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Optimizing Micro-Turning Parameters during Step Turning Process on Titanium Alloy with RSM

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An attempt was made to evaluate and improve the machining parameters of micro-turning titanium alloy with cermet insert on the titanium alloy's surface roughness. The experiments were done using a strong statistical tool to construct a matrix by utilizing Response Surface Methodology (RSM) and Box-Behnken design for performing the micro turning. Quadratic model was generated to predict the response and also used to appraise the effect of outcomes. The results of the investigation suggest that the cutting feed as well as speed rate are the input elements that have the greatest impact on surface roughness. Numerical with graphical optimization methods are figured out to seek out the optimum method parameters. The subsequent machining conditions lead to minimum surface roughness on speed 2944 rpm, 7.23 µm/rev feed along with 15 µm depth of cut that helps to attain the great surface quality with minimum machining value and at the same time improves the productivity with 86% of optimum desirability rate.

Keywords: Desirability, Graphical, Numerical, Productivity, Surface roughness

Introduction

Miniaturized elements play a very important role in numerous applications within the fields like aerospace, automotive, physical science, communications, biomedicine and environmental engineering fields. Micro machining processes support the trend of miniaturization. Because of their incredibly high surface to volume relation, they produce high heat transfer together. However, manufacture of tiny elements needs reliable and repeatable producing ways by correct devices. The complete micromachines consume less quantity of energy. As a result they will utilize smaller elements and lesser materials for their production. Rahman *et al*. stated that the cutting tool concert in micro turning was considered however machining of cermets and brass PCD inserts.[1] Throughout machining, cermet insert's abrasive wear has been produced on the flank face, whilst groove wear of PCD insert was revealed within the flank face. Masuzawa *et al*. mentioned, micro turning have the ability to manufacture 3D shape in micro size.[2] In micro turning, a hard cutting tool is used to produce three-dimensional forms that are certain to be accurate. During the machining process, the cutting route generation process using CNC coding is carried out carefully and accurately controls the cutting tool motions. The machining accuracy of the micro turning process is a significant drawback of the technique and so the perimeter of machining geometry is mainly affected by machining forces. Alberto *et al.* insisted, the scale of small technological products ranges from 0.5 to 499 µm and therefore the products having sizes higher than 500 µm are thought about macro scale elements.[3] The miniature elements are utilized during the subsequent utilizations; like in biotechnology and drugs.

Titanium alloy is lustrous with low density, reasonable strength and has great corrosion resistance. It's ductile only when it is free of oxygen. Titanium is as robust as steel, however it's lighter. The metal is heavier than aluminum; however it's twice as strong. Titanium alloys are utilized in a spread of engineering applications like aerospace industry, marine industry and fabrication industry. Tooling value and machining time is one amongst the key factors in industries for higher production with low production value. Surface quality mainly affects numerous practical qualities of elements like contact inflicting exterior rubbing, tiring, illumination, warm up, capacity of issuing and hold with lubricant, supporting capability, covering tiredness. With the higher alloy composition and

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rigidity, the machining character of titanium alloys by standard chip-making ways occasionally decreases. The superior problem in operations like drilling, tapping, milling, and broaching may be anticipated with hardness over 38 R_C (350 BHN). The real features of titanium are taken into account, with the goal that the working system of titanium and its compounds shouldn't make any undesirable issues. Worldwide, there are many medium scale production industries that manufacture elements made from titanium alloys that are outscored by large manufacturing giant. In most cases a moderate surface finish is needed which might be obtained in an exceedingly single machining operation. However, it’s unfortunate that in most industries, thanks to the dearth of information of optimizing techniques, the machining parameters are set in associate pseudoscientific and unproductive manner. This necessitates the industries to have an extra grinding operation that may be a waste of productive time and resource. The eminence of the goods is chiefly acting as a key part in any of producing industry. The quality of surface is of extreme important for the accurate alignment and working of the machine parts that instantaneously have an effect on the attributes of product like fatigue strength, resistance force, reflection, lubrication, coating and wear resistance.[4,5] In addition to this condition, there are various elements that influence surface roughness of each and every manufacturing product. Among these, the crucial factors are machining parameters, tool geometry, work material, chip formation, rigidity of machine and coolants used in the cutting cycles.[6,7] To achieve the desired roughness, it is common practice to do a parameter swap among the parameters which have the greatest effect on the roughness. As discussed, feed rate, cutting speed, along with depth of cut in micro turning should be disseminated by utilizing Ti alloy with a cermet insert to provide the best surface roughness distribution. Few authors have quoted the machining parameters on surface roughness.[8–12] Patil *et al.* concluded that micro turning being the accurate technology and slight deviation in grain size and material properties, throughout turning it would have an effect on the machinability and induce machining connected issues.[13] The developed surface roughness especially depends on cutting situations like depth of cut, cutting speed, feed rate, and tool geometry such as nose radius, tool edge, rake angle, etc. used for the machining. Muthukrishnan and Davim carried out the machinability extensively on surface roughness under conventional machining operations by the blow of coolants during machining.[14] The experimental findings were analyzed using the response surface approach in conjunction with a CCD.

Satyanarayana and Venu Gopal observed that the machining force rises with the rise of feed and depth, and attenuated with the higher cutting speed rate as well as rake angle, while surface roughness attenuated by means of rise in rake angle, cutting speed, and improved cutting velocity and depth of cut.[15] Optimization of input machining factors was done on steel tool using RSM and the most output obtained were for the mix of variables with optimized desirability as 99% of prediction.[16] Arunkumar *et al.* published the statistical analysis leading to optimum parameter combination of feed, speed along with depth of cut in process conditions during the wet situation of machining since the most excellent surface roughness to the cylindrical parts.[17] The analysis of ASTM A36 with spindle feed and its speed, along with cut depth by exploiting Taguchi L27 completes the optimum parameters for process capability index of frequency of tool vibration and average surface roughness that have been found to be 240 rpm optimal speed, 0.16 mm/rev feed along with 0.12 mm depth of cut.[18] In their conclusion, Song *et al*. said that the optimal machining parameters had been identified and the percentage errors of the regression models were within the acceptable limits.[19] In machining industries; the challenges are primarily targeted on the action of top quality, work piece geometry, surface quality and machine economics in requisites on price reduction with improved quality of the part with the condensed ecological effect. According to Ravi Kumar *et al*., the surface roughness of a hybrid composite material is impacted by cavities, uncut chips, deformation, micro-cracks, tearing, and other factors occurring during the process of machining via hole by abrasive water jet machining in the material.[20] The surface quality plays an important role in numerous fields and could be an issue of massive importance within the estimation of machining accuracy and productivity.

From the compilation of literature review, it had been known that only limited authors have studied on cutting and micro turning factors of Ti alloy machining. However micro turned parts in Ti alloy were found in several field applications like aerospace components, medical appliances. During this investigation, the design analysis were carried out conjointly for the impact of machining parameters using Minitab 19 version and therefore the optimization method were also analyzed by using these cutting parameters.

Materials and Methods

Titanium Alloy has heat strength, is highly treatable but it has low weight. Ti Alloy is considered to be the "workhorse." Among all of the titanium alloys, titanium is the most commonly found in nature. On the whole, it accounts for half of all titanium consumption on the world today. The configuration and their level of Ti Alloy are presented below in Table 1.

Machining Parameters and Experimental Design

The experimental design includes the choice of appropriate levels for the machining parameters e.g. cutting speed, feed and depth of cut. Based on the machine cutter and workpiece capability, choice of the parameters has been given in Table 2. As shown in Table 3, the parameters are varied at three levels, resulting in fifteen trials and a Box-Behnken style largely based matrix for each parameter.

The RSM is the most recognized competitive optimization ways to gauge the optimization problem. It is a dominant numerical tool. Statistical approach that examines the relationships between a range of descriptive parameters and one or more outcome variables is known as correlational statistical modelling. The RSM could be a combination of numerical and applied mathematical methods. It is purposeful for the model and analysis of issues during the responses which is affected by several variables and therefore the goal is to optimize the outcomes.[15] This investigation which approaches through Box Behnken Design needs three sets of every issue coded as 1, 0 along with −1, that indicates high, medium and low levels to be considered for design matrix. The coded computing program is disbursed for sustaining the experiments with the investigation of variations. The experiments were performed by using all the 15 trials and the results of impact on variables were analyzed and implied. The experimentation was conducted by the Micro machining centre as shown in Fig. 1. The cutting conditions were randomized according to the methodology. In dry operating conditions, a round rod of 5 mm diameter and 150 mm length was utilized as a piece of work to machine the part by using cermet. As per the design matrix combination (Table 3) experiments were conducted so as to get surface roughness. The output parameters surface roughness (Ra) is evaluated by employing a Surfcorder (SE3500). The experimental setup with measuring system is presented in Fig. 1.

Table 1 — Chemical composition (%) of Titanium Alloy

Element	O	H	N	C	Fe	V	Al	Ti
Weight %	—	0.005	0.01	0.05	0.09	4.40	6.15	Balance”

Table 2 — Experimental Process parameters with levels

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

Results and Discussion

For executing the experimental design based on variables as selected in Table 2, and the levels of the machining variables for every trial within the design matrix as per RSM using Box-Behnken design, as well as the determined outcomes are shown in Table 3. The following is the general form of a second order regression equation (Eq. 1) for the proposed model for predicting the response y:

$$y=\beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_3x_3 + \beta_{11}x_{12} + \beta_{22}x_{22} + \beta_{33}x_{32} + \beta_{12}x_1x_2 + \beta_{13}x_1x_3 + \beta_{23}x_2x_3 \quad \ldots (1)$$

Here, y represents expected response, model constant is signified by β_0; freelance variables are x_1, x_2 and x_3; linear coefficients are defined by β_1, β_2, and vector coefficients are given as β_3; β_{12}, β_{13}, and β_{23}

Table 3 — Design matrix-input data

Exp Run	Cutting Speed, v (rpm)	Feed, f (μm/rev)	DOC, dc (μm)	Surface roughness (μm)
1	2500	4	10	0.712
2	3500	4	10	1.093
3	2500	12	10	1.120
4	3500	12	10	1.132
5	2500	8	5	0.623
6	3500	8	5	0.997
7	2500	8	15	0.896
8	3500	8	15	0.987
9	3000	4	5	0.662
10	3000	12	5	0.879
11	3000	4	15	0.809
12	3000	12	15	0.875
13	3000	8	10	0.612
14	3000	8	10	0.612
15	3000	8	10	0.612

while quadratic coefficients are defined by β_{11}, β_{22}, and β_{33}. The analyses are carried out with three factors and three levels through Box-Behnken Design, employed by the way of using Minitab 19 environment. All of the factors are to be estimated from the experimental work using the experimental information supported by the result displayed in Table 4, and the resulting formal equation is shown in Eq. (2) based on the experimental information.

$$\text{Surface roughness, } (Ra) = +\,6.486 - (0.004795 \times CS) + (0.0137 \times Feed) + (0.0878 \times DOC) - (0.000046 \times CS \times Feed) - (0.000028 \times CS \times DOC) - (0.001887 \times Feed \times DOC) + (0.000001 \times CS^2) + (0.01040 \times Feed^2) + (0.001115 \times DOC^2) \quad \ldots (2)$$

From the Eq. (2), the foremost vital parameter is cutting speed followed by depth of cut along with feed rate having the smallest amount of vital impact on surface roughness. The interactive terms in the Table 3 are feed rate and depth of cut, and square terms depth of cut are insignificant for predicting the surface roughness. Therefore, these terms in the mathematical model are not very important (ineffective terms).

Fig. 1 — Experimental setup with measuring device

Adequacy Check for the Developed Model

The mathematical equations capabilities are given in Table 4. The analysis of variance in surface roughness having p-value less than 0.05 indicates that the mathematical model is noteworthy. The most important impacts on every linear factor in addition to quadratic factors are significant model terms other than square terms of depth of cut and the interactive effect of feed with depth of cut for the surface roughness as shown in Table 4. This suggests that the effect on surface roughness depends on feed rate; from the analysis of the interactive impact on depth of cut along with feed are insignificant terms. The "Lack of Fit F-value" indicates insignificance of the terms. The insignificant lack-of-fit is necessary for any model to be suited.

The plot of experimental and predicted information for surface roughness, which has been utilized for assessing the model's accuracy, is presented in Fig. 2. The importance of model indicates the significance report of surface roughness (Fig. 2). The relation between the input factors and output responses are satisfactory with the small p values (<0.05) and higher rate of coefficients (R^2 = 98.91%, R-Sq (adj) = 96.94%, R-Sq (pred) = 82.52%) as tabulated in Table 4. Additionally, for Ra the response surface model was validated through the use of residual analysis. The outcome indicated that equated model is

Table 4 — Analysis of variance for surface roughness

Source	DOF	Adj SS	Adj MS	F-Value	p-Value
Model	9	0.526044	0.058449	50.30	0.000
CS	1	0.092021	0.092021	79.19	0.000
Feed	1	0.066613	0.066613	57.33	0.001
DOC	1	0.020604	0.020604	17.73	0.008
CS*CS	1	0.205429	0.205429	176.79	0.000
Feed*Feed	1	0.102205	0.102205	87.96	0.000
DOC*DOC	1	0.002869	0.002869	2.47	0.177*
CS*Feed	1	0.034040	0.034040	29.29	0.003
CS*DOC	1	0.020022	0.020022	17.23	0.009
Feed*DOC	1	0.005700	0.005700	4.91	0.078*
Error	5	0.005810	0.001162	—	—
Pure Error	2	0.000000	0.000000	—	—
Lack-of-Fit	3	0.005810	0.001937	*	*
Total	14	0.531854	—	—	—

S = 0.0340881, R-Sq (adj) = 96.94%, R-Sq = 98.91%, R-Sq (pred) = 82.52%

significant based on 0.0001 possibility value.[21] For surface roughness, residual plots is given in Figs 2–4. The normal probability graph (Fig. 2) shows that the data lies almost close to the straight line indicating as honest association between experimental and predicted values for the responses.[21]

The graph between residual versus expected values show the lesser difference between the fitted and determined values (Fig. 3). The residuals graph was generated as a result of the experimentation. Moreover, it is said that the inclination to own runs of variations in residuals is recognized as the existence of their connection. From this analysis of residual graphs for surface roughness, the model invariably meets the objectives it doesn’t expose inadequacy. It may be found that the model developed is very much compatible with the determined data (Fig. 4). The residual errors are calculation because distinction among expected and determined value lies within the collection of −0.036 to +0.034.

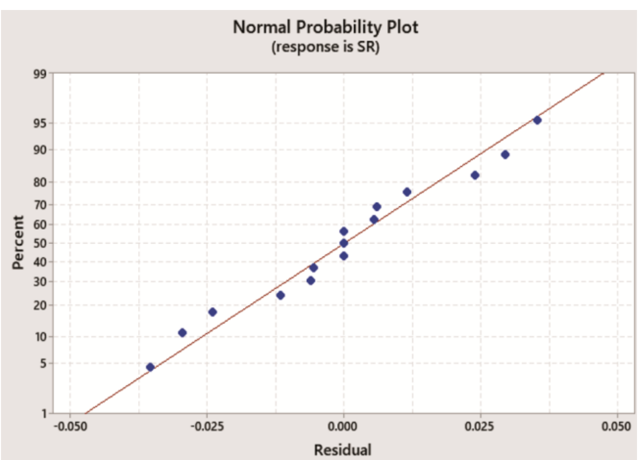

Fig. 2 — Normal probability plot of residuals

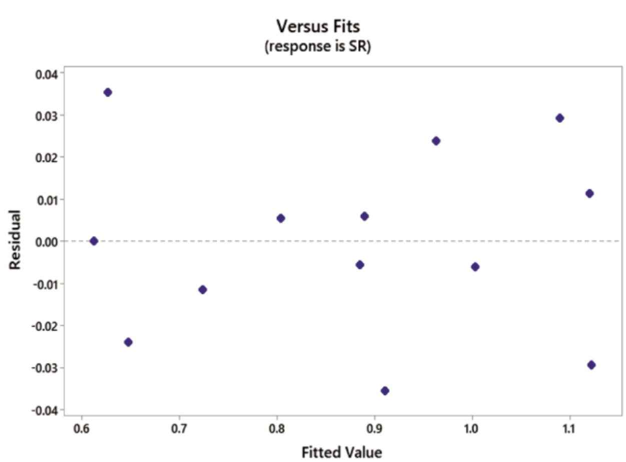

Fig. 3 — Plot of residuals and fitted values

Interactive Effect on Surface Roughness (Ra)

The interactive impact of cutting feed and speed rate on surface roughness with constant cut’s depth is shown in Fig. 5. The speed rises from 2995 to 3496 rpm with 8.01 µm/rev feed and 15 µm invariable depth of cut, while roughness value raises from 0.690 to 0.959 µm which results in a raise of 38% (Eq. 2). The same analysis which is carried out in the vertical direction, the feed increases from 4 to 8.01 µm/rev and 8.01 to 11.96 µm/rev at 2995 rpm with 15 µm depth of cut, the surface roughness reduces from 0.800 to 0.690 µm that results in 14% decreases on surface roughness and second part rise from 0.690 to 0.907 µm at the output of 24% increases on surface roughness (Eq. 2). This is recognized that resultant impact of interfacing among cutting speed along with feed rate will manipulate higher rate than main effect. From the above point of view, it is stated that the cutting depth is not a major influencing factor on surface roughness than feed rate. So to get the least

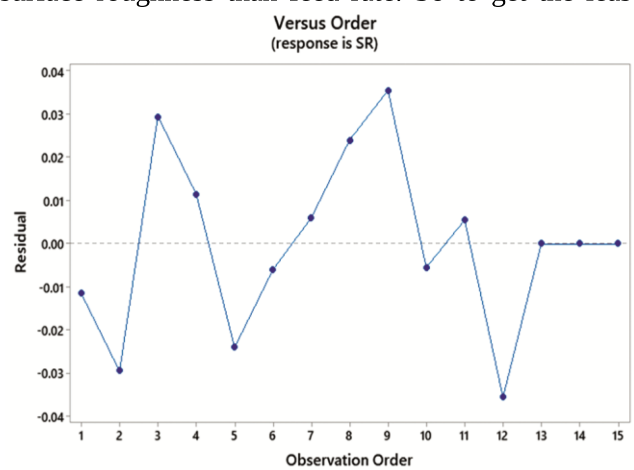

Fig. 4 — Plot of residuals vs. order of the data

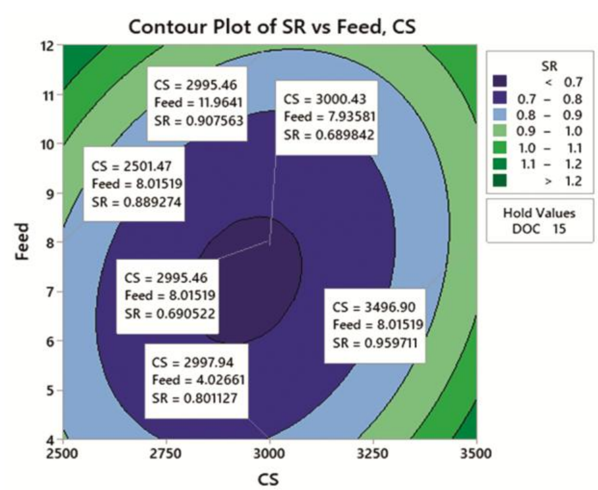

Fig. 5 — Effect of CS and feed on surface roughness

amount of surface roughness, processes have to be executed at feed rate. Therefore, cutting feed and speed rate are the most significant factors in reducing surface roughness to the bare minimum. As can be seen, medium speed with high feed rate and a deeper cut depth produces better results than the other options.[22,23] This impact was identified with flag display in the Fig. 5.

The relationship between feed rate along with depth of cut with cutting speed is stable, as seen in Fig. 6. The parabolic shape of the graph shows a medium feed rate with intermediate cutting speed having 10 µm depth of cut, along with 0.602 µm surface roughness value.

This is necessary for assessing and depicting as a contour plot, the impact of two input factors on surface roughness while keeping the third parameter constant. On the surface roughness scale, Fig. 7 illustrates the relationship between depths of cut along

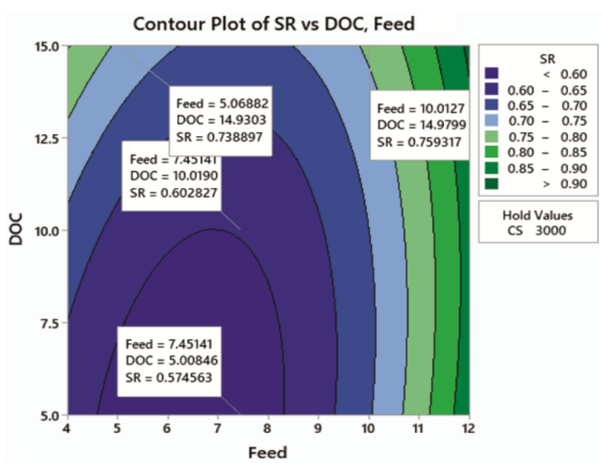

Fig. 6 — Effect of feed and DOC on surface roughness

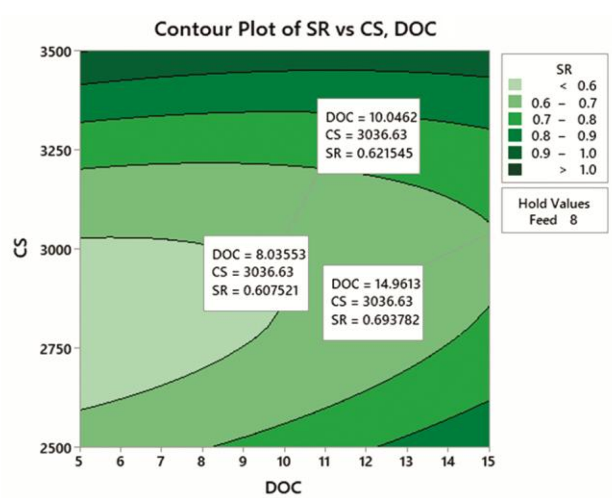

Fig. 7 — Effect of DOC and CS on surface roughness

with cutting speed. The curvature demonstrates that with rise in feed rate as well as cutting speed, surface roughness also rises marginally i.e. from 0.607 to 0.621 µm, which results in only 2% increase. Furthermore, it indicates that the higher rate of depth of cut is not affecting much on surface roughness.[24]

Surface roughness rises from 0.607 to 0.621 µm and from 0.621 to 0.693 µm when depth of cut (contact length) rises from 8 to 10 µm and 10 to 14.9 µm at an 8 µm feed at a 3036 rpm cutting speed (Eq., 2), which amounts to 2% increases of surface roughness on one side and 10% increase on the other side (Eq.2),

According to the graphical impact of the interaction effect, increase in feed rate has a negative effect on the surface quality. Though, depth of cut has no impact on the surface integrity; it just raises the machining zone's temperature. It will improve the plastic deformation of the work piece and reduces tool impact. Medium feed improved the surface quality of the product which implies that uninterrupted chips are formed. In order to get a longer tool life, it is essential to configure the chip in an uninterrupted shape.[25] Based on the proportional influence of depth and feed, it has been determined that cutting speed along with feed rate have a more important role in determining the quality of the product than the depth of the cut. In view of the fact, machining time is reduced by the way of raising the cutting speed; it leads to rise in the tool life and increased the production rate. This anticipation is founded from the given tool nose radius; the theoretical surface roughness is $(Ra = f^2/(32 \times r_e))$ and generally feed rate was the functional parameter.[26] Based on the impact, the average feed rate and cutting speed will give better quality of product. It indicates that feed rate plays primary role, while cutting speed contributes secondary impact on surface quality of the manufacturing products and depth of cut has the least effect in the responses.

Optimizing the Surface Roughness

For obtaining the best quality product at low cost with a high production rate, the price of the tool may be minimized as well as the surface roughness. The parameter settings in micro turning can be optimized to obtain these ultimate goals. Accordingly, the process optimization intentions for finding the best set of cutting speed with feed rate have a great impact on the machining operation geometry. The mathematical equations for machining parameters are created as a way to attain quality machining operation, the correct and optimal combination of machining parameters should be determined. By this criterion, the main focus is to identify the most important parameter to find the best quality product with minimum surface roughness and optimum machining parameters to satisfy the customer requirements. The ANOVA test is carried out for focusing the consequence of the model, coefficients along with lack of fit. The main goal of analysis of variance is to minimize the surface roughness surrounded by parameters position is shown in Table 5. The best possible response is developed by numerical optimization for the experimental conditions on surface roughness value as 0.683 µm with 2944 rpm cutting speed, 7.2 µm/rev feed rate and 15 µm depth of cut with 86% desirability. The optimized value of desirability histogram for the machining condition is given in Fig. 8.

The graphical display shows the optimization results of surface roughness, which easily identifies the feasible limit that allows the illustration to desire the optimal parameters in machining. The preserved constant input parametric condition of machining with overlaid graph is shown in Fig. 8. As part of the shaded boundaries in the overlay graph being feasible limits showed to meet the expected conditions of machining. The different point in the curve signifies the effort of input factors and the related reactions to show and locate the optimized responses with more desirability.

Verification tests were performed utilizing the model for forecasting the response at specific location, and then the predicted response could be compared with actual consideration by performing further experiment at identical point. The residual as well as percentage error calculated from the predicted and observed values are as shown in Table 6. In order to found the best result of input factors to fulfill the above objectives of maximum productivity with minimum surface quality, it has been developed by Response optimizer desirability minimization utility by RSM with Box-Behnken design using Minitab 19 resources.

The graphical output of optimized result in minimum surface roughness with feasible input parameters are showed in Fig. 9. The observed response at 0.683 µm surface roughness was achieved for the following combination of the variables as 2944 rpm cutting speed, 7.23 µm/rev feed along with 15 µm depth of cut for 86% of optimal desirability. The validation trials carried out for evaluating the outcomes from the developed model with the real observed data(s) are arrived from the experimentation, and the errors are (−1.50% to +0.55%) acknowledged and are within the tolerable limit as shown in Table 6.

Scanning Electron Microscopy

Scanning Electron Microscope (SEM) is utilized to evaluate the uniqueness of quality on machinable material. In order to attain the high resolution of

Table 5 — Optimized results for surface roughness

Solution	CS (rpm)	Feed (µm/rev)	DOC (µm)	Surface roughness (Ra) (µm)	Composite desirability
1	2944	7.2	15	0.683	0.86
2	2836	5.5	15	0.718	0.80
3	2733	5.4	15	0.743	0.75
4	2842	4.0	15	0.786	0.66
5	2564	7.1	15	0.817	0.61

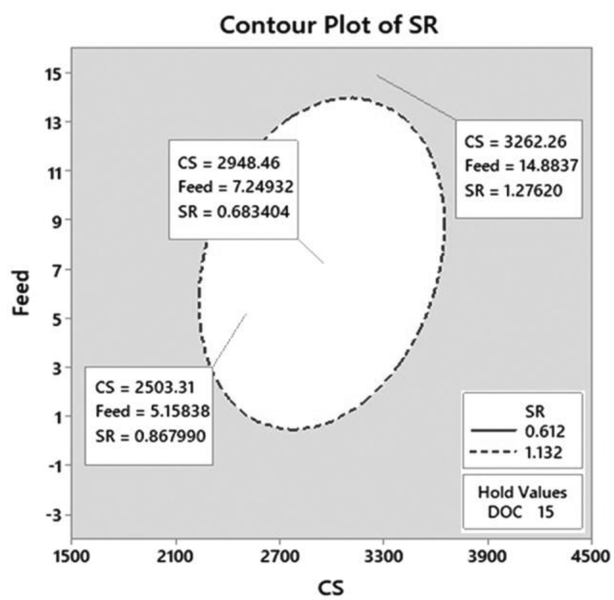

Fig. 8 — Overlaid contour plot

Table 6 — Validation experiments for surface roughness *(Ra)*

Solution	CS (rpm)	Feed (µm/rev)	DOC (µm)	Surface roughness (µm)		Residual	% error	Composite desirability
				Actual	Predicted			
1	2944	7.2	15	0.682	0.683	−0.001	−0.15	0.86
2	2836	5.5	15	0.722	0.718	0.004	0.55	0.80
3	2733	5.4	15	0.732	0.743	−0.011	−1.50	0.75

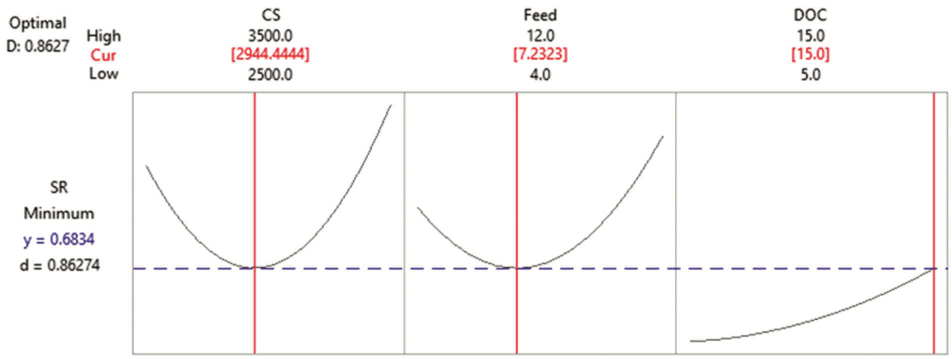

Fig. 9 — Optimization plot

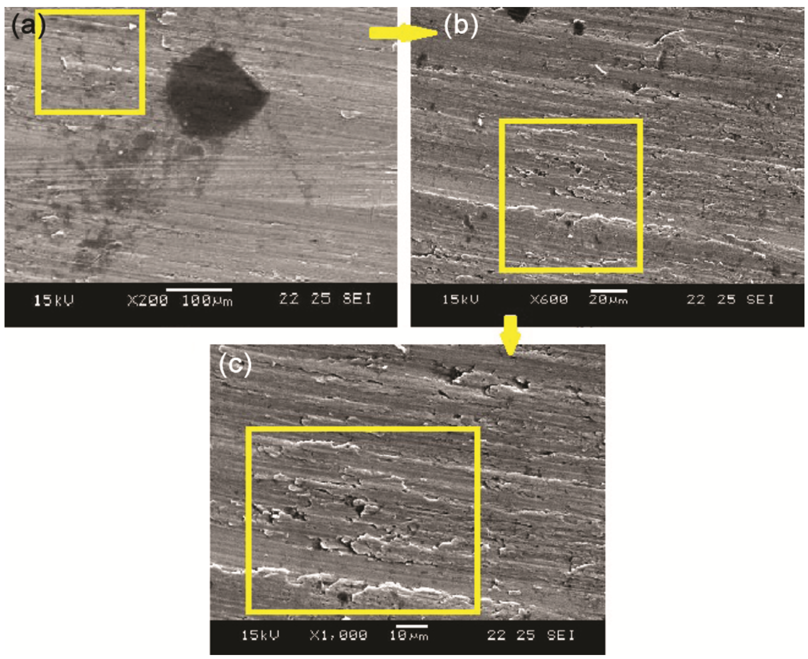

Fig. 10 — SEM image of surface texture of titanium alloy machining conditions (Medium level conditions)

appearance, it needs to use something with a shorter wavelength. In this investigation, the meticulous images of surface quality of machined materials were evaluated. The micrograph analysis of surface integrity on micro machined titanium alloy with medium cutting conditions is presented in Fig. 10 where reasonable defect-free surface could be grasped. The dissimilar formation of shallow layer can be visualized. The increase in depth between work piece and tool has resulted in increase in the machining zone, consecutively condensed process wear, simultaneously improved quality, and produced uninterrupted chips.[20] Therefore, the development of uninterrupted chip is a primary situation of higher life of tool.[4,25] The texture belonging to higher level of input parameters shows wavy texture and incoherent pattern of cutting results. Yet the lay pattern can be visualized to be smooth one. This shows that this machining condition is not suitable to machine titanium alloy bar at higher level of operating conditions. It is evident from SEM analysis that the micro particle deposits are visible at higher cutting speed and feed rates.

Conclusions

The micro-turning experiments were performed, and the optimization of machining parameters during the micro turning process was examined using both graphical and numerical methods. In review of the investigation, the following conclusions can be drawn:

- Feed rate is considered the important component impacting surface roughness, followed by low cutting speed, with the depth of cut having the least amount of impact.

- It was determined that the minimal surface roughness from experiments was 0. 683 µm when the feed rate, cutting speed, as well as cutting depth have been kept at 2944 rotations per minute, 7.2 µm/rev, and 15 µm.
- The lower cutting feed and speed developed stress in the work and cutting wedge action taking place. It also creates a pit on tool rake face and affects the surface quality.
- The contact span increases between tool and work; it improves heat flow in the machining zone that simultaneously progresses the quality of product and creates indestructible chips.
- The predicted surface roughness values coincide with experimental data(s) realistically well, the higher value of coefficient of determination shows R^2 is 98.9% for surface roughness *(Ra).*
- The error variations between observed as well as projected data(s) for roughness quality were detailed below: surface roughness –1.55 to +0.55%.
- From the SEM analysis, it indicates that the micro particle deposits are visible at higher cutting speed and feed rates.

Nomenclature

ANOVA	Analysis of Variance
PCD	Polycrystalline Diamond
CNC	Computer Numerical Control
RSM	Response Surface Methodology
BBD	Box-Behnken Design
Ra	Surface Roughness
DOC	Depth of Cut
CS	Cutting Speed
SEM	Scanning Electron Microscope

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