Some investigations on surface roughness and cutting force in face turning of biocompatible Co-Cr-Mo alloy

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Abstract

Biomanufacturing integrates life science and engineering fundamentals to produce biocompatible products improving the pre-eminence of living. Face turning is an important process used for producing the higher accuracy on metal implants especially on sliding parts. In this experiment effect of depth of cut, feed rate and cutting speeds are considered on machined Co-Cr-Mo bio-implant alloy by application of RSM. The offline and online measured surface roughness (*Ra*) and cutting force (*Fc*) were considered respectively as response variables for investigations. The experimental result shows that depth of cut and feed rate are having predominating effect on measured surface roughness and cutting force respectively. Therefore, the developed models can be efficiently used to predict the surface roughness and cutting force on the machinability of Co-Cr-Mo alloy within 95% confidence intervals ranges of measured parameters. For checking the adequacy of model a confirmation test has been conducted. The optimized parameters can be useful for industrial developments in surface generation for bio-implants. Copyright © 2018 VBRI Press.

Keywords: Co-Cr-Mo bio-implant alloy, face turning, RSM, surface roughness, cutting force, optimization.

Introduction

Machinability of a work material indicates its easiness to manufacture by machining process. The parameters such as cutting force, power consumed, material removal rate, surface roughness, tool wear and dimensional accuracy are used to represent machinability index. The desirable values of above indicators are considered to be higher machinability index [1]. Surface roughness is one of the most important requirements in machining process, as it is considered as an index of product quality. It is critical to obtain desired surface quality to achieve longer functional life of the parts. The surface roughness not only influences the part performance and its cost of manufacture but also affects frictional properties, lubricant holding capacity and geometrical tolerances, etc. While machining the parameters related to cutting tool, process conditions and work material properties plays a major role in surface generation process.

Co-Cr-Mo alloy is the most popular material for biomedical purposes such as dental and orthopedic implants owing to their excellent mechanical properties, wear resistance and biocompatibility. Among them the cast alloys (ASTM-75) reveal low ductility and higher fatigue strength compared to other forged alloys. These are well known alloys used in joint replacements. Artificial joint replacement (arthroplasty) is mostly used and successful surgical treatment for patients suffering from arthritis and trauma. On an average one million arthroplasties are performed per annum worldwide [3]. Co-Cr-Mo alloy is the most appropriate alloy often used in sliding parts, such as artificial knee and hip joints. When it is used in the femoral head of an artificial joint, a glossy surface finish is necessary to extend the life of the joint by compact abrasive wear and improved chemical stability. Retrievals of Co-Cr-Mo metal-on-metal hip implants which did not experience seizing (some serviced in patients over 25 years) revealed little to no wear of the articulating surfaces [6]. As a result, there is novel importance on the optimization of the wear concert of Co-Cr-Mo metal-on-metal implants used in THR. To achieve the higher accuracy and surface finish using these processes, the available information of dimensional manufacturing process parameters is not adequate. Nowadays, industries are searching the perfect parameters for producing the higher accuracy implants for patients.

Some of the related key publications which emphasizes on studying the Co-Cr-Mo hip implants based on laboratory as well as clinical experiences are discussed below.

Table 1. Literature on machinability with input parameter's effect on difficult-to-cut materials.

Investigator	**Input parameters**	**Effect of parameters**	**Material used**	**Methodology used**
Ashwin *et al.* [9]	V_c, *f*, a_p *and r*	Feed rate was the dominating factor while tool nose radius and cutting speed have shown secondary effect	AISI 410 steel	Taguchi DOE and RSM
Lalwani *et al.* [10]	V_c, *f and* a_p	Feed rate have shown severe effect on machined surface roughness	MDN 250 steel	RSM
Saini *et al.* [11]	V_c, *f and* a_p	Feed rate and cutting speed were dominating factor on final machined surface roughness	AISI H-11 steel	RSM
Mandal *et al.* [12]	V_c, *f and* a_p	Cutting speed and depth of cut have predominant effect on feed rate force whereas feed rate and depth of cut are the two most influencing factors for thrust force	AISI 4340 steel	RSM
Pawade *et al.* [13]	V_c, *f*, a_p *and Cutting edge geometry*	Cutting speed, feed rate, depth of cut and edge geometry have highest grey relational grade and therefore are the optimum parameter values producing better turning performance in terms of cutting forces and surface roughness	Inconel 718	Taguchi GRA
Liu *et al.* [14]	V_c, *f and* a_p	Radial and tangential cutting forces were highly influenced by the depth of cut	TC 11 Titanium alloy	RSM
Stefania *et al.* [15]	V_c, *f and* a_p	Feed rate was influencing the final machined surface roughness	Co-Cr-Mo (ASTM F-1537) alloy	One-factor-at a time
Jagtap *et al.* [16]	V_c, *f*, a_p *and* α	Feed rate shows dominating effect on surface roughness in turning operation, whereas the factor rake angle have nearly predominant influence on the machined surface roughness	Co-Cr-Mo (ASTM F-75) alloy	Taguchi DOE
Bordin *et al.* [17]	V_c, *f and* a_p	Feed rate was the dominating factor on machined surface roughness	Co-Cr-Mo (F-1537) alloy	Taguchi DOE
Bernhard et al. [18]	V_c, *f*, a_p *and Cutting edge geometry*	Tool wear and roughness is highly influenced by cutting speed	Co-Cr-Mo alloy	Keeping *f and* a_p were kept constant varying V_c
Ilhan et al. [19]	*f*, a_p, *r and spindle speed*	Tool nose radius and feed rate has influenced on roughness parameters	Co-Cr-Mo (F-1537) alloy	Taguchi DOE and RSM
Pawade *et al.* [20]	V_c, *f*, a_p *and Cutting edge geometry*	Degree of work hardening increased significantly and was influenced by the edge geometry and the depth of cut	Inconel 718	Taguchi DOE
Jagtap et al. [21]	V_c, *f and* a_p	Feed rate and cutting speed are the most significant factors	Co-Cr-Mo (ASTM F-75) alloy	RSM

Fischer *et al.* conducted simulation study and experimental investigation of subsurface areas of retrieved metal-on-metal hip joints and laboratory specimens of worn surfaces of fcc Co-Cr-Mo alloys. They found deposition of a nano-crystalline (nc) layer with a thickness of up to 200 nm on the specimen [3]. Ohmori *et al.* observed the surface roughness, R_a of 7 nm and also reported that surface roughness achieved in ELID grinding was superior than polished surface roughness 4]. Grgazka *et al.* analyzed the influence of chosen modifiers on mechanical properties of composite materials on the base of Co-Cr-Mo alloy [5]. The effect of various burnishing parameters on grain size distribution, microstructural phases and residual stresses has been studied by yang *et al.* [6] using pin on disc wear tests in Co-Cr-Mo alloy. The machining trials of biomedical grade stainless steel have been reported for manufacturing of femoral head. The author Uddin *et al.* [7] found significant effect of feed rate and depth of cut on the surface roughness and sphericity of femoral heads. Satyanarayana *et al.* [8] performed turning of Ti-6Al-4V biomaterial alloy and noted the optimized cutting parameters as 75 m/min cutting speed, 0.25 r/min and 0.25 mm depth of cut at -3 degree approach angle. In the past, authors have optimized the process parameters using RSM and DOE to achieve best surface finish. **Table 1** shows some of the studies on machinability of different metals in optimization of surface finish.

RSM is a collection of mathematical and statistical methods that are helpful for the modelling and analysis of problems in which a response of attention is prejudiced by a number of variables and the purpose is to optimize this response. RSM also computes relationships among one or more measured responses and the crucial input parameters [21].

A regression is necessary to illustrate the data gathered whereby an observed, experimental variable (response) is approximated based on a convenient relationship between the predictable variable, y_{est} and single or multiple regressor or key variable $x_1, x_2, \ldots\ldots x_i$. In the case, if there exist a non-linear relationship between a meticulous response and three input variables, it is expressed by a quadratic equation as given in equation 1.

$$y_{est} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_1x_2 + b_5x_1x_3 + b_6x_2x_3 + b_7x_1^2 + b_8x_2^2 + b_9 x_3^2 + error \quad (1)$$

It may be used to illustrate the practical relationship between the predictable variable, y_{est} and the key variables x_1, x_2 and x_3. The least square technique is being used to fit a model equation including the supposed regressors or input variables by minimizing the residual error considered by the addition of square variations between the definite and the estimated responses. The calculated coefficients or the model equation necessitate to however be tested for algebraic significance. In this respect, the test for significance of the regression model, test for significance on individual model coefficients and test for lack-of-fit are carried out accordingly.

The Design Expert® software (Stat-Ease Inc; USA) version 10.0.3.1 was used to develop the experimental plan for RSM. The software has also used to analyze data gathered from experimentation. The RSM was employed for modelling and analyzing machining parameters in face dry turning process to obtain the machinability performances in terms of surface roughness and cutting forces.

Experimental

Work material

The work material used in the present investigation has been bio-implant alloy, which is a casted low carbon wrought version of ASTM F75 Co-Cr-Mo used for THR. The actual chemical composition (in wt. %) of Co-Cr-Mo alloy [Co, 28.61% Cr, 5.53% Mo, 0.10% C, 0.72% Si, 0.52% Mn, 0.01% P, 0.01% Ni, 0.007% S, 0.18% Fe] as provided by the supplier. A Co-Cr-Mo alloy bar (25 mm in diameter) has been used to prepare a sample of 20 mm in diameter and a thickness of 10 mm.

Experimental set up and procedure

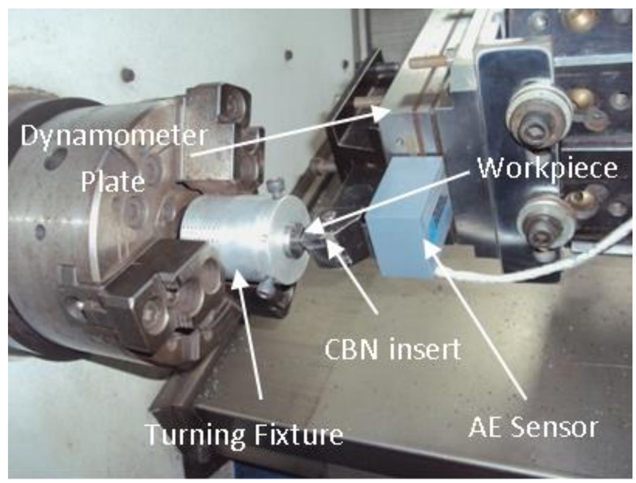


Fig. 1. Closed view set up of CNC face turning of Co-Cr-Mo bio-implant alloy.

Fig. 2. Experimental set up.

Table 2. Design layout for machining Co-Cr-Mo bio-implant alloy by CCD using RSM with experimental results.

Std. substrate no.	**Run sequence**	a_p (µm)	f (mm/rev)	V_c (m/min)	*Ra* (µm)	*Fc*(N)
15	1	0.4	0.15	150	0.89	236.2
6	2	0.6	0.1	200	1.13	787.7
4	3	0.6	0.2	100	1.11	218.5
14	4	0.4	0.15	200	0.98	459.0
7	5	0.2	0.2	200	1.21	213.0
18	6	0.4	0.15	150	0.91	444.3
9	7	0.2	0.15	150	0.91	256.3
5	8	0.2	0.1	200	0.87	412.0
3	9	0.2	0.2	100	1.09	271.0
10	10	0.6	0.15	150	1.00	446.8
12	11	0.4	0.2	150	0.94	329.6
19	12	0.4	0.15	150	0.84	246.0
2	13	0.6	0.1	100	1.21	288.1
17	14	0.4	0.15	150	0.92	304.6
1	15	0.2	0.1	100	0.97	327.1
20	16	0.4	0.15	150	0.95	274.0
8	17	0.6	0.2	200	1.06	271.0
13	18	0.4	0.15	100	0.88	296.0
16	19	0.4	0.15	150	0.95	291.1
11	20	0.4	0.1	150	0.92	659.2

Fig. 2 shows online cutting force measurement set up used for measurement of cutting forces in all three directions. In this experiment the axial and radial force components have no significant effect on machining performance. This has been confirmed from the model formulation using Design Expert 10.0.3.1 for these force components. In view of this, only tangential cutting force (*Fc*) is considered which is more significant on machining performance. CBN is the most common insert material used to machine difficult-to-cut materials. The inserts used for machining were manufactured by Kyocera® Korea with ISO designation of CNGA120404 S01225 ME (80 degree rhombic insert/negative). The insert is mounted on right hand style tool holder manufactured by Sandvik® Asia designated by ISO as PCLNL 2525M 12 having 0 degree rake angle, 25 degree clearance angle, 95 degree tool cutting edge angle, -5 degree tool lead angle and full functional length 150 mm.

The basic objective of experimental design is to utilize the result quality and reduce the test activity. In the present work, the experimental data have been collected by the face centred, CCD method. **Table 2** shows the cutting parameters of the design layout with experimental results.

Initially, twenty workpieces to the required piece from a long rod of Co-Cr-Mo were cut as substrates. These organized substrates exactly made to size Ø20 × 10 mm thickness. An aluminium turning fixture was fabricated having size of Ø50 × 120 mm length to make easy holding of substrates during turning operation. Three grub screws were used to hold the sample tight against the fixture. Fixture along with sample was mounted on three jaw chuck of the machine. After appropriate mounting pressure, fixture was aligned properly for perfect rotation as shown in **Fig. 1**. To begin with a rough cut of 0.05 mm on face of sample and then finish cut was taken on surface of 20 mm diameter. For considering the environment care, all the substrates were machined in dry cutting environment as per the experimental design given in Table 2 in a single block of RSM.

During machining trials, the cutting forces were measured along with diametric cut of tool on workpiece. For measurement of cutting forces KISTLER Model 9257A (made in Switzerland) tool dynamometer has been used along with CNC machine **(Fig. 2).** After machining trials, the machined surfaces were measured to analyze profile on surface tester having model no. SJ- 210 made by Mitutoyo, Japan. Each machined surface was measured at three different locations. The 2D profiles were traced for the 10 mm assessment length with 0.25 mm sampling length.

Results and discussion

The results from the machining trials performed as per the experimental plan is shown in **Table 2**. These results were input into the Design Expert® software for further analysis. Without conducting any transformation on the response, examination of the fit review output revealed that the quadratic models are statistically significant for '*Ra'* and '*Fc*' respectively and therefore it will be used for further analysis.

Table 3. ANOVA table (partial sum of squares) for response surface quadratic model for surface roughness, *Ra*.

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value (Prob > F)**	**Significance**
Model	0.21	9	0.023	9.71	0.0007	significant
A-Depth of Cut	0.021	1	0.021	8.83	0.0140	significant
B-Feed rate	9.610E-003	1	9.610E-003	4.01	0.0731	
C-Cutting Speed	1.000E-005	1	1.000E-005	4.173E-003	0.9498	
AB	0.050	1	0.050	20.70	0.0011	significant
AC	2.812E-003	1	2.812E-003	1.17	0.3041	
BC	7.812E-003	1	7.812E-003	3.26	0.1011	
A^2	0.016	1	0.016	6.69	0.0271	significant
B^2	7.255E-003	1	7.255E-003	3.03	0.1125	
C^2	7.255E-003	1	7.255E-003	3.03	0.1125	
Residual	0.024	10	2.397E-003			
Lack of Fit	0.015	5	3.073E-003	1.79	0.2698	not significant
Pure Error	8.600E-003	5	1.720E-003			
Cor Total	0.23	19				
Std. Dev.	0.049		R-Squared	0.8973		
Mean	0.99		Adj R-Squared	0.8049		
C.V. %	4.96		Pred R-Squared	0.1896		
PRESS	0.19		Adeq Precision	9.355		

Table 4. ANOVA table (partial sum of squares) for reduced quadratic model for surface roughness, *Ra*.

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value (Prob > F)**	**Significance**
Model	0.19	6	0.032	9.92	0.0003	significant
A-Depth of Cut	0.021	1	0.021	6.57	0.0236	significant
B-Feed rate	9.610E-003	1	9.610E-003	2.99	0.1077	
C-Cutting Speed	1.000E-005	1	1.000E-005	3.107E-003	0.9564	
AB	0.050	1	0.050	15.41	0.0017	significant
A^2	0.029	1	0.029	9.09	0.0099	significant
C^2	0.016	1	0.016	4.96	0.0443	significant
Residual	0.042	13	3.219E-003			
Lack of Fit	0.033	8	4.156E-003	2.42	0.1731	not significant
Pure Error	8.600E-003	5	1.720E-003			
Cor Total	0.23	19				
Std. Dev.	0.057		R-Squared	0.8207		
Mean	0.99		Adj R-Squared	0.7380		
C.V. %	5.75		Pred R-Squared	0.4268		
PRESS	0.13		Adeq Precision	8.699		

ANOVA analysis

For analysis, test for regression model's significance, test for individual model coefficient significance and test for lack-of-fit need to be conducted. **Table 3** shows the ANOVA table for response surface quadratic model for surface roughness (*Ra*). The assessment of "Prob. > *F*" in **Table 3** for model is less than 0.05 which indicates that the model is significant, which is advantageous as it designate that terms in the model have a significant effect on the response. In the same manner, the main effect of depth of cut (*A*), the two-level interaction of depth of cut and feed rate (*AB*) and the second order effect of depth of cut (A^2) are significant model terms. Other model terms are not statistically significant. These insignificant model terms can be removed and may result in an improved model. The lack-of-fit can also be said to be insignificant. This is desirable and wants a model that fits.

By choosing the backward elimination method to automatically diminish the terms that are not significant, the resulting ANOVA table for the reduced quadratic model for surface roughness is shown in **Table 4**. A result from **Table 4** indicates that the model is still significant. However, the main effect of depth of cut (*A*), the two-level interaction of depth of cut and feed rate (*AB*) and the second order effect of depth of cut (A^2) and cutting speed (C^2) are significant model terms. The main effect of depth of cut (*A*) is the most significant factor associated with surface roughness.

Table 5. ANOVA table (partial sum of squares) for reduced quadratic model for cutting force, *Fc*.

Source	Sum of Squares	df	Mean Square	F Value	p-value (Prob > F)	Significance
Model	2.985E+005	5	59709.86	6.82	0.0020	significant
A-Depth of Cut	28376.93	1	28376.93	3.24	0.0935	
B-Feed rate	1.371E+005	1	1.371E+005	15.65	0.0014	significant
C-Cutting Speed	55056.40	1	55056.40	6.28	0.0251	significant
AC	34479.38	1	34479.38	3.94	0.0672	
BC	43512.50	1	43512.50	4.97	0.0427	significant
Residual	1.227E+005	14	8761.33			
Lack of Fit	94075.78	9	10452.86	1.83	0.2623	not significant
Pure Error	28582.89	5	5716.58			
Cor Total	4.212E+005	19				
Std. Dev.	93.60		R-Squared	0.7088		
Mean	351.58		Adj R-Squared	0.6048		
C.V. %	26.62		Pred R-Squared	0.3099		
PRESS	2.907E+005		Adeq Precision	12.084		

This is expected because it is well known that tool material plays an important role while initializing depth of cut to achieve final surface integrity. Additionally, the results show that the interaction between the depth of cut and feed rate terms provides secondary contribution to the surface roughness. The second order effect of depth of cut (A^2) and cutting speed (C^2) are also having secondary effect on surface roughness. The lack-of-fit can still be said to be insignificant. The R^2 value is moderate, which is desirable.

Similarly backward elimination method is applied on response (*Fc*) and **Table 5** shows the reduced quadratic model for cutting force and it indicates that the model is still significant. However, the main effect of feed rate (*B*) and cutting speed (*C*), the two-level interaction of feed rate and cutting speed (*BC*) are significant model terms. The main effect of feed rate (*B*) is the most significant factor associated with cutting force.

It is found that the tool geometry, the cutting force is primarily a function of the feed rate. Additionally, the results show that the cutting speed (*C*) and interaction between the feed rate and cutting speed terms provides secondary contribution to the cutting force. The lack-of-fit can still be said to be insignificant.

The equation no. 2 and equation no. 3 are the final empirical models in terms of coded factors for surface roughness (*Ra*) and cutting force (*Fc*), respectively.

$$Ra = 0.90 + 0.046A + 0.031B - (1 \times 10^{-3})\,C - 0.079AB + 0.096A^2 + 0.071C^2 \quad (2)$$

$$Fc = 351.57 + 53.27A - 117.10B + 74.20C + 65.65AC - 73.75BC \quad (3)$$

However, the equation no. 4 and equation no. 5 are the final empirical models in terms of actual factors for surface roughness (*Ra*) and cutting force (*Fc*), respectively.

$$Ra = 1.26750 - 0.50125\ \text{depth of cut} + 3.77000\ \text{feed rate} - (8.49500 \times 10^{-3})\ \text{cutting speed} - 7.87500\ (\text{depth of cut} \times \text{feed rate}) + 2.39063\ \text{depth of cut}^2 + (2.82500 \times 10^{-5})\ \text{cutting speed}^2 \quad (4)$$

$$Fc = 103.88500 - 718.40000\ \text{depth of cut} + 2083\ \text{feed rate} + 3.28300\ \text{cutting speed} + 6.56500\ (\text{depth of cut} \times \text{cutting speed}) - 29.50000\ (\text{feed rate} \times \text{cutting speed}) \quad (5)$$

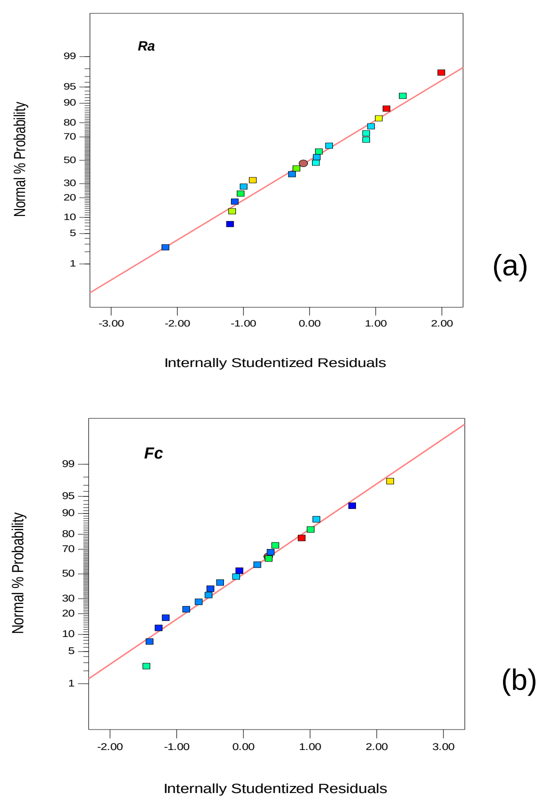


Fig. 3. Normal probability plot of residuals for (a) *Ra* and (b) *Fc*

After the quadratic model of surface roughness (*Ra*) and 2FI model of cutting force (*Fc*) were developed, the model adequacy checking have been conducted in order to verify that the underlying assumption of regression analysis is not violated. The normal probability plots of the residuals for surface roughness and cutting force are shown in **Fig. 3 (a)** and **(b)** which shows no sign of the violation follows a straight line pattern involving that the errors are spotted normally. This involving that the models proposed are satisfactory and there is no cause to suspect any violation of the independence or constant variance assumption.

In order to investigate the influences of machining parameters on the surface roughness and cutting force, the three-dimensional response surfaces plots are shown in **Figs. 4 (a)** and **(b),** respectively. **Fig. 4 (a)** shows that the surface roughness increases with increase in depth of cut and feed rate. This event has been attributed to increasing in the friction effect of chip which leads to increase in stress and temperature on nose radius of the tool. **Fig. 4 (b)** shows that as the cutting force increases with increase in cutting speed and decreases in small amount with increase in feed rate. This can be attributed to the fact that from the fundamental of metal machining that any increase in cutting speed increases the cross sectional area and the corresponding deforming volume. Therefore, increase in cutting speed produces larger cutting forces during machining.

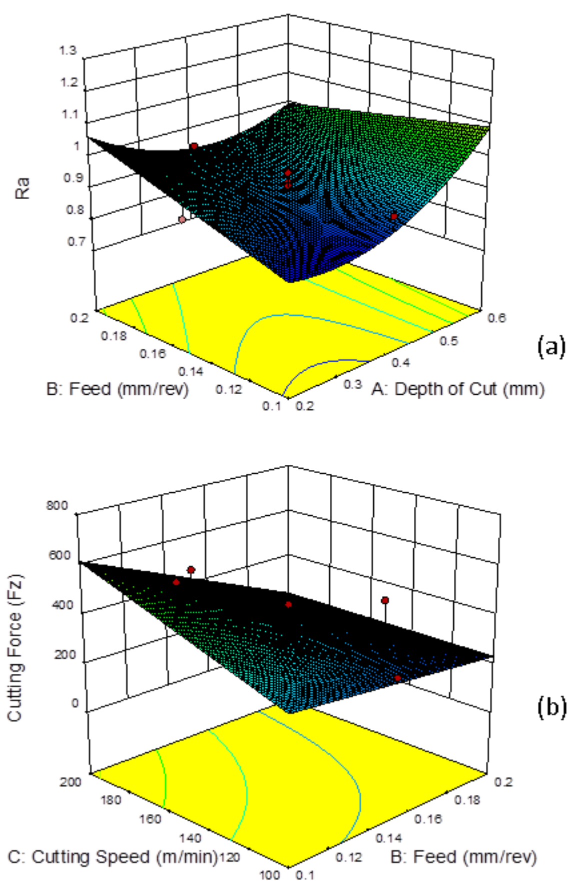
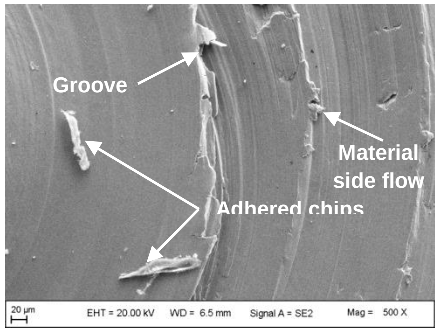
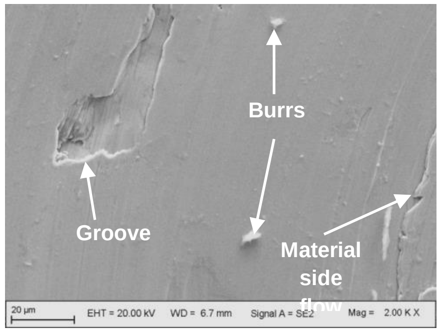


Fig. 4. Response surface 3D plot of residuals for (a) *Ra* and (b) *Fc*



(a_p = 0.6 mm, f = 0.1 mm/rev, V_c = 200 m/min)



(a_p = 0.6 mm, f = 0.1 mm/rev, V_c = 100 m/min)

Fig. 5. SEM micrographs of machined surfaces of Co-Cr-Mo alloy

Fig. 5 shows the SEM micrographs of machined surfaces of Co-Cr-Mo alloy for different machining parameters. No chatter marks were observed on the turned surfaces, since no chattering occurs for all the tested cutting conditions. A considerable variation in the density and morphology of the surface damages has been observed in this study, being associated with the cutting parameters, namely depth of cut and feed rate, as found in machined surfaces. Grooves could be produced due to severe abrasion of the strain hardened material by the cutting tool during machining. It is also found that, an increase in the cutting speed causes more thermal influence in the machining zone, which leads to smearing of more material.

Confirmation test

For the confirmation of second order response surface quadratic and 2FI model, four confirmation experiments were performed for the surface roughness (*Ra*) and tangential force (*Fc*) respectively in order to validate the adequacy of obtained model. Using the point prediction ability of the software, the surface roughness and cutting force of the selected experiments were predicted together with in the prediction interval of 95%. The predicted value and actual experimental value were compared, and the residual and percentage error were calculated. The results of the confirmation test and their comparisons with the predicted values for the surface roughness and cutting force are listed in Table 6. The results of **Table 6** show that both the residual and percentage error are small. The percentage error range between the actual and the predicted value of surface roughness lies between the ranges of -8.33 to 7.52% and cutting force lies between the ranges of -1.65 to 1.39%.

Table 6. The results of the confirmation test for surface roughness (*Ra*, µm) and tangential force (*Fc*, N).

Expt. No.	Machining parameters			For Surface roughness, *Ra*				For Cutting force, *Fc*			
	a_p (µm)	*f* (mm/rev)	V_c (m/min)	Actual	Predicted	Residual	Error (%)	Actual	Predicted	Residual	Error (%)
1	0.25	0.1	126	0.91	0.84	0.07	-8.33	389.4	383.05	6.35	-1.65
2	0.27	0.1	119	0.89	0.85	0.04	-4.70	364.6	369.75	-5.15	1.39
3	0.41	0.2	149	0.86	0.93	-0.07	7.52	236.2	237.63	-1.43	0.60
4	0.42	0.2	152	0.97	0.93	0.04	-4.30	239.6	238.78	0.82	-0.34

Conclusions

In this research, the quadratic and 2FI model for surface roughness (*Ra*) and cutting force (*Fc*) have been developed respectively so as to investigate the influences of machining parameters in turning Co-Cr-Mo bio-implant alloy. The experimental plan has been based on face cantered, CCD. The effect of machining parameters such as depth of cut, feed rate and cutting speed were evaluated by using RSM. The authors made following conclusions based on this experiment:

1. The surface roughness (*Ra*) increases with increase in the depth of cut and feed rate, and decreases with decrease in cutting speed and depth of cut.
2. The cutting force (*Fc*) increases with increase in cutting speed, and decreases in small amount with decrease in feed rate.
3. The ANOVA of surface roughness (*Ra*) revealed that depth of cut is the most significant factor influencing the response variables investigated. The depth of cut and the feed rate interaction factors provided secondary contribution to the responses investigated.
4. Additionally, the ANOVA for cutting force (*Fc*) discovered that feed rate is having dominating effect on cutting force (*Fc*) during machining. However, feed rate and cutting speed interaction factors are having secondary effect.
5. The quadratic and 2FI models developed using RSM are practically accurate and can be used for prediction within the restrictions of the factors investigated.
6. The results of ANOVA and the conducting confirmation tests have verified that the developed models of the surface roughness (*Ra*) and cutting force (*Fc*) fit and predicted values which are near to those readings recorded experimentally with a 95% prediction interval.

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Author's contributions

Ketan Jagtap and Raju Pawade conducted the experiments and prepared the manuscript. Both authors read and approved the manuscript. Authors have no competing financial interests.

Notations

V_c: cutting speed (m/min)
f: feed (mm/rev)
a_p: depth of cut (µm)
r: tool nose radius (mm)
γ: side cutting edge angle (degrees)
α: rake angle (degrees)
Ra: surface roughness (µm)
Fc: cutting force (Newton)
Co-Cr-Mo: Cobalt Chromium Molybdenum
RSM: Response Surface Methodology
THR: Total Hip Replacement
ASTM: American Society for Testing and Materials
CCD: Central Composite Design
DOE: Design of Experiments
ANOVA: Analysis of Variance
CBN: Cubic Boron Nitride
AE: Acoustic Emission

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