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Effect of Machining Environment on Surface Integrity in Precision Turning of Co-Cr-Mo Bio-implant Alloy

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ABSTRACT

The practical applications of joint implants are resolute by the contact surface layer properties. The identified causes of failure of metal-on-metal joint implants are wear/debris induced osteolysis and aseptic loosening. A critical requirement for the long-term stability of the artificial joint is to minimize the release of debris particles. Severe plastic deformation (SPD) processes have been used to adapt the surface integrity properties by generating ultrafine or even nano-sized grains and grain size gradients in the surface region of many materials. These fine grained materials often show enhanced surface integrity properties and improved functional performance (wear resistance, corrosion resistance, fatigue life, etc.) compared with their predictable coarse grained counterparts. The present work focuses the effect of machining environments i.e. wet and dry machining on machined surface integrity of Co-Cr-Mo alloy.

Keywords: - Co-Cr-Mo alloy, Hip implants, Surface roughness, Taguchi DoE, Precision turning

1. INTRODUCTION

The most popular successful surgical treatments for patients suffering from arthritis and trauma is the arthroplasty (artificial joint replacement). On an average 1 million arthroplasties are performed annually worldwide [1]. At present, vivo metallic biomaterial used is the stainless steel followed by Ti (titanium) alloy and Co-Cr-Mo (cobalt–chromium–molybdenum) alloy [2-3]. Metal-on metal bearings have a long history in total hip replacement. In the past, total hip replacements (THR) involved the use of metal-metal Co-Cr-Mo alloys as the implant material, largely due to their relatively high strength, bio-compatibility and corrosion resistance. However, limitations in the manufacturing methods adversely affected the performance of these joints [4].

In addition, young patients with dynamic lifestyles undergoing total hip arthroplasty will require improved performance over a period of 30-40 years from now. Co-Cr-Mo alloy is the most suitable alloy often used in sliding parts, such as artificial hip and knee joints. 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 improved chemical stability. The search for a longer wearing behavior has led to the development of metal-on-metal hip implants. These devices are commonly used today in patients less than 60 years of age [5-8]. 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 renewed interest on the optimization of the wear performance of Co-Cr-Mo metal-on-metal implants used in Total Hip Replacement (THR) [10]. Currently, more and more hip implants are machined from wrought Co-Cr-Mo alloys. There are very few precision processes which can be employed for machining of Co-Cr-Mo alloy such as grinding and turning. To achieve the higher accuracy and surface finish using these processes, the available information of the process parameters is in adequate. Precision turning is one of the important processes producing the higher accuracy and surface finish on metal implants. The recent review of key publications which emphasizes on studying the Co-Cr-Mo hip implants based on laboratory as well as clinical experiences is presented below.

Geetharani et al. (2002) described the surface morphology and wear behavior of Co-Cr-Mo alloy by using polishing and coating methods (MPCVD). He used Polishing parameters as Abrasive paper (SiC) sizes as #P220, #P400C,

#P1200 and 3-micron diamond suspension and MPCVD parameters as Power is 1.5 KW with freq. as 2.45 GHz. He observed “brain-coral” like surface morphology and rough surface morphology of 5 µm. Nevelos et al. (2004) tried to address the main metallurgical design issues in metal-on-metal bearing design. These authors also show that the difference in wear performance when bi-axial motion was used for pin-on-disk test is much less pronounced than uniaxial tests, which introduces a degree of polishing into the wear mechanism as compared to a hip simulator. Reclaru and Luthy et al. (2004) reported that “inclusions” type microstructure observed in electrochemical testing and polishing methods employed on Co-Cr-Mo alloy. Howie et al. (2005) investigated twenty-four cobalt-chrome alloy McKee-Farrar matching acetabular and femoral components after 16 years in situ for wear and loss of sphericity. They classified the wear on the components into four parts: polishing wear; fine abrasive wear; multidirectional dull abrasive wear and unidirectional dull abrasive wear. Affatato et al. (2006) investigated the effect of surface profile parameters on amount of wear in metal artificial hip joints. The surface roughness of the metallic ball heads was qualified in terms of average surface roughness R_a, total surface roughness Rt and skewness Rsk. The authors used a linear regression analysis to correlate the wear and the surface profile parameters. The authors observed that all three parameters R_a, R_t and R_{sk} were capable of predicting the observed variability of the weight loss in a statistically significant way ($p < 0.01$). Ohmori et al. (2006) observed the surface roughness (R_a) of 7 nm and also reported that surface roughness is superior than polished surface roughness. He used the ELID grinding process in the experiments. Lee and Nomura et al. (2007) found significant improvement in mechanical properties of Ni free Co-Cr alloy even under the as-cast condition. They have investigated the hardness and tensile strength of Co-Cr-Mo alloy by preparing different chemical compositions. They have used vacuum induction melting process for the experiments. Grgazka et al. (2008) analysed the influence of chosen modifiers on mechanical properties of composite materials on the base of Co-Cr-Mo alloy. Results show that composites can be the alternative materials for biomedical applications. Young Chan et al. (2010) machined Co-Cr-Mo alloy using elliptical vibration cutting process. A fine mirrored surface (with a maximum surface roughness under 25 nm P-V) was maintained up to a cutting length of about 14 m. Shu Yang et al. (2012) have done systematic experimental study to investigate the influence of different burnishing parameters on distribution of grain size, phase structure and residual stresses of the processed material. The wear performance of the processed Co-Cr-Mo alloy was tested via pin-on-disk wear tests. The results from this work show that the cryogenic burnishing can significant improve the surface integrity of the Co-Cr-Mo alloy which would finally lead to advanced wear performance due to refined microstructure, high hardness, compressive residual stresses and favorable phase structure on the surface layer.

2. EXPERIMENTAL WORK

2.1 Material, Tooling and Design

Precision turning process is employed for investigation on surface integrity of Co-Cr-Mo alloy in dry and wet cutting environments. A production type CNC turning precision lathe (Model Jobber XL Make Micromatic) having spindle speed 5000 rpm and 13 KW capacity is used for conducting the experiments.

Table -1 Standard experimental design of L9 (3^4) Orthogonal Array

Expt. Run	Column			
	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

A Taguchi experimental design L9 orthogonal array is used for designing the parameter combinations for each experimental trial (See Table 1). In this orthogonal array, number of factors are 4 and number of levels are 3. Hence total numbers of runs are 9. The response variable chosen is the arithmetic average surface roughness R_a for both the experiments on precision turning. The input control factors selected for both experiments are: depth of cut (200-600-1000 µm), feed rate (0.05-0.1-0.15 mm/sec), cutting speed (95-190-285 m/min) and cutting tool material (Ceramic-Carbide-CBN). Table 2 shows the experimental runs with the assigned factors to each of the columns of OA for precision turning process.

Table -2 Experimental design with actual factor values for precision turning experiments in dry and wet cutting environment

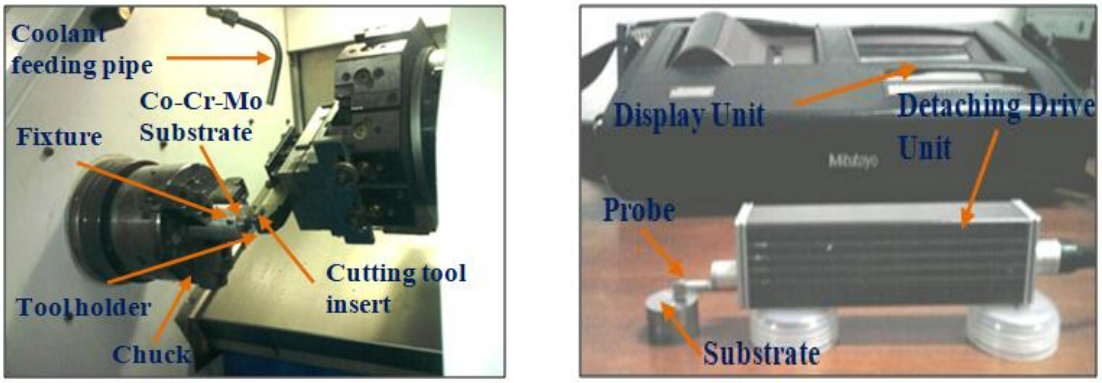
Expt. Run	Depth of cut (µm)	Cutting speed (m/min)	Feed (mm/sec)	Tool Material
1	200	95	0.05	Ceramic
2	200	190	0.1	Carbide
3	200	285	0.15	CBN
4	600	95	0.1	CBN
5	600	190	0.15	Ceramic
6	600	285	0.05	Carbide
7	1000	95	0.15	Carbide
8	1000	190	0.05	CBN
9	1000	285	0.1	Ceramic

Table -3 Chemical composition of Co-Cr-Mo alloy (ASTM F75)

Elements	C	Si	S	Cr	Mo	Ni	Co
%	0.34	1.0	0.007	27.8	4.9	0.9	Bal

The work material used in the present investigation is bio-implant alloy, which is a low carbon wrought version of ASTM F75 Co-Cr-Mo Alloy. The basic chemical composition of this Co-Cr-Mo alloy is shown in Table 3. A Co-Cr-Mo alloy bar (23 mm diameter) is used to prepare samples which have a diameter of 20 mm and a thickness of 10 mm.

2.2 Experimental Procedure



(a) **(b)**

Fig -1 **(a)** Closed view of set up of Precision Turning Operation, and **(b)** Surface Roughness Tester

Initially nine workpieces to the required length from a long rod of Co-Cr-Mo are cut as substrates. These substrates are exactly made to size Ø20 x 10 mm thickness. An aluminium turning fixture to hold these substrates was fabricated to size Ø50 x 120 mm length to facilitate holding of substrates during turning operation. Four screws are used to hold the substrate tight against the fixture. Fixture along with substrate is mounted on the three jaw chuck of the machine. After proper mounting pressure, fixture is trued properly for perfect rotation as shown in Fig. 1 a. To begin with a rough cut of 150 micron on substrate face was taken on each substrate and finish cut was taken on surface of 20 mm diameter. Finally each substrate is machined in dry and wet cutting environment as per the experimental trials given in Table 2. After each experiment the machined substrate is kept in a vacuum tight small container. After machining trials, the machined surfaces were measured to analyze profile on surface tester having model no. SJ- 210 made by Mitutoyo (See Fig. 1 b). The 2D profiles are traced for the 10 mm assessment length with 0.25 mm sampling length.

2. RESULTS AND DISCUSSION

The surface characteristics especially the surface roughness of Co-Cr-Mo substrates machined using precision turning is presented in this section. Table 4 shows the roughness values (R_a) for each substrate machined in dry as well as in wet environment.

Table -4 Roughness values of precision turned substrates in dry and wet cutting environments

Expt. Run	Roughness Values (R_a) in µm	
	Dry Machining	Wet Machining
1	1.67	1.46
2	0.68	1.59
3	1.32	0.74
4	1.69	1.08
5	2.89	2.65
6	1.36	1.71
7	1.55	2.71
8	0.76	1.76
9	2.55	2.34

2.1 Analysis of Surface Roughness in Dry Machining Environment

The main effects plots for surface roughness (ANOM) and the table of analysis of variance (ANOVA) are shown in Fig. 2 and Table 5 respectively. It is observed from the ANOVA that none of the factors show statistical significance on surface roughness at 95% confidence level as the P-value in the ANOVA for any input variable is not less than 0.05. But among the selected parameters the type of cutting tool shows statistical significance at 95 % C.I. The percentage contribution of the input variables influencing the surface roughness is depth of cut: 20.16 %, cutting speed: 3.15 %, feed: 15.45 % and tool material: 61.22 % showing the higher impact of tool material on the surface roughness. The effect of each input factors on the surface roughness is presented using ANOM plots.

Table -5 ANOVA for surface roughness in dry machining environment

Source	**DF**	**SS**	**MS**	**F**	**P**	**% Cont.**
Depth of cut, *d*	2	0.8619	0.43098	0.5	0.62	20.1
Feed, *f*	2	0.6604	0.33025	1.3	0.36	15.4
Cutting speed, *s*	2	0.1349	0.0674	0.0	0.92	3.15
Tool Material, *t*	2	2.6167	1.3083	5.2	0.07	61.22
Residual error	0	-	-	-	-	-
Total	8	4.27414	-	-	-	-

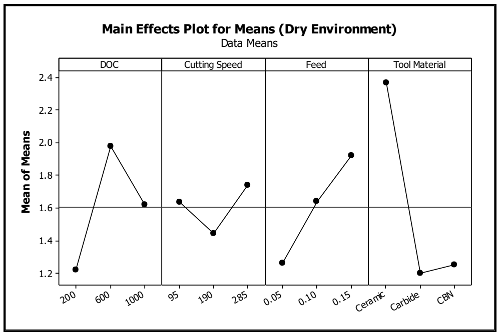


Fig -2 Main effects plot of surface roughness in dry environment

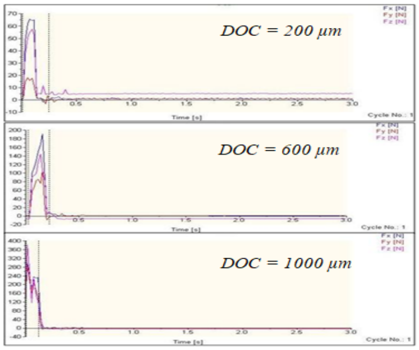


Fig -3 Cutting forces at different depth of cuts in dry machining environment

Effect of DOC on surface roughness

The main effects plot (Fig. 2) shows the increase in the surface roughness from 1.2 µm to 2 µm, when the depth of cut increases from 200 µm to 600 µm. But further increase in depth of cut from 600 µm to 1000 µm, causes reduction in the surface roughness to 1.6 µm.

An increase in the cutting forces is observed due to increase in the depth of cut. Fig. 3 shows the measurement of cutting forces by tool dynamometer. This is probably due to corresponding increase in the cross sectional area of the deformation zone. This led to severe plastic deformation during machining that has adverse effect on increase in surface roughness. However, it is seen from the graph that when the depth of cut increases from 600 µm to 1000 µm, surface roughness decreases due to expose of submicron size defects below the machined surface. Therefore it could be postulated that there is a critical value of the depth of cut beyond which the surface roughness decreases considerably.

Effect of Cutting Speed on surface roughness

When the cutting speed increases from 95 m/min to 190 m/min, surface roughness reduces from 1.65 µm to 1.45 µm. However, there is a sudden increment in surface roughness from 1.45 µm to 1.7 µm when the cutting speed moves from 190 m/min to 285 m/min. It was observed that at lower and higher cutting speeds a continuous chipping is generated. Due to this there is a continuous material removal from the surface directly affected on higher peaks. But at considerable cutting speed it was observed that there is a generation of fair chipping affected the minimal peak that produced minimum surface roughness values.

Effect of Feed on surface roughness

The effect of feed rate is linear on the roughness of machined surface. When the feed rate increases from 0.05 mm/sec to 0.1 mm/sec, surface roughness considerably increases from 1.25 µm to 1.65 µm. Also an increment in feed rate till 0.15 mm/sec, the surface roughness again increases to 1.9 µm. At the lower feed rates there is reduction in cross sectional area of deformation zone i.e. minimum surface roughness. At the highest level of feed rate the material removal area is more which cause in homogeneity in surface generation mechanism due to involvement of other factors during machining. Therefore, the roughness is maximum at this condition.

Effect of Tool material on surface roughness

The tool material shows significant effect on the surface roughness. The main effect plot shows that when the tool material is ceramic, surface roughness value is quiet higher up to 2.4 µm. When the tool materials are carbide and CBN then there is a drastic reduction in roughness values up to 1.2 µm and 1.25 µm respectively. Tool materials play a vital role in machining of Co-Cr-Mo alloy. If the hard tool can be employed in machining operations then it will affect the final surface integrity of machined components. In this experiment tool material is having higher impact on machined surface roughness.

2.2 Analysis of Surface Roughness in Wet Machining Environment

The main effects plots for surface roughness (ANOM) and the table of analysis of variance (ANOVA) are shown in Fig. 3 and Table 6 respectively. It is observed from the ANOVA, that none of the factors show statistical significance on surface roughness at 95% confidence level as the P-value in the ANOVA for any input variable is not less than 0.05. As far as the impact of process parameter is concerned percentage contribution of the input variables influencing the surface roughness is depth of cut: 41.59 %, cutting speed: 7.85 %, feed: 6.84 % and tool material: 43.70 % showing the higher impact of tool material on the surface roughness. The effect of each input factors on the surface roughness is presented using ANOM plots. Both depth of cut and the tool material are equally important to generate machine surface as can be seen from ANOVA.

Table -6 ANOVA for surface roughness in dry machining environment

Source	DF	SS	MS	F	P	% Cont.
Depth of cut, *d*	2	1.5110	0.75551	1.6	0.30	41.5
Feed, *f*	2	0.2852	0.14260	0.3	0.74	6.84
Cutting speed, *s*	2	0.2486	0.12434	0.2	0.77	7.85
Tool Material, *t*	2	1.5874	0.7937	1.8	0.27	43.70
Residual error	0	-	-	-	-	-
Total	8	3.63236	-	-	-	-

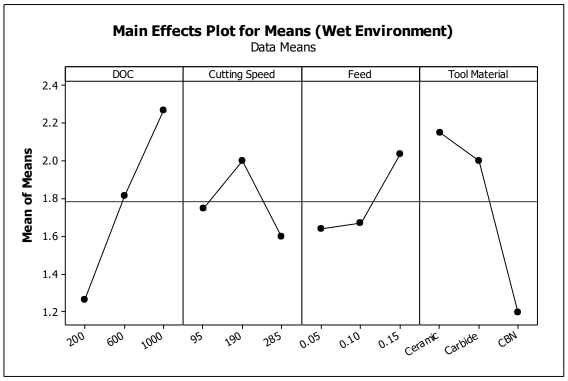


Fig -3 Main effects plot of surface roughness in wet environment

Effect of DOC on surface roughness

Depth of cut show linear trend on the roughness of machined surface. When the depth of cut increases from 200 µm to 600 µm, surface roughness considerably increases from 1.25 µm to 1.85 µm. However, further increment in feed rate up to 1000 µm, the surface roughness again increases to 2.30 µm. In wet environment when the depth of cut is minimum, continuous chips are produced due to smooth shearing action. Therefore, these chips generated by shear stresses, the former by separation along the simple shear plane, and later in shear zone. Therefore, the machined surface is smooth and accurate.

Effect of Cutting Speed on surface roughness

When the cutting speed increases from 95 m/min to 190 m/min there is an increase in surface roughness from 1.75 µm to 2 µm. However, there is a drastic decrease in surface roughness from 2 µm to 1.5 µm when the cutting speed increases from 190 m/min to 285 m/min. This can be attributed to the fact that the spindle speed has less effect on surface roughness.

Effect of Feed on surface roughness

The effect of feed is linear on the roughness of machined surface. When the feed increases from 0.05 mm/sec to 0.1 mm/sec, surface roughness considerably increases from 1.6 µm to 1.65 µm. However, further increment in feed rate up to 0.15 mm/sec, the surface roughness again increases to 2 µm. It was observed that when the feed rate is high a sudden temperature rise in between tool and chip interface on account of higher friction. In this case burned black chips are generated while machining. However, when the coolant is applied in machining there is a possibility of sudden temperature fall in machining zone and chips fragment remain same on the machined surface. Due this at higher feed rate, the surface roughness value is also increased.

Effect of Tool material on surface roughness

The MEP’s shows that when the tool material is ceramic, surface roughness value is on the higher side (2.2 µm). However in the case of carbide and CBN, there is a drastic reduction in roughness values up to 2 µm and 1.2 µm respectively. Also in wet machining, tool material is having higher impact on machined surface roughness due to the material behavior changes in machining with different tool materials.

4. CONCLUSIONS

Following conclusions can be drawn from the investigation carried out on surface characteristics assessment of Co-Cr-Mo alloy by precision turning process.

- As far as the effect of input factors is concerned, the tool material shows dominating effect on surface roughness for the precision turning operation in dry environment, whereas the factor depth of cut and feed rate both have nearly predominant influence on the machined surface roughness.
- Also in wet machining environment, tool material shows dominating effect on surface roughness for precision turning, whereas the factor depth of cut and cutting speed both have nearly predominant influence on the machined surface roughness.
- It is found that minimum surface roughness values obtained are 0.68 and 0.74 in dry and wet machining environment respectively. Therefore, for achieving the higher surface accuracy on Co-Cr-Mo alloy dry machining is preferable.
- In both experiments i.e. in dry and wet machining the tool material of CBN has given the better results on final quality of the machined surface of Co-Cr-Mo alloy.

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