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Experimental Investigation on Surface Roughness of Face Turned Co-Cr-Mo Biocompatible Alloy Followed by Polishing

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ABSTRACT
Biomanufacturing integrates life science and engineering basics to manufacture biocompatible products improving the superiority of living. Face turning is one of the important process producing the higher accuracy with surface finish on metal implants especially on sliding parts of metal-on-metal implants. Surface roughness is the most significant constraint in machining process, as it is considered an index of machined manufactured goods quality. In this experiment effect of depth of cut, feed rate and cutting speeds have been considered on face turned Co-Cr-Mo biocompatible alloy by application of RSM. The face turned substrates followed by polishing process for surface improvement required for functional life of an implant. The CNC turned surface roughness (Ra_1) have considered as the response variables for investigation. The experimental plan with RSM and experimental result indicates that feed rate and cutting speed have dominating effect on CNC turned surface roughness (Ra_1). Therefore, the developed model can be efficiently used to expect the surface roughness on the machining of Co-Cr-Mo biocompatible alloy. A confirmation test has been carried out in order to verify the suitability of the developed model.

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Abbreviations and Nomenclatures:

V_c: cutting speed (m/min)
f: feed rate (mm/rev)
a_p: depth of cut (μm)
r: tool nose radius (mm)
γ: side cutting edge angle (degrees)
α: rake angle (degrees)
Ra_1: Surface roughness after turning (μm)
Ra_2: Surface roughness after polishing (μm)
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

Introduction

Machinability of a work material indicates its easiness to manufacture by machining process. The parameters such as cutting force, power consumption, 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 vital necessities in machining process, as it is considered as an index of product quality. It is critical to produce component with minimum surface roughness to achieve longer functional life of the products. 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 play 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 due to their outstanding mechanical properties, wear resistance and biocompatibility. Among them the cast alloys (ASTM-75) exhibit low ductility and higher fatigue strength evaluated to other forged alloys. These are the most popular alloys for artificial joint replacements. Artificial joint replacement (arthroplasty) is widely used and successful surgical treatment for patients experiencing from trauma and arthritis. On an average one million arthroplasties are performed annually worldwide [3]. Co-Cr-Mo alloy is the most suitable alloy often used in sliding parts, such as artificial hip and knee joints due to its higher biocompatibility in human body. When it is used in the head of an artificial joint, a mirrored finish is necessary to extend the life of the joint by compact abrasive wear and enhanced chemical stability. The exploration for a minimum friction surfaces has led to the progress of metal-on-metal hip implants. These devices are commonly used today in patients less than 60 years of age [6]. 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. 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. Especially face turning is one of the important manufacturing process producing the higher accuracy and surface finish on metal implants. In order to enhance the machinability and hence product quality, there has been rising focus on improvement of machined surface finish by post finishing techniques such as polishing. 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 presented below.

Fischer *et al.* conducted simulation study and experimental investigation of subsurface areas of retrieved metal-on-

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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
K. Venkatesan [21]	V_c, f, a_p, approach angle and laser power	Feed rate, cutting speed and laser power are the dominating factors on machined roughness	Inconel 718	RSM and Taguchi DOE

metal hip joints and laboratory specimens of worn surfaces of fcc Co-Cr-Mo alloys. Author 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 -3^0 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. Seemikeri *et al.* [22] investigated surface roughness, microhardness, surface integrity, and fatigue life aspects of AISI 316L work material, which is most commonly used in prosthesis. Surface roughness up to 0.56 µm, surface hardness up to 765 Hv, and fatigue life up to 13,23,700 cycles could be achieved by this low plasticity burnishing (LPB) process.

In turning operation the surface roughness depends on cutting speed, feed rate, depth of cut, tool nose radius, tool wear, machine vibrations, lubrication of the cutting tool and on mechanical and thermo physical properties of the material going to machined. Even small variation in any of the given parameters may have a significant effect on the generated surface. In machinability study, statistical design of experiment is used quite broadly. Statistical design of experiments refers to the process of scheduling the experiment so that the proper data can be analyzed by statistical techniques, resulting in applicable and objective conclusions. Design and methods such as full factorial, RSM and fractional factorial (Taguchi) methods are now generally used instead of one-factor-at-a-time experimental approach which is time consuming and absurd in cost. Present research focuses the application of RSM in face turning of Co-Cr-Mo biocompatible alloy with CBN inserts by CNC machine followed by polishing and developing mathematical model of surface roughness (*Ra*).

Response Surface Methodology (RSM)

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 [23]. Statistical software has been used to extend the experimental preparation for RSM. After analyzing each response, multiple response optimizations have been carried out, either by assessment of the interpretation plots, or with the graphical and statistical tools offered for this purpose. It was revealed previously that RSM designs also helps in computing the bond between single or multiple considered responses and the fundamental input parameters. In order to resolve if there exist a relationship between the aspects and the response variables considered, the data composed must be analysed in a statistically sound approach using regression. A regression is carried out in order to illustrate the data gathered whereby an observed, experimental variable (response) is approximated based on a practical relationship among the predictable variable, y_{est} and single or multiple regressor or key variable x_1, x_2,……. 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 modeling and analyzing machining parameters in dry face turning process as well as polishing process in order to obtain the machinability performances in terms of surface roughness.

Experimental

Materials

The work material used in the present investigation was biocompatible alloy, which was 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) was used to prepare a sample of 20 mm in diameter and a thickness of 10 mm.

Experimental method

Initially face turning process was employed to determine the machinability of Co-Cr-Mo biocompatible alloy in dry cutting environment. A production type CNC turning precision lathe (Model Jobber XL Make Micromatic, India) having maximum spindle speed 5000 rpm and 13 KW capacity was used for machining the samples. The CNC machined samples were polished for improvement of surface finish. All the machined specimen were polished by a die grinder machine (Model DSJ02-25 Make Dongchang, China) having maximum spindle speed 27000 rpm and 400 W capacity at a constant time for 5 mins for each substrate. Fig. 1 shows the schematic of the experiment for surface finish improvement of Co-Cr-Mo biocompatible alloy.

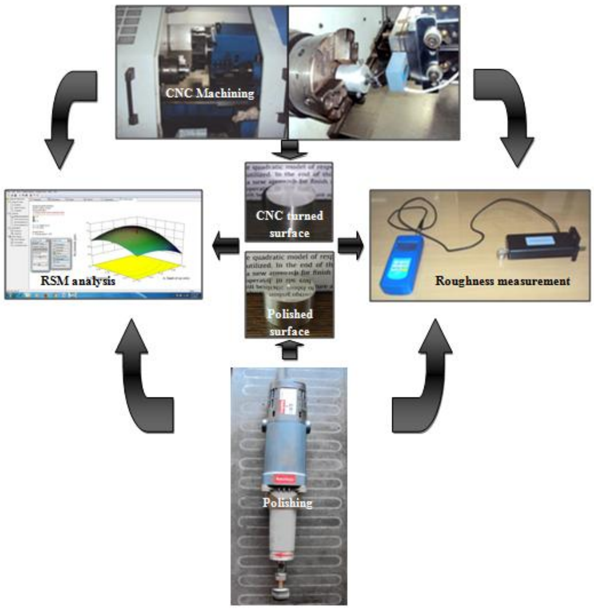


Figure 1: Schematic of experimental set up

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 tool geometry and cutting parameters have selected by preliminary experiments conducted on same alloy.

The objective of experimental design is to reduce the test activity and utilize the result quality. In the present work, the experimental data have been collected by the face centered, CCD method. The factorial fraction of the CCD is a full factorial design with all mixtures of factors at two levels (low -1 and high +1) and composed of eight star points, six central points (coded levels 0), along with the high and low levels is the midpoint. The star points at face of the cubic fraction on the design corresponding to a value of 1. This type of design is generally called as face centered. Table 2 shows the cutting parameters with the design layout with experimental results.

Initially, twenty work pieces 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,

Table 2: Design layout for machining and polishing of Co-Cr-Mo biocompatible alloy with experimental results

Std. substrate no.	Run sequence	a_p (µm)	f (mm/rev)	V_c (m/min)	Surface roughness after turning Ra_1(µm)	Surface roughness after polishing Ra_2(µm)
11	1	0.2	0.15	125	1.09	0.37
9	2	0.2	0.15	100	1.15	0.64
10	3	0.2	0.15	150	1.34	0.17
8	4	0.2	0.2	125	1.18	0.66
6	5	0.3	0.15	125	1.04	0.42
4	6	0.1	0.1	100	0.72	0.41
3	7	0.1	0.2	150	1.13	0.72
13	8	0.2	0.15	125	1.19	0.43
2	9	0.3	0.1	150	0.83	0.47
15	10	0.2	0.15	125	1.20	0.53
5	11	0.1	0.15	125	1.08	0.39
12	12	0.2	0.15	125	1.14	0.40
7	13	0.2	0.1	125	0.88	0.39
14	14	0.2	0.15	125	1.25	0.45
1	15	0.3	0.2	100	1.27	0.67

Table 3: ANOVA table (partial sum of squares) for response surface quadratic model for CNC machined surface roughness, Ra_1

Source	Sum of Squares	df	Mean Square	F Value	p-value (Prob > F)	Significance
Model	0.39	9	0.044	14.65	0.0043	significant
A-Depth of cut	8.000E-004	1	8.000E-004	0.27	0.6267	
B-Feed rate	0.045	1	0.045	15.08	0.0116	significant
C-Cutting speed	0.018	1	0.018	6.05	0.0573	-
AB	0.014	1	0.014	4.69	0.0825	-
AC	5.208E-003	1	5.208E-003	1.75	0.2437	-
BC	9.075E-003	1	9.075E-003	3.04	0.1416	-
A^2	0.034	1	0.034	11.36	0.0199	significant
B^2	0.054	1	0.054	18.13	0.0080	significant
C^2	0.013	1	0.013	4.44	0.0889	-
Residual	0.015	5	2.984E-003	-	-	-
Lack of Fit	9.804E-008	1	9.804E-008	2.628E-005	0.9962	not significant
Pure Error	0.015	4	3.730E-003	-	-	-
Cor Total	0.41	14	-	-	-	-
Std. Dev.	0.055	-	R-Squared	0.9635	-	-
Mean	1.10	-	Adj R-Squared	0.8977	-	-
C.V. %	4.97	-	Pred R-Squared	0.9509	-	-
PRESS	0.020	-	Adeq Precision	13.904	-	-

Table 4: ANOVA table (partial sum of squares) for reduced quadratic model for CNC machined surface roughness, Ra_1

Source	Sum of Squares	df	Mean Square	F Value	p-value (Prob > F)	Significance
Model	0.39	7	0.055	18.51	0.0005	significant
B-Feed rate	0.22	1	0.22	73.72	0.0001	significant
C-Cutting speed	0.018	1	0.018	6.04	0.0437	significant
AB	0.014	1	0.014	4.69	0.0672	-
BC	0.016	1	0.016	5.23	0.0561	-
A^2	0.034	1	0.034	11.33	0.0120	significant
B^2	0.054	1	0.054	18.09	0.0038	significant
C^2	0.013	1	0.013	4.43	0.0733	-
Residual	0.021	7	2.990E-003	-	-	-
Lack of Fit	6.008E-003	3	2.003E-003	0.54	0.6817	not significant
Pure Error	0.015	4	3.730E-003	-	-	-
Cor Total	0.41	14	-	-	-	-
Std. Dev.	0.055	-	R-Squared	0.9487	-	-
Mean	1.10	-	Adj R-Squared	0.8975	-	-
C.V. %	4.97	-	Pred R-Squared	0.5341	-	-
PRESS	0.19	-	Adeq Precision	15.008	-	-

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. After CNC machining trial, the machined surfaces have been measured to analyze profile on surface tester having model: SRT-1 made by MGW precision, India. 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 at three point locations. After assessment of CNC machined substrates polishing was carried out for surface finish improvement. The same fixture was used to hold the substrates during polishing trial by portable grinder machine as shown in Fig. 1. Small rounded buffing pad is used as a tool for polishing. Polishing was conducted with 27000 rpm spindle speed on each substrate having polishing time as 3 minutes per sample by using diamond paste on functional surface of substrate. Polished specimens measured by the roughness tester and accordingly data were recorded for further analysis.

Results and Discussion

The results from the machining trials performed as per the experimental plan are 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_1' and therefore it will be used for further analysis.

ANOVA analysis

For analysis, test for significance of the regression model, test for significance on individual model coefficients and test for lack-of-fit need to be performed. ANOVA table is commonly used to summarize the tests performed. Table 3 shows the ANOVA table for response surface quadratic model for CNC machined surface roughness (Ra_1). The value of "Prob. > *F*" in Table 3 for model is less than 0.05 which designates that the model is significant, which is desirable as it designates that the terms in the model have a significant result on the response.

In the same manner, the main effect of feed rate (*B*) and the second order effect of depth of cut (A^2) and feed rate (B^2) are significant model terms. Other model terms are not statistically significant. These insignificant model terms (not including those required to support hierarchy) can be removed and may result in an improved model. The lack-of-fit can also be said to be insignificant. This is beneficial and wants a model that fits.

By selecting the backward elimination practice to automatically reduce the terms that are not significant, the resulting ANOVA table for the reduced quadratic model for surface roughness is shown in Table 4. Results from Table 4 indicate that the model is still significant. However, the main effect of feed rate (*B*) and cutting speed (*C*), and the second order effect of depth of cut (A^2) and feed rate (B^2) are significant model terms. The main effect of feed rate (*B*) is the most significant factor allied with surface roughness, Ra_1.

This is expected because it is well known that tool material plays an important role while initializing feed rate to achieve final surface integrity. Additionally, the results show that the cutting speed provides secondary contribution to the surface roughness. The second order effect of depth of cut (A^2) and feed rate (B^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 high and close to 1, which is desirable. The predicted R^2 is in reasonable agreement with the adjusted R^2. The adjusted R^2 value is mostly useful when comparing models with different number of terms. This evaluation is however done in the conditions when model reduction is taking place. Enough precision compares the range of the predicted values at the design points to the standard prediction error. The lack-of-fit can still be said to be insignificant. The R^2 value is high and close to 1, which is desirable. The predicted R^2 is in practical agreement with the adjusted R^2. The adjusted R^2 value is mostly useful when comparing models with different number of conditions. This evaluation is however done in the conditions when model reduction is taking place. Enough accuracy compares the range of the predicted values at the design points to the regular prediction error.

The equation 2 is the final empirical model in terms of coded factors for CNC machined surface roughness (Ra_1).

$$Ra_1 = 1.17 + 0.19B + 0.095C + 0.10AB - 0.063BC - 0.11A^2 - 0.14B^2 + 0.071C^2 \quad (2)$$

However, the equation 3 is the final empirical models in terms of actual factors for CNC machined surface roughness (Ra_1).

$$Ra_1 = -0.53038 + 25.39961\,\text{feed rate} - 0.011824\,\text{cutting speed} + 24.80198\,(\text{depth of cut} \times \text{feed rate}) - 0.069824\,(\text{feed rate} \times \text{cutting speed}) - 9.92024\,\text{depth of cut}^2 - 59.32893\,\text{feed rate}^2 + (1.06684 \times 10^{-4})\,\text{cutting speed}^2 \quad (3)$$

After the quadratic model of CNC turned surface roughness (Ra_1) was developed, the model adequacy checking have been carried out in order to validate that the underlying theory of regression analysis is not violated. The normal probability plot of the residuals for Ra_1 is shown in Fig. 2.

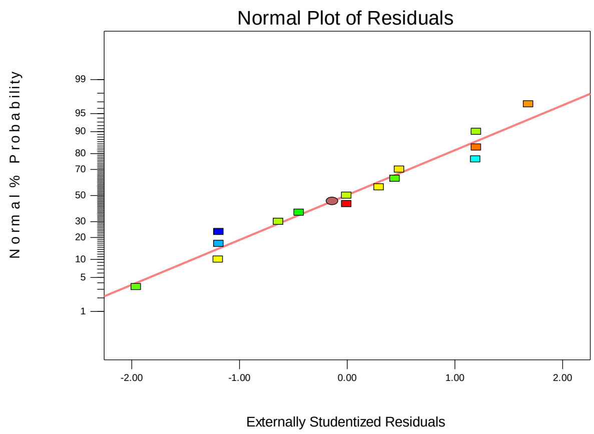


Figure 2: Normal probability plot of residuals for machined surface roughness (Ra_1)

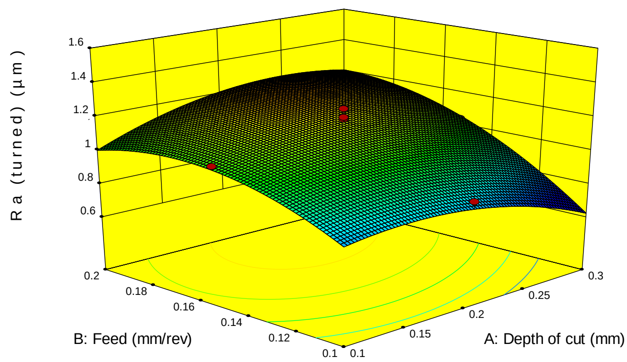


Figure 3: Response surface 3D plot of machined surface roughness (Ra_1)

In order to investigate the influences of machining parameters on the CNC turned surface roughness (Ra_1), the three-dimensional response surface plots are shown in Fig. 3 and it shows that the CNC turned 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 shows that by using post finishing process i.e. polishing on CNC turned surfaces, the surface roughness reduced extensively and occurred mirror finish on surfaces.

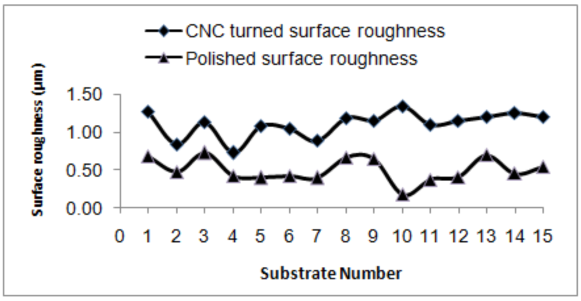
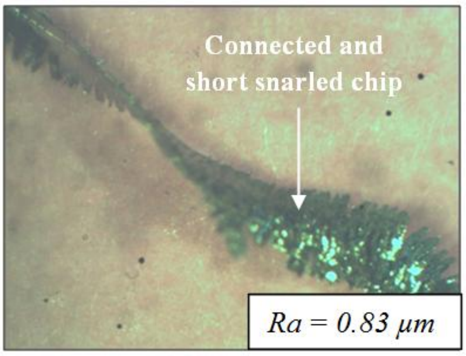
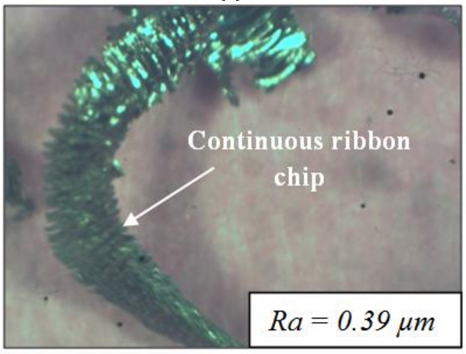


Figure 4: Improvement of surface roughness by polishing process



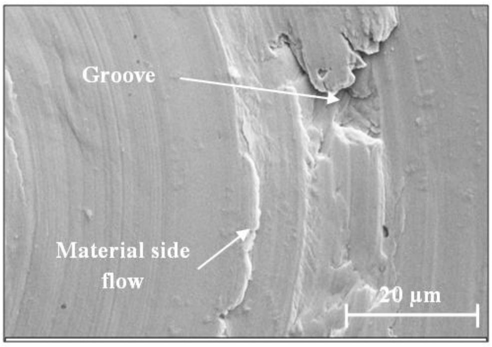
(a)



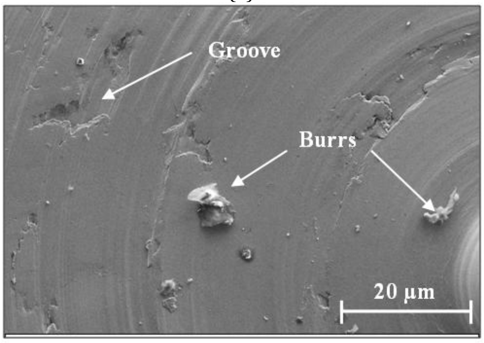
(b)

Figure 5: Microscopic images of chips generated during CNC turning of Co-Cr-Mo alloy (a) $a_p = 0.3$ mm, $f = 0.1$ mm/rev, $V_c = 150$ m/min; (b) $a_p = 0.1$ mm, $f = 0.15$ mm/rev, $V_c = 125$ m/min

Figure 5 shows the microscopic images of chips during CNC machining of Co-Cr-Mo biocompatible alloy for different machining parameters. It has been observed that the connected and short snarled chips were generated when depth of cut was 0.3 mm. At that time the turned roughness was 0.83 µm. Also tight coiled spring chips were generated when feed rate was 0.15 mm/rev and surface roughness was increased at 1.04 µm. When the depth of cut was as small 0.1 mm then continuous ribbon chips were generated and surface roughness was again increased up to 1.09 µm. This can be attributed to continuous chips that are produced probably due to predominant mechanical oriented plastic deformation by the chamfered cutting edge of the insert. Fig. 6 shows the SEM micrographs of machined surfaces of Co-Cr-Mo alloy for different machining parameters. Material side flow grooves and burrs have observed on turned surfaces. This could be produced due to severe abrasion of the harden material by the cutting tool during machining. 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. However, Fig. 7 shows the polished surface image included some inclusions and shows a repetitive pattern type on surfaces. The SEM image for polished surfaces clearly shows that surface finish improvement on polished surfaces than CNC turned surfaces.

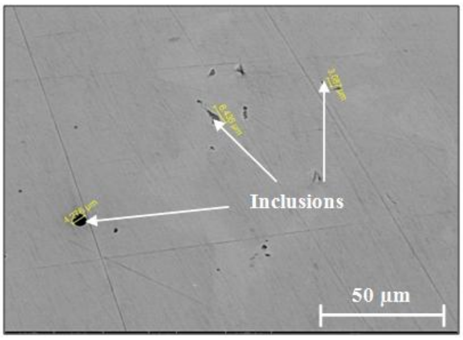


(a)

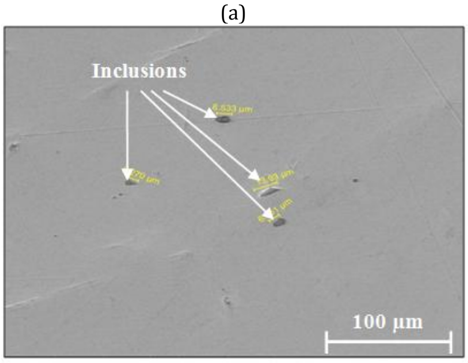


(b)

Figure 6: SEM micrographs of CNC turned surfaces of Co-Cr-Mo alloy (a) $a_p = 0.3$ mm, $f = 0.1$ mm/rev, $V_c = 150$ m/min; (b) $a_p = 0.3$ mm, $f = 0.15$ mm/rev, $V_c = 125$ m/min



(a)



(b)

Figure 7: SEM micrographs of polished surfaces of Co-Cr-Mo alloy

Table 5: The results of the confirmation test for CNC turned surface roughness (Ra_1)

Expt. No.	Machining parameters			CNC turned surface roughness (Ra_1)			
	a_p (µm)	f (mm/rev)	V_c (m/min)	Actual (µm)	Predicted (µm)	Residual	Error (%)
1	0.1	0.1	120	0.83	0.79	0.04	4.82
2	0.12	0.1	125	0.90	0.84	0.06	6.67
3	0.18	0.1	135	0.85	0.92	-0.07	-8.24
4	0.29	0.1	150	0.83	0.91	-0.08	-9.64

Confirmation test

For the confirmation of second order response surface quadratic model, four confirmation experiments have been performed for CNC turned surface roughness (Ra_1) in order to verify the adequacy of attained model. Using the point forecasting capability of the software, the CNC turned surface roughness (Ra_1) of the selected experiments has been predicted mutually within the prediction interval of 95%. The predicted value and actual experimental value has been compared, and the residual and percentage errors were calculated. The results of the confirmation test and their comparisons with the predicted values for the CNC turned surface roughness (Ra_1) is listed in Table 5. The result from Table 5 shows that both the residual and percentage error are small. The percentage error range between the actual and the predicted value of CNC turned surface roughness (Ra_1) lies between the ranges of -9.64 % to 6.67%. All the experimental values of confirmation test are within the 95% prediction interval.

It can be said that the empirical models developed has been practically precise for Ra_1. All the authentic values for the confirmation run are within the 95% prediction interval.

Conclusions

In this research, the quadralic models for CNC turned surface roughness (Ra_1) have developed so as to investigate the influences of machining parameters of Co-Cr-Mo biocompatible alloy. 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 CNC turned surface roughness (Ra_1) increases with increase in the depth of cut and feed rate.
2. The ANOVA of CNC turned surface roughness (Ra_1) revealed that feed rate and cutting speed are the most significant factors influencing the response variables investigated. The second order effect of depth of cut and feed rate have been provided secondary contribution to the responses investigated.
3. The quadratic models developed for CNC turned surface roughness (Ra_1) using RSM is reasonably accurate and can be used for prediction within the limits of the factors investigated.
4. The results of ANOVA and the conducting confirmation tests have proved that the developed models of CNC turned surface roughness (Ra_1) fits and predicted values which are close to those readings traced experimentally with a 95% prediction interval.
5. The results of machined and polished surfaces can useful for manufacturing of hip and knee implants also CNC turned Co-Cr-Mo biocompatible alloy needs a post finishing process such as polishing process for practical applications used in implant surfaces improvement.

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