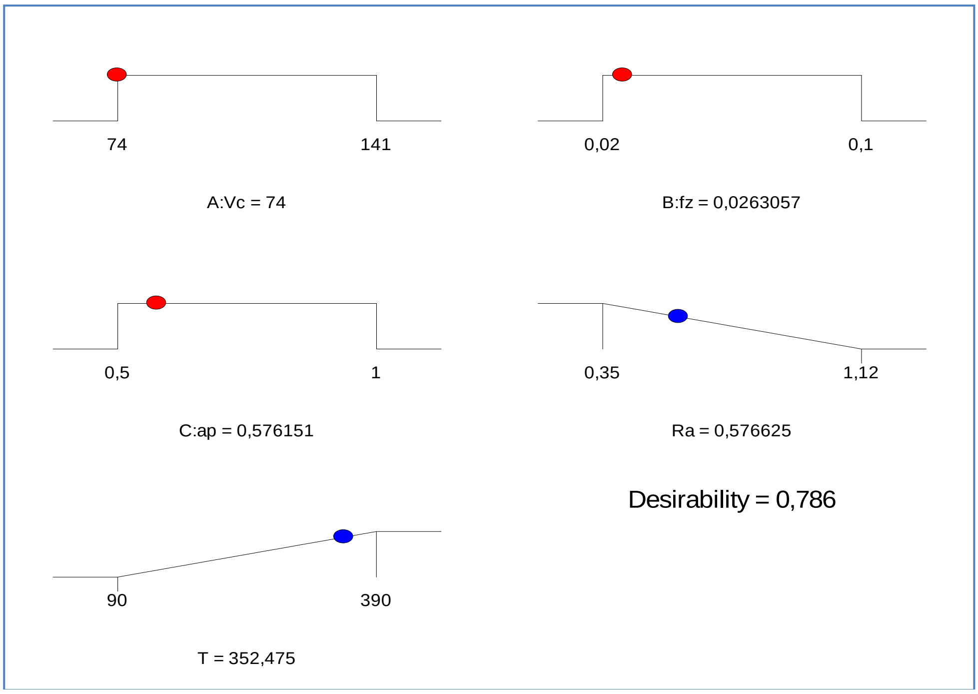

Fig. **7** Ramp Diagram of desirability function

The ramp diagram of Fig. 7 shows the optimal values of the input parameters which are a cutting speed *Vc*= 74m / min with a feed per tooth *fz*= 0.02mm / t and a depth of cut *ap*=0.57mm. these values gave a tool life T = 352 min and a surface roughness *Ra* = 0.57 µm. these values will be used for industrial application in the case of milling AISI 52100 steel.

4. Conclusion

The following conclusions can be drawn based on the experimental results of this study:

- Response surface methodology combined with the Taguchi27 design of experiment is found to be a successful technique to perform trend analysis of surface roughness and tool life with respect to various combinations of design variables (cutting speed, feed rate, and depth of cut).
- Among the cutting parameters, feed rate has the greatest influence, followed by cutting speed. Higher feed rates lead to higher surface roughness values, whereas cutting speed has a contrary effect and cutting depth has no significant effect.
- The first order mathematical models are found to adequately represent the surface roughness and tool life..
- The model indicates that the feed rate was the most dominant parameter on surface roughness followed by cutting speed and depth of cut has less influence on surface roughness.
- The model indicates that the cutting speed was the most dominant parameter on tool life followed by feed per tooth and depth of cut has less influence.
- The machining performance of PVD coated multi-layer TiCN/Al2O3/TiN carbide tool was assessed during milling of AISI 52100 bearing alloy steel at different levels of cutting parameters

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