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Experimental analysis and mathematical modeling of optimized cutting parameters in microturning

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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 tool wear and surface roughness in micro-turning of titanium alloy using Cermet insert. The experiments are carried out based on response surface methodology and sequential approach using rotatable second-order Box-Behnken design. Mathematical model is developed and used to evaluate the minimum tool wear and surface roughness under optimum micro-turning conditions. Analytical and graphical optimization techniques have been carried out to find out the optimum process parameters. Direct and interaction effects of the process parameters are analyzed, and the major parameter influencing tool wear and surface roughness is found to be feed rate, followed by the cutting speed and depth of cut. The following cutting conditions result in minimum tool wear and surface roughness: 3180 rpm cutting speed, 8 µm/rev feed rate and 15 µm depth of cut, which improve the productivity and surface quality with minimum machining cost.

Keywords: Microturning, Response surface methodology, Titanium alloy, Tool wear, Surface roughness

Metal cutting is one of the most significant processes in material removal. It has been recognized that the reliable quantitative predictions of various technological performance measures, preferably in the form of equations, are essential to develop the optimization strategies for selecting the cutting conditions in process planning. Micromachining is the key technology of microengineering to produce miniature components and microproducts. Microturning is a conventional material removal process that has been miniaturized. Miniature components provide low power consumption and high heat transfer, since their surface-to-volume ratio is very high. The geometric and material capabilities of micromachining have been studied by various researchers; industrial application of micromachining has been hindered by the lack of experience and knowledge on the micro-machinability of materials. Fabrication of miniature components requires reliable and repeatable methods with accurate tools. One of the common methods of manufacturing miniature components is micromachining. Microturning is a preferred manufacturing process to produce miniaturized parts such as micropin, microshaft, and semiconductor in large scales with low cost and high quality. The majority of these methods are slow and limited to a few silicon-based materials. Titanium alloy is one of the most extensively used alloys, due to its light weight and high strength. It is used in aerospace engines, mainly in the gas turbine compartment. The progress in the development of predictive models, based on the cutting theory, has not yet met the objective when concerned with the individual machines. The most important cutting performance measures in turning are tool life, cutting force, roughness of the machined surfaces, and energy consumption.

A recent survey in the USA showed that the selection of appropriate cutting tool is less than 50%, the tool is used at the cutting speed as only 58%, and only 38% of the tools are used up to their entire lifespan. This result is true in the case of American aircraft industry, showing that the selected cutting speed is far below the optimal speed. Azizur Rahman *et al.*[1] applied CNC microturning to miniaturization of parts. The cutting tool performance in microturning was investigated using machining of brass PCD and cermet inserts. During this machining, abrasive wear of cermet insert and groove wear in PCD insert were observed on the flank face. Masuzawa *et al.*[2] reported that microturning has the capacity to produce 3D structures at microscale. They used solid cutting tool CNC microturning, which can produce definite 3D

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shapes. In order to accurately and precisely control the motion of cutting tools during machining, cutting path generation by CNC programming has been employed. The major drawback of microturning process was that the machining force influences machining accuracy and the limit of machinable size. Nabhani *et al.*[3] studied the machining effect of titanium alloys and reported that owing to their high strength and low thermal conductivity, titanium alloy components make up to 20-30% of dry weight in a jet engine. Lalwani *et al.*[4] investigated the experimentation of cutting parameters in finish hard turning of MDN 250 steel. Cutting speed had no significant effect on cutting forces and surface roughness. They concluded that good surface roughness can be achieved when the cutting speed and the depth of cut were set nearer to their higher limit of the experimental range and the feed rate was at the lower limit of the experimental range.

Haron *et al.*[5] analyzed that titanium alloys are generally difficult to machine at cutting speeds of over 30 m/min with high-speed steel (HSS) tools and over 60 m/min with cemented tungsten carbide (WC) tool, which results in very low productivity. Kumar *et al.*[6] reported that the cutting of copper is mostly restricted to nose portion, with the cutting edge radius playing a significant role in tool performance and also stated that during microturning at 32 m/min speed, 8 µm/rev feed, and 10 µm depth of cut the flank tool wear trend of around 0.1 to 0.15 mm, it is seen that despite the cutting conditions, identical acoustic emission energy release occur. Kilickap *et al.*[7] studied the tool wear and surface roughness in machining of Sic-p reinforced metal matrix and reported that the tool wear doubled when the cutting speed was maximum limit to minimum condition. The influence of depth of cut was limited; it slightly increased tool wear when higher depth of cut was used. Higher feed rate produced poor surface quality. Piotrowska *et al.*[8] developed a novel 2DOF mathematical model of microturning process. They concluded that the input feed is changing because of the cutting forces during turning process and the feed rate is reduced by elastic deflection of the tool in opposite direction. It showed that the model predicts the real position of the tool tip as well as the cutting and feed forces.

Yildiz *et al.*[9] presented a new hybrid optimization approach based on the particle swarm optimization algorithm and receptor editing of immune system. The results obtained by the proposed method are compared with a hybrid genetic algorithm (HGA), scatter search algorithm (SSA), genetic algorithms (GA), and Hooke-Jeeves pattern search. It is observed that the optimization performance of the new hybrid optimization approach is better than that of GA, SSA, and HGA algorithms. Basim *et al.*[10] analyzed the effect of cutting parameters on tool wear and surface roughness using a nickel base alloy. They observed that the interaction effect of cutting speed and depth of cut influences surface roughness and tool wear, which generates the built-up edge in low to medium speed. Their recommendation is to increase the feed rate with the cutting speed and low to medium depth of cut. Aruna *et al.*[11] presented the design optimization of cutting parameters when turning Inconel 718 with cermet insert using response surface methodology with central composite design. They used machining parameters (cutting speed, feed rate, and depth of cut) with three levels of studying surface roughness. They concluded that among the selected parameters, cutting speed has the strongest effect on surface roughness. It is inversely proportional to the response.

Nadolny *et al.*[12] studied the effect of sulfurization of grinding wheels on internal cylindrical grinding of titanium grade 2 with ceramic bond. They explained the application and properties of materials and carried out experimental tests for the development of a new mathematical model. They concluded that during the grinding process, the material removal rate is doubled in both the non-impregnated and the sulfurized grinding wheels. Debroy *et al.*[13] reviewed the application of non-conventional optimization techniques in optimizing non-traditional machining processes. They reported the non-traditional machining sequence based on non-conventional optimization techniques with parametric combinations. Yildiz *et al.*[14] introduced a new optimization technique, called cuckoo search algorithm (CS), for solving manufacturing optimization problems. They carried out the comparative analysis of milling optimization problem using CS technique and compared the results with those of other non-traditional optimization problems such as ant colony algorithm, genetic algorithm, particle swarm optimization, and handbook recommendation. They concluded that the cuckoo search algorithm is very effective and robust approach for machining optimization problems. Machining optimization problems have been investigated by many researchers. Gilbert *et al.*[15] presented a theoretical analysis of optimization of the process using two criteria: maximum production rate and minimum machining cost. Since the results obtained by using these two different criteria are always different, a maximum profit rate, which yields a compromise result, has been used in subsequent investigations. In an earlier work, the concept of experimental design was planned and details are presented[16]. In the present work, experimentation and analysis of machining parameters using optimization methods have been tried and implemented. From the literature survey, it has been observed that there is a necessity to make an attempt to machine and analyze titanium alloy in microturning as it is required for many applications.

The challenges modern machining industries face today are achieving high quality, in terms of product's dimensional accuracy, surface finish, increasing tool life, economy of machining in ways of cost saving, and increasing the performance of the product with reduced environmental impact. Most of the researchers have used various techniques in the area of machining optimization for finding the optimal machining parameters in single and multipass turning operations. Traditional techniques are not efficient when the practical search space is too large. In this work, investigation was carried out into microturning of titanium alloy with cermet insert by using numerical and graphical optimization of cutting parameters in minimum tool wear and surface roughness.

Motivation and Problem Statement

A solid cutting tool can produce definite 3D shapes in microturning. To carry out the process of microturning, the workpiece and the cutting tool must be moved relatively to each other in order to separate the excess layer of material in the form of chips. Thus, the notion of the cutting tool with respect to the workpiece is important. In this respect, the cutting path generation has been given emphasis. A microshaft with a high aspect ratio and a micron-range diameter cannot be machined by a cut parallel to the axis of the job as in conventional machining, as shown in Fig. 1. The major drawback of microturning process is that the machining force influences machining accuracy and the limit of machinable size. Therefore, the control of the reacting force during cutting is one of the important factors for improving machining accuracy. During machining, reduced diameter and unsupported increase in length of the workpiece make the shaft tend to deflect, which reduces process precision. The value of the cutting force must be kept low by increasing the cutting speed, and this causes the plastic deformation of the workpiece. This is an effective method to overcome workpiece deflection in microturning process, and the continuous chip formation indicates high tool life[1].

Figure 2 describes a possible way of the fabrication of miniature shafts by step cutting process. Unlike the conventional parallel cut turning, in this research work, turning is carried out in a step-wise manner, which will help minimizing the deflection of the shaft.

In order to increase the productivity with good surface quality in shorter machining time, we go for the best combination of input parameters and control these parameters to increase the output quality, based on specified criteria and economical aspects. The tool wear and surface roughness play an important role in many areas and is a factor of great importance in the evaluation of the machining accuracy.

Experimental Process

Workpiece and tool materials

The chemical composition of pure titanium (titanium alloy grade 2) is given in Table 1. In microturning, a single-point cutting tool executes a generic motion, leading to the production of fine

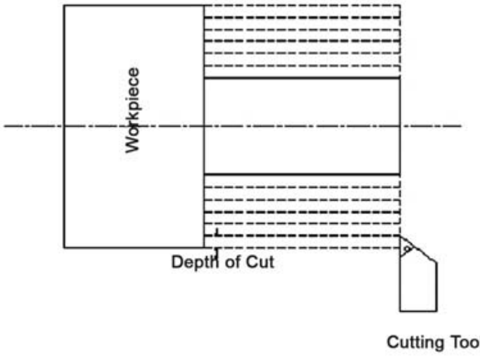


Fig. 1 – Turning by parallel cut to workpiece axis

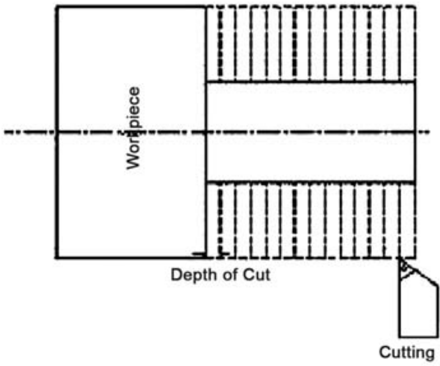


Fig. 2 – Turning by step cutting

surface structures. Micro-turning operation involves the cutting by using the cermet single point cutting tool to machine titanium alloy.

The cermets have small, well controlled grain structures; hence, they have a higher wear resistance. The Sumitomo type STGCR 10-10-09 is used as mini tool holder and the composition of cermet as 85% TiC_2 Binder Ni. In addition, the cermets maintain a sharp edge which is longer than the carbide. The cermets have superior resistance to built-up edge.

Machine tool

Titanium alloy is the target material used in this investigation. Experiments were performed using a Micro Machining Centre (Micro tools DT 110), and the experimental set-up with surface tester is shown in Fig. 3. A cylindrical rod of 5 mm diameter and 150 mm length is used to turn a material by using the cermet insert. Experiments are conducted for different sets of machining conditions in order to achieve tool wear and surface roughness. The work material is fixed to the chuck, which is centered. The insert is clamped to the tool holder and the necessary settings are made. The process parameters selected for the experiments are cutting speed, feed and depth of cut. Tool wear (V_B) and surface roughness (R_a) are measured using a non-contact video measuring system and surface tester (Surfcorder SE3500).

Table 1 – Chemical composition (%) of titanium alloy grade 2

ELEMENT	C	Fe	H	N	O	Ti
WEIGHT %	Max 0.1	Max 0.3	Max 0.015	Max 0.03	Max 0.25	Bal

Fig.3 – Experimental set-up with measuring device

Cutting conditions

Experimental design means the selection of machining parameters cutting speed, feed rate, and depth of cut with three levels, the design matrix is 3^3= 27 combinations, and full-factorial experiments are carried out in order to achieve the tool wear and surface roughness. As there are three factors and three levels, the design of experiments which suits the three factors with minimum number of trials and comprises the mixing levels is Box-Behnken design (BBD). The design has three replications of the central point, which results in 15 trials. The machining process variables and their levels are given in Table 2. The combination of experimental process variables based on Box-Behnken design matrix and the measured responses are given in Table 3.

Mathematical Modeling

Computer program is carried out for supporting the experimental design and for performing the analysis of variance[21]. Mathematical modeling of turning operation is performed by using all the 15 trial data, and the effects of each factor on the turning parameters are determined. The response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize the response[25]. The general form of the second-order RSM model is given as:

$$Y = b_o + \sum_{i=1}^{k} b_i X_i + \sum_{i,j=1,i\neq j}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \qquad \ldots(1)$$

Table 2 – Independent process variable and design levels

Variables	Units	Low (-1)	Medium (0)	High (+1)
Cutting speed	rpm	2500	3000	3500
Feed rate	μm/rev	4	8	12
Depth of cut	μm	5	10	15

$$y=\beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_{11}x_1^2+\beta_{22}x_2^2+\beta_{33}x_3 +\beta_{12}x_1x_2+\beta_{13}x_1x_3+\beta_{23}x_2x_3 \quad \dots (2)$$

Where y is the predicted response, β_0 is the model constant; x_1, x_2 and x_3 are independent variables; β_1, β_2, and β_3 are linear coefficients; β_{12}, β_{13}, and β_{23} are cross product coefficients and β_{11}, β_{22}, and β_{33} are the quadratic coefficients. All the coefficients mentioned above are estimated by using the computer program[21]. A three-factor three-coded level Box-Behnken design is used to determine the responses. The mathematical models in coded form and in actual form are obtained from the above analysis. Mathematical model in coded form is given in Eqs (3) and (4) to predict the responses namely the tool wear and surface roughness. To determine the responses (V_B and R_a), the input parameters (CS, Feed and DOC) are to be substituted in coded form in the corresponding equations to predict the machining geometry.

Table 3 – Machining design matrix and measured responses

Exp run	Cutting speed (rpm)	Feed (µm/rev)	DOC (µm)	Average tool wear (mm)	Average surface roughness (µm)
1	0	0	0	0.187	0.612
2	-1	+1	0	0.231	1.12
3	0	-1	+1	0.181	0.809
4	0	+1	+1	0.197	0.875
5	-1	0	+1	0.221	0.896
6	-1	-1	0	0.309	0.712
7	+1	0	-1	0.261	0.997
8	-1	0	-1	0.282	0.623
9	+1	-1	0	0.254	1.093
10	+1	+1	0	0.189	1.132
11	0	+1	-1	0.203	0.879
12	+1	0	+1	0.133	0.987
13	0	-1	-1	0.367	0.662
14	0	0	0	0.185	0.636
15	0	0	0	0.186	0.639

$$\text{Tool wear } (V_B) = 0.19 - 0.026{*}CS - 0.036{*}Feed - 0.048 {*}DOC+3.250E\text{-}003{*}CS{*}Feed - 0.017{*}CS{*}DOC +0.045 {*}Feed{*}DOC +0.023{*}CS^2 + 0.036{*}Feed^2 +0.015 {*}DOC^2 \quad \dots (3)$$

$$\text{Surface roughness } (R_a) = 0.63+0.11{*}CS +0.091{*} Feed +0.051{*} DOC - 0.092 {*}CS{*}Feed - 0.071{*}CS{*}DOC - 0.038{*}Feed{*}DOC+0.23{*}CS^2+0.16{*}Feed^2 +0.019 {*}DOC^2 \quad \dots (4)$$

Mathematical model analysis

Tests for the significance of the regression models, individual model coefficients, and the lack of fit are performed. Table 4 summarizes the ANOVA of quadratic model, other model terms for tool wear and other adequacy measures R^2, adjusted R^2, and predicted R^2 . Larger values of R^2 are more desirable. The entire adequacy measures are close to 1, which is in reasonable agreement and indicate the adequacy of the models. If the values of "Prob > F" is less than 0.0500 indicate model terms are significant[21]. Based on the previous report[18] that the

Table 4 – ANOVA table for tool wear

ANOVA for response surface quadratic model- tool wear Analysis of variance table [Partial sum of squares - Type III

Source	Sum of squares	df	Mean square	*F*- *p*-value	*p*-value Prob > *F*	Remarks
Model	0.050	9	5.573E-003	1149.02	< 0.0001	significant
A-Cutting Speed	5.305E-003	1	5.305E-003	1093.71	< 0.0001	
B-Feed rate	0.011	1	0.011	2182.50	< 0.0001	
C-DOC	0.018	1	0.018	3741.26	< 0.0001	
AB	4.225E-005	1	4.225E-005	8.71	< 0.0318	
AC	1.122E-003	1	1.122E-003	231.39	< 0.0001	
BC	8.100E-003	1	8.100E-003	1670.10	< 0.0001	
A^2	2.039E-003	1	2.039E-003	420.43	< 0.0001	
B^2	4.852E-003	1	4.852E-003	1000.40	< 0.0001	
C^2	8.033E-004	1	8.033E-004	165.63	< 0.0001	
Residual	2.425E-005	5	4.850E-006			
Lack of Fit	2.225E-005	3	7.417E-006	7.42	< 0.1211	not significant
Pure Error	2.000E-006	2	1.000E-006			
Cor Total	0.050	14				

Notes: R^2=0.9995, Adj. R^2=0.9986, Pred. R^2= 0.9928, Adeq precision=128.952

model terms are significant, if the probability value (*p*-value) is less than 0.05. Here, the model terms are significant as *p*-value is less than 0.05. The output showed that the model is significant with probability value (*p*-value) < 0.0001. The *p*-value for no lack of fit is 0.1211, which is larger than the reference limit of *p* of 0.05. The model *F*-value of 1149.02 implies that the model is significant, and the adequate precision measures the signal-to-noise ratio. As per the Design-Expert Statease corporation, the adequate precision ratio is greater than 4 is desirable[21]. The adequate precision ratio means, it indicates the signal-to-noise ratio for the quadratic model. The adequate precision ratio of 128.952 indicates an adequate signal. It is observed that the effect of cutting speed and the factor associated with the cutting speed is having least significance on the responses when compared to other input parameters, i.e., feed rate and depth of cut. In this case factors A, B, C, AC, BC, A^2, B^2 and C^2 are significant model terms.

Table 5 summarizes the ANOVA of quadratic model and other model terms for surface roughness. The output shows that the model is significant with the probability value (*p*-value) 0.0001 as values of the probability (*p*-value) are less than 0.05 which indicate, model terms are significant and no lack of fit with p = 0.1033, which is larger than the reference limit of p of 0.05.The model *F*-value of 44.76 implies that the model is significant. The precision ratio observed is 17.185, which indicates the adequate signal. The normal probability plots of the residuals (i.e. Error = Predicted value from model – Actual value) for the tool wear and the surface roughness is shown in Figs 4 and 5, respectively, which reveals that the residuals lie reasonably close to a straight line, giving support only to the model that is significant[25].

Results and Discussion

In machining, minimizing the tool wear and surface roughness is an important criterion. Response surface methodology with Box-Behnken design of experiments and their models are developed and applied in this work for the identification of the best levels of cutting parameters, significance, and optimization of the parameters. By considering the cutting speed, feed

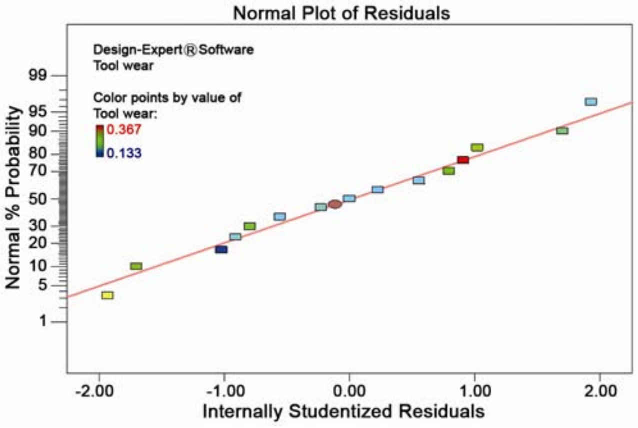


Fig. 4 – Normal probability plot of residuals for tool wear (V_B) data

Table 5 – ANOVA Table for Surface roughness

ANOVA for response surface quadratic model- surface roughnessAnalysis of variance table [Partial sum of squares - Type III

Source	Sum of squares	df	Mean square	*F*- *p*-value	*p*-value Prob > *F*	Remarks
Model	0.050	9	0.050	44.76	0.0003	significant
A-Cutting Speed	0.092	1	0.092	73.64	0.0004	
B-Feed rate	0.067	1	0.067	53.31	0.0008	
C-DOC	0.021	1	0.021	16.49	0.0097	
AB	0.034	1	0.034	27.24	0.0034	
AC	0.020	1	0.020	16.02	0.0103	
BC	5.700E-003	1	5.700E-003	4.56	0.0858	
A^2	0.19	1	0.19	152.76	<0.0001	
B^2	0.092	1	0.092	73.65	0.0004	
C^2	1.386E-003	1	1.386E-003	1.11	0.3405	
Residual	6.248E-003	5	1.250E-003			
Lack of Fit	5.810E-003	3	1.937E-003	8.84	0.1033	not significant
Pure Error	4.380E-004	2	2.190E-004			
Cor Total	0.51	14				

Notes: R^2=0.9877, Adj. R^2=0.9657, Pred. R^2= 0.8156, Adeq precision=17.185

rate, depth of cut, and their interactions, the minimum number of experiments required was calculated as fifteen, and the experiments were conducted with cermet insert based on the design matrix level shown in Table 3. The following discussion focuses on the effects of process parameters on the observed values (tool wear and surface roughness) based on the response surface methodology.

Observations on tool wear

Figure 6(a-c) shows the observed parametric influence on flank tool wear, and the flank wear is progressively increases with lower depth of cut of 5 µm. It is observed that as the feed rate increases from 4 µm/rev to 12 µm/rev the wear rate decreases. As in the case of low cutting speed and all the range of feed rates the tool wear is maximum than other cutting speeds, in addition, there is a possibility of cutting wedge action taking place against tool to workpiece. The cutting wedge is under the influence of stresses applied on the tool to chip and tool to workpiece. Moreover, due to the heat that flows into the cutting tool, this wedge has high temperature. As a result, the stress grows in the workpiece and, as might be expected, the maximum stress occurs in front of the cutting edge due to stress singularity at the point[26]. The wedge action tends to rub over the work surface, with leads to a higher wear rate and affects the surface quality. Further increase in feed rate leads to better cutting, which in turn leads to reduced tool wear. By increasing the feed rate, there is a possibility to reduce the stress in the tool and workpiece. Because of the faster movement of tool, the contact between the tool and workpiece is minimum, hence friction and heat is reduced.

According to this observation, the feed rate 12 µm/rev had lower wear rate than the other two feed rates. In addition to this, further analysis against the interactive action of depth of cut and feed rate was carried out, in which depth of cut has the primary effect on tool wear, followed by feed rate. Higher cutting speed and lower feed rate lead to better surface quality[4]. In such a way, by increasing the cutting speed with medium feed rate, tool wear can be reduced.

Influences of the two input parameters on the tool wear while the third parameter is kept constant are

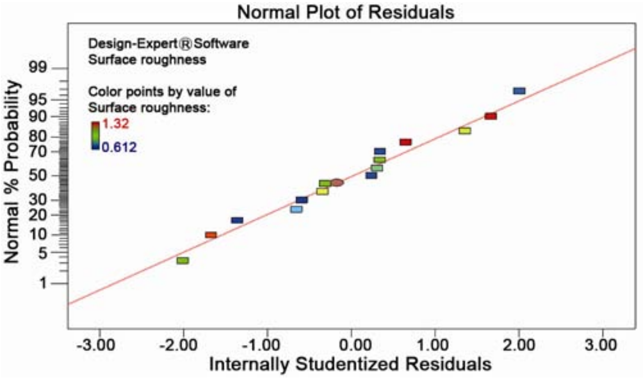
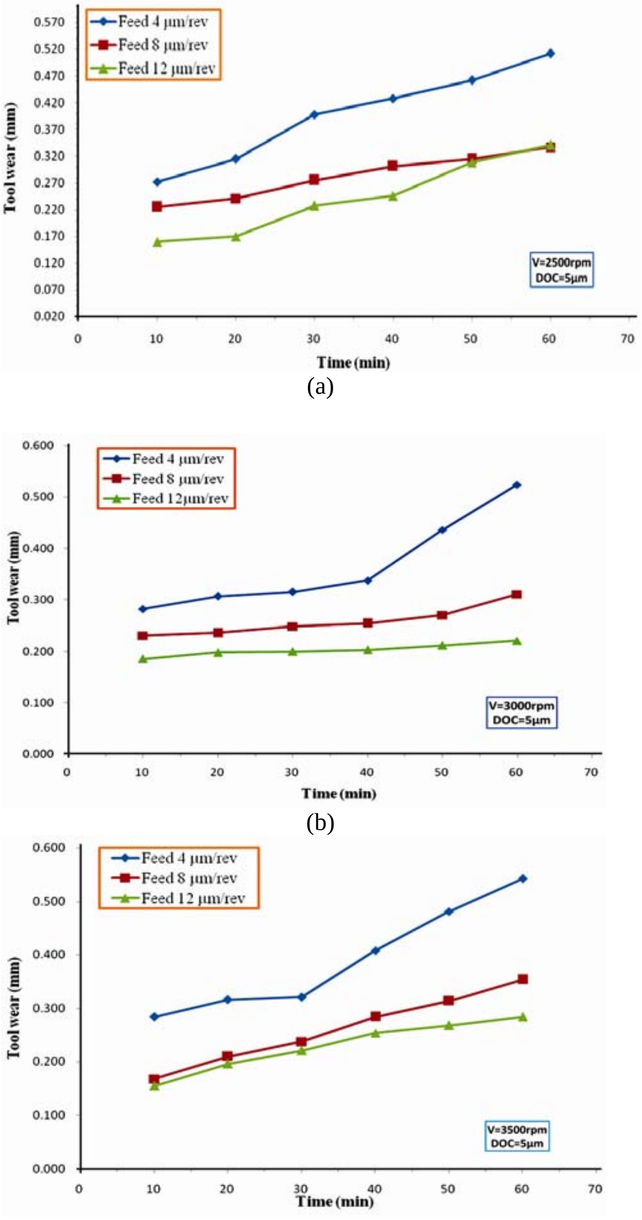


Fig.5 – Normal probability plot of residuals for surface roughness (R_a) data



(a)

(b)

(c)

Fig. 6 – Typical parametric influences on flank tool wear for depth of cut 5 µm (a) cutting speed = 2500 rpm,(b) cutting speed = 3000 rpm and (c) cutting speed = 3500 rpm

analyzed and plotted as a surface plot. Figure 7 shows the interaction effect of the cutting speed and feed rate on the tool wear. As the cutting speed increases, the machining time decreases and the tool wear decreases. In micro turning, tool wear was mainly affected by the cutting speed, which was decreased with increasing cutting speed. Tool wear was lower when the coated cutting tool was used. As per the inferences from the curve, it shows that the minimum tool wear is obtained from the higher range of cutting speed with medium feed rate. Thus, the contribution of cutting speed is essential for the reduction on tool wear.

Surface roughness

The interaction effect of the cutting speed and feed rate on surface roughness is shown in Fig. 8. The curve in the shape of elliptical section infers that at a

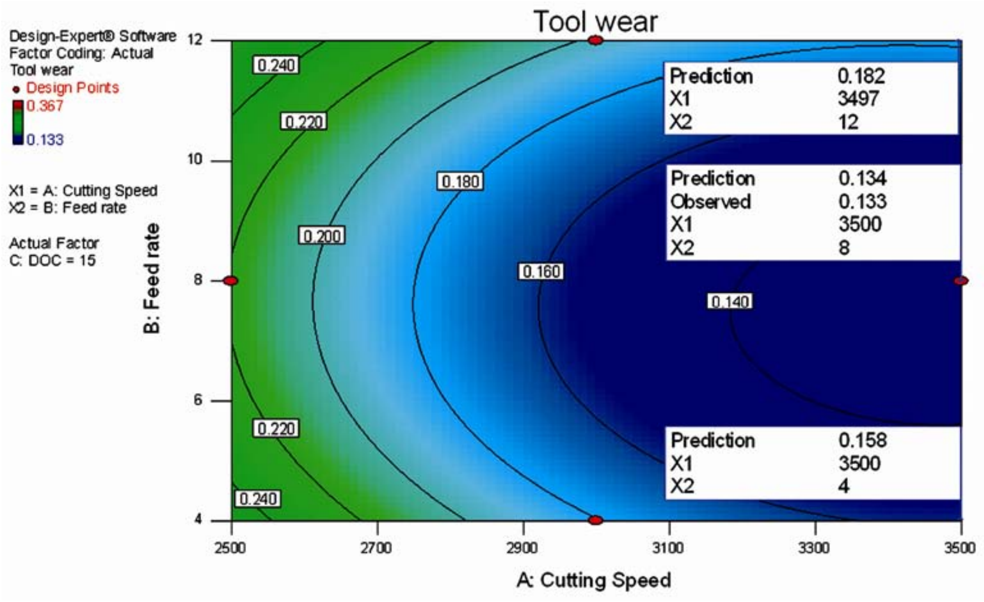


Fig. 7 – Contour plot showing the effect of cutting speed and feed rate on tool wear (DOC = 15 µm)

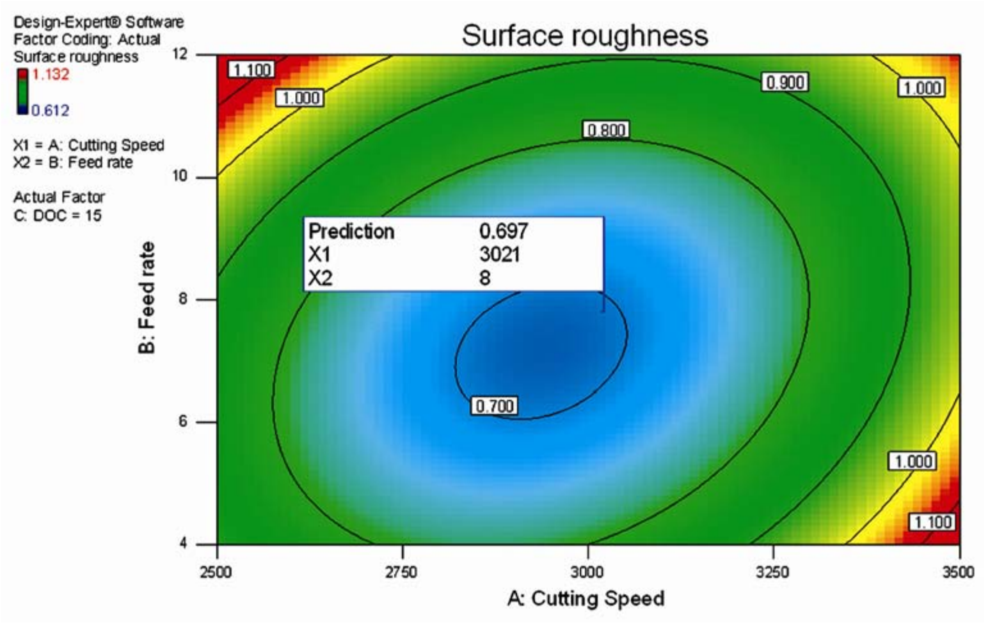


Fig. 8 –Contour plot showing the effect of cutting speed and feed rate on surface roughness (DOC = 15µm)

high cutting speed and low feed rate, the surface roughness value is 1.160 µm, and then the higher rate of cutting speed and feed rate the surface roughness value is 1.082 µm. But in the case of medium level of cutting speed and feed rate gives better performance than others, which shows that the surface roughness is affected by feed rate. The theoretical surface roughness ($R_a = f^2 / (32*r_e)$) is mainly a function of the feed rate[22]. It is due to the anticipation of tool nose radius. To obtain minimum surface roughness, the turning operations have to be performed at 8 µm/rev with 3000 rpm cutting speed. The light blue-shaded area indicates the possibility of minimum surface roughness at medium range of cutting speed and feed rate cutting condition.

The interaction effects of the feed rate and the depth of cut on surface roughness with low and high cutting speed are shown in Figs 9 and 10. At low cutting speed and low feed with low depth of cut, the surface roughness is low and then rises to moderate level. But in the case of 3000 rpm cutting speed, medium range of feed rate and high depth of cut, the surface roughness is low. But in machining, the contact length (depth of cut) increases between the tool and the workpiece. The condition of heat flow improves from the cutting zone, reduces tool wear, improves the surface quality, and produces continuous chips. Hence, the formation of continuous chip is a prime condition of high tool life[20,24]. During machining, if the tool reaches certain temperature range, then tool wear reaches the steady state condition and the surface roughness quality reaches the minimum level.

Based on the comparative analysis between Figs 9 and 10, it shows that the cutting speed and feed rate play an important role in surface quality than the depth of cut. The use of higher cutting speed and lower feed rate are produced better surface quality[4] and this is mainly attributed to the high temperature. The surface roughness influenced with the cutting speed and feed rate. So, the depth of cut is not influenced in surface quality.

As per the analysis of direct and interaction effects, the feed rate is the major parameter influencing the tool wear and surface roughness, followed by cutting speed and depth of cut. Based on the individual and interaction effects, the combined output of minimum tool wear and surface roughness has been achieved at medium level of cutting speed and feed rate with high depth of cut with more desirability.

Optimization of Process Parameters for Turning Operation

Optimization of cutting parameters is one of the most important elements in any process planning of metal parts. In view of achieving the best quality product with higher rate of productivity, tooling cost, surface roughness, and tool wear is to be minimized. Turning process parameters can be optimized for the above requirements. In traditional optimization problem, there are many drawbacks and it does not fare well in solving problems in over a broad

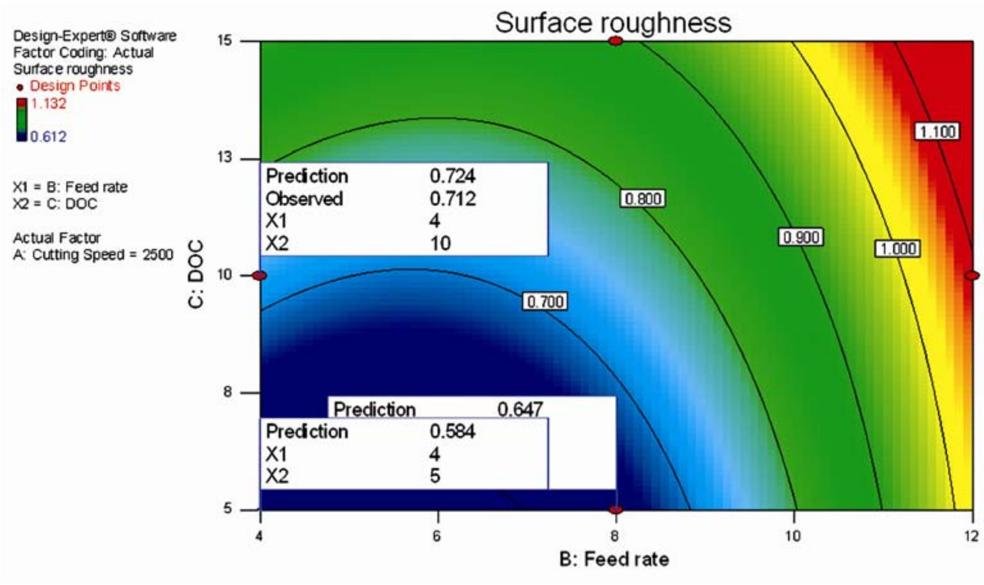


Fig. 9 – Contour plot showing the effect of feed rate and depth of cut on surface roughness (cutting speed = 2500 rpm)

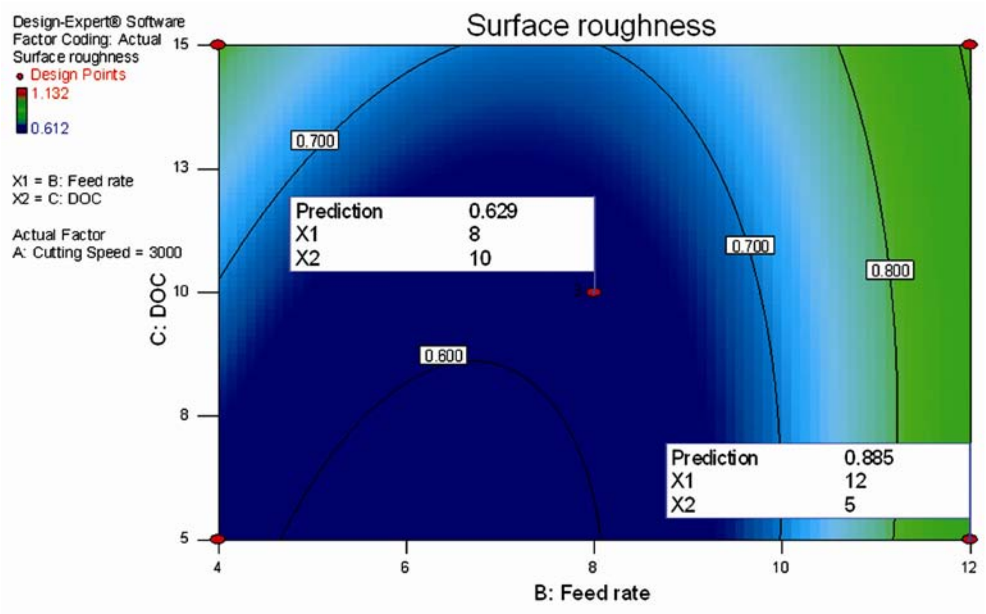


Fig. 10 – Contour plot showing the effect of feed rate and depth of cut on surface roughness (cutting speed=3000 rpm

spectrum of domains[17]. There are non-traditional optimization methods such as genetic algorithm, simulated annealing algorithm, particle swarm optimization, ant colony algorithm and so on. Many engineering optimization problems have multiple optimum solutions, among which one or more may be the absolute minimum or maximum solutions. In statistics, RSM explores the relationships between several explanatory variables and one or more response variables. The RSM is useful for analyzing problems in which several independent variables influence a dependent variable or response. The accuracy and effectiveness of an experimental program depends on careful planning and carrying out the experimental procedures. The experiment is designed to allow us to estimate interaction and even quadratic effects, and therefore give us an idea of the (local) shape of the response surface we are investigating. This approach is based on the RSM, and sequential approach using the Box-Behnken design is used to formulate the experimental layout, to analyze the effect of each parameter on the machining characteristics, and to predict the optimal choice for each machining parameter such as cutting speed, feed rate and depth of cut. The process optimization aims at obtaining the best combination of the cutting speed, feed rate and depth of cut. Process optimization aims at obtaining the best combination of the cutting speed, feed rate, and depth of cut that has the maximum influence on the machining geometry.

The optimization module in design-expert searches for a combination of factor levels that simultaneously satisfy the requirements placed (i.e., optimization criteria) on each of the responses and process factors (i.e., multiple response optimization). The numerical and graphical optimization methods are used by choosing the desired goals for each factor and response. The objective function may be stated as maximum cutting speed, maximum depth of cut, and the feed rate to be within the range of 4 µm/rev to 12 µm/rev. Numerical optimization finds a point or more that minimizes both the tool wear and the surface roughness. In the graphical optimization with multiple responses, it is required to define regions where the requirements simultaneously meet the proposed criteria by superimposing or overlaying critical response contours on a contour plot. Then, visual search for the best compromise becomes possible. As per the previous quote for multiple responses, numerical optimization has been recommended to be done first; otherwise, it may be impossible to uncover a feasible region[19]. Hence, numerical optimization is carried out first, followed by graphical optimization. Table 6 illustrates the goal then lower and upper limits of independent variables and the importance of each factor on the responses.

Table 7 shows the optimal turning conditions that lead to minimum level of tool wear and surface roughness. It is evident that using the cutting speed has to be between 3166 and 3222 rpm, feed rate has

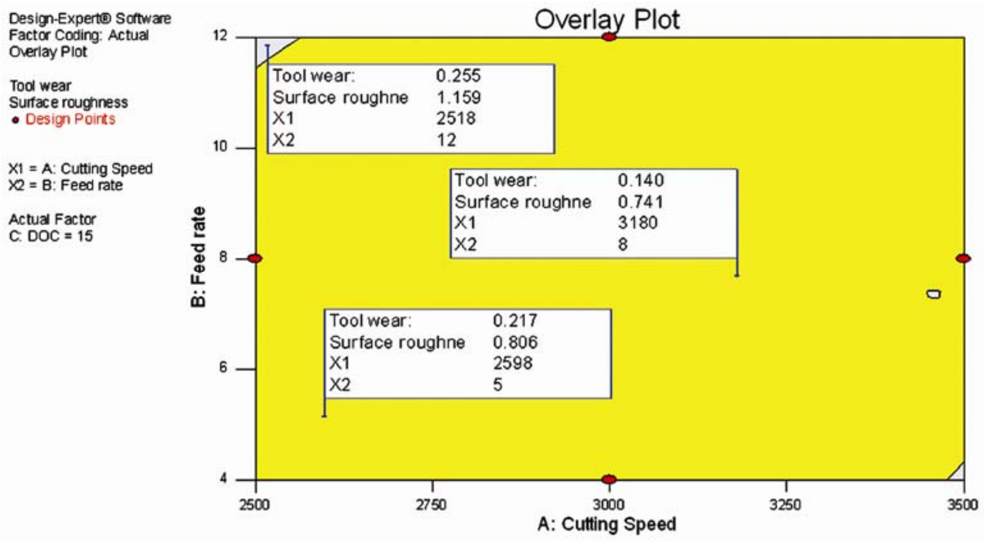


Fig. 11 –Overlay plot shows the region of the optimal working condition on the criteria

Table 6 – Criteria for numerical optimization

Variable name	Units	Goal	Lower limit	Upper limit	Importance
Cutting speed	rpm	Maximize	2500	3500	3
Feed rate	µm/rev	Is in Range	4	12	3
Depth of cut	µm	Maximize	5	15	3
Tool wear	mm	Minimize	0.133	0.367	4
Surface Roughness	µm	Minimize	0.612	1.132	5

Table 7 – Optimal machining conditions based on the criteria

S.No	Cutting speed (rpm)	Feed rate (µm/rev)	Depth of cut (µm)	Tool wear (mm)	Surface roughness (µm)
1	3180	8	15	0.140	0.741
2	3181	8	15	0.140	0.742
3	3181	8	15	0.140	0.742
4	3173	8	15	0.141	0.738
5	3173	8	15	0.141	0.738
6	3182	8	15	0.140	0.742
7	3189	8	15	0.140	0.745
8	3166	8	15	0.141	0.735
9	3173	8	15	0.141	0.738
10	3222	8	15	0.139	0.761

8 µm/rev and depth of cut 15 µm leads to minimum tool wear and surface roughness.

The graphical optimization results allow the visual inspection to choose the optimum turning parametric conditions. Figure 11 shows the overlay plot drawn between cutting speed and feed rate. The shaded areas on the overlay plots are the regions that do to meet the proposed criteria. At various locations, contour flag represents the input variables and the corresponding responses. The yellow-shaded area is the optimized region to achieve the desired machining qualities. It may be noted that as the cutting speed increases, the machining cost decreases, resulting in improved productivity of the machine. It is evident that the results are proposed. Validation trials are conducted to compare the results of the optimization and the mathematical models with the actual experimental results and are in acceptable range.

Conclusions

This paper presents the findings of an experimental investigation of the effect of cutting speed, feed rate and depth of cut on the tool wear and surface roughness in microturning of titanium alloy using cermet insert. The following conclusions are drawn:

(i) The ANOVA tables of the tool wear and surface roughness shows the model is significant with probability value (*p*-value) 0.0001.

(ii) The numerical and graphical optimization are carried out, and combinations of process parameters are identified to achieve the minimum tool wear and surface roughness.

(iii) The feed rate plays a dominant role in the cutting conditions of titanium alloy with cermet insert. This indicates that the lower feed rate, small depth of cut and large negative rake angle, facilitates ploughing effect (rubbing effect), and material side flow can also be observed as the result of ploughing effect.

(iv) The interactive and individual effects of process parameters on responses are studied. It is observed that cutting speed plays a dominant role in tool wear and feed rate significantly influences tool wear and surface roughness.

(v) Contour plots can be used graphically for selecting the cutting parameters and providing the desired tool wear and surface roughness values.

(vi) It is observed that the depth of cut has the least influence on the tool wear and surface roughness.

(vii) The minimum tool wear and surface roughness is obtained from the analysis were 0.140 mm and 0.741 µm, when the process parameters such as cutting speed, feed rate and depth of cut were maintained at 3180 rpm, 8 µm/rev, and 15 µm. It is possible to obtain the minimum tool wear and surface roughness using the above values of process parameters.

(viii) The good surface quality with minimum tool wear can be achieved when cutting speed and feed rate are set nearer to their middle level (3180 rpm, 8 µm/rev) and depth of cut is at high level of the experimental range (15 µm).

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