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The application of Taguchi approach to optimise the processing conditions on bonnet polishing of CoCr alloys

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Abstract. This paper applied the Taguchi approach to investigate the effects of polishing parameters to obtain the optimal processing conditions for CoCr alloy polishing using a multi-axis CNC controlled corrective polishing machine. The polishing medium used was 1m diamond paste with a Microcloth(polishing cloth). Surface finish parameter Sa was chosen as the criterion for process optimization. The experimental results indicate that the optimal polishing conditions for CoCr alloy polishing is 5^0 precess angle, 800 rpm head speed, 0.2mm tool offset and 1.5 bar tool pressure. With this optimal condition, a confirmatory experiment was conducted. The surface roughness Sa reduced from an initial 24nm to 7nm and reduction ratio was 70.8% which was very close to the estimated ratio of 64%.

1. Introduction

A crucial factor affecting the performance and reliability of CoCr alloy when it is used as the bearing surface for artificial joints(knees or hips) is the quality of the machined surface. It is a well documented fact that many failures of prosthetic joints originate from surface imperfections [1]. Therefore it is of paramount importantance that the surface finish should be of the highest quality with minimal defects so that the longevity of prosthetic joints can be improved to levels of 20 years plus.

Conventional polishing bearing surfaces of artificial joints are mainly carried out by semi-automated polishing machines using purpose designed fixtures for specific geometries or in some circumstances final polishing is carried out manually which is a time-consuming and labour-intensive work. To minimize the processing time, significantly improve flexibiligy and surface quality, a technique of CNC corrective polishing which known as bonnet polishing has been developed. The bonnet polishing originally developed by Walker et al. is being exploited commercially by Zeeko Ltd Company in the optics production industry [2, 3, 4]. In terms of the actual material removal process bonnet polishing has a larger and submissive contact area so that higher polishing efficiency and improved polished surface roughness and local curvature precision can be achieved.

When using bonnet polishing to finish the surfaces of artificial joints made of CoCr alloy, several key polishing parameters, such as precess angle, head speed, tool offset, head pressure, point spacing, track spacing and surface feed, need to be considered. Full analysis of all factors using classical approaches would be time consuming. In order to reduce experimental time a design of experiments (DOE) using Taguchi approach was utilised[5]. Compared to factorial and fractional factorial design of experiments, Taguchi methods simplify and standardize the procedure of the experiments reducing the number of tests when the number of factors is large.

Taguchi approach has been used to optimize several finishing process. Jiang et al. have applied Taguchi approach to optimise the finishing conditions in Magnetic Float Polishing [6]. Tsai et al. used the Taguchi methods to identify the optimal parameters of abrasive jet polishing and investigate the respective effects of the additive type and the abrasive particle material and area in polishing[7]. Nalbant et al. employed the Taguchi methods to find the optimal cutting parameters for surface roughness in turning[8]. Kwak et al. evaluated the effect of grinding parameters and determined the optimum grinding conditions for minimizing the geometric error based on the Taguchi method [9]. The purpose of the present paper is to investigate the effect of bonnet polishing parameters and to find the optimal processing conditions for polishing CoCr alloy. This investigation will potentially increase the efficiency of manufacturing of prosthetic hip joint and knee joints especially where non spherical geometries are required.

2. Experimental details

2.1 Experimental setup and polishing parameters

The experiments were conducted on a Zeeko IRP 200 polishing machine (Fig.1). This machine is a typical bonnet polishing machine that uses a rotating bulged bonnet with internal pressure as the polishing tool. The bonnet is flexible and covered with polishing cloths. When polishing, the inflated bonnet can conform to the variable curvature of a curved surface of a component. A key feature of this machine is that it has high polishing efficiency as well as the ability to generate smooth surface texture. However this polishing approach has largely been limited to optics polishing of glasses[4, 10]. To achieve high accuracies of form and surface texture, several machine parameters need to be set. These parameters includes precess angle, head speed, tool offset and head pressure and will be outlined in the following:

Fig. 1: Zeeko IRP 200 machine

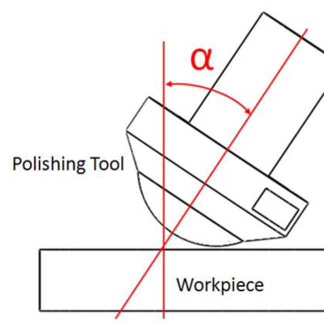

Fig. 2: Precess angle

Precess angle: This parameter describes the angle of the centre line of bonnet and the perpendicular line of the workpiece (Fig.2).

Head speed: This parameter relates to the speed of the rotation of polishing tool (bonnet)(rpm)(Fig.3).

Head pressure: This is the pressure of bonnet which inflates the bonnet into a spherical shape(bar, 1bar = 0.1Mpa)(Fig.4).

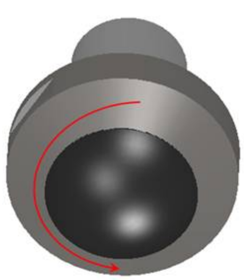

Fig. 3: Head Speed

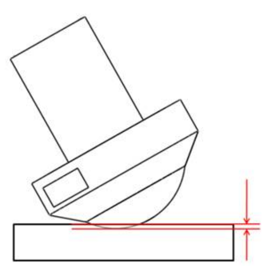

Fig. 4: Tool Offset

Tool offset: This parameter relates to the deformation deep of bonnet when the bonnet touched the workpiece (mm)(Fig.5).

Table 1: Polishing parameters with three levels

Parameters	level1	level2	level3
Precess angle(degs)	5	10	15
Head Speed(rpm)	800	1200	1600
Tool offset(mm)	0.1	0.15	0.2
Tool pressure(bar)	0.5	1.0	1.5

Fig. 5: Head Pressure

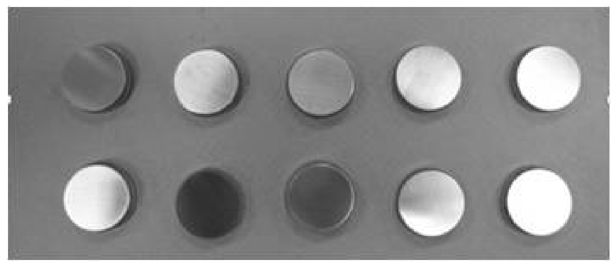

Fig. 6: CoCr samples before polishing

According to the previous experimental experience[11], precess angle, head speed, tool offset and tool pressure were chosen to design the experiments. Each the above parameters has three levels as shown in Table 1. Other polishing parameters are fixed and given in Table 2. All specimens were polished using a raster toolpath first and then spiral toolpath with the same parameters except point spacing (0.3mm in raster and 0.1mm in spiral).

Table 2: The fixed polishing parameters

Fixed factors	Values
Tool overhang	3mm
Point spacing	0.3mm(raster) and 0.1mm (spiral)
Surface feed	1500mm/min
C-axis speed	500rpm
Number of passes	50

2.2 Experimental design

The experimental design was based on Taguchi method. The samples used in the experiments were cylindrical CoCr alloy and the diameter of planar surface was 26mm (Fig.6). The polishing medium was 1m diamond paste on a Microcloth polishing cloth. With the above parameters and their three levels, a standard 3-level Orthogonal Array (OA) L9(3^4) was selected to construct the design of experiments(Table3). This array has 9 rows and each row represents a run condition with parameter levels indicated by the numbers in the row. The vertical columns related to the parameters specified in the investigation.

2.3 Experimental results and ANOVA

The experimental results were measured using the surface finish parameter Sa. Table 4 presents the initial and final surface roughness Sa, variation, S.R. ratio and S/N ratio. Each specimen was measured at points across the surface by optical interferometery (Talor Hobson CCI) one point was in the centre and the other four points randomly distributed around the periphery. The values shown in the table were the mean of the five points. The experimental results were

Table 3: L9 Orthogonal Arrays used

Runs	Precess angle(degs)	Head speed (rpm)	Tool offset(mm)	Tool Pressure(bar)
1	5	800	0.1	0.5
2	5	1200	0.2	1.0
3	5	1600	0.3	1.5
4	10	800	0.2	1.5
5	10	1200	0.3	0.5
6	10	1600	0.1	1.0
7	15	800	0.3	1.0
8	15	1200	0.1	1.5
9	15	1600	0.2	0.5

Table 4: The experimental results of Sa parameter

Runs	Initial (nm)	Final (nm)	Variation	S. R. ratio (%)	S/N ratio
1	33.11	18.79	14.31	43.2	-7.28
2	18.75	11.28	7.47	39.8	-7.99
3	22.02	11.62	10.38	47.2	-6.52
4	25.98	11.26	14.72	56.6	-4.93
5	11.84	7.92	3.94	33.2	-9.57
6	17.27	11.96	5.31	30.7	-10.24
7	12.84	8.55	4.29	33.4	-9.53
8	14.59	8.72	5.87	40.2	-7.91
9	17.35	9.94	7.41	42.7	-7.39

analysed based on ANOVA of Taguchi method output. For use in orthopaedic industries, the surface roughness of prosthetic joints should be as smooth as possible with little variation. As shown in table 4, the ratio of variations of Sa has been calculated and converted into an S/N ratio. S/N ratio signifies the Signal to Noise Ratio the concept of which has been applied in the area of acoustics, electrics, mechanics and other engineering disciplines over years [5]. The S/N value should be large. In the analysis, the S/N ratio is taken as a single data point for each trial condition.

Table 5 gives the main effects on the S/N ratio. The optimal experimental condition using Microcloth with 1m diamond paste shown in Table 5 is $A_1B_1C_2D_3$, i.e. 5^0 precess angle, 800 rpm head speed, 0.2mm tool offset and 1.5 bar tool pressure.

Analysis of Variance (ANOVA) is a statistical method which used to analyze the variance of experimental results. The main objective of ANOVA is to find the percentage of contribution of individual factor related to the total output. In the analysis of variance, many quantities are calculated and organized in a standard table. Table 6 showed the ANOVA results of the polishing experiments. The full ANOVA generally involves Degree of Freedom (DOF), Sum of Squares, Variance, F-value, Pure Sum of Squares and Percent Contribution. As can be seen in

Table 5: The main effects of S/N ratio

Parameters	Level1	Level2	Level3
A: Precess angle (degs)	-7.27	-8.25	-8.28
B: Head speed (rpm)	-7.25	-8.49	-8.38
C: Tool offset (mm)	-8.48	-6.77	-8.54
D: Tool Pressure (bar)	-8.08	-9.25	-6.46

Table 6: ANOVA

Variables	DOF	Sum of squares	Variance	F-value	Pure sum of squares	Percent contribution	Rank
Precess angle	2	1.98	0.99	2	0.99	4.44%	4
Head speed	2	2.38	1.19	2.41	1.39	6.26%	3
Tool offset	2	6.03	3.02	6.1	5.04	22.68%	2
Tool pressure	2	11.85	5.92	11.99	10.86	48.84%	1
Error	2	0	0	1	3.95	17.78%	
Total	8	22.24	2.78				

table 6, the greatest contribution for surface roughness is tool pressure, accounting for 48.84%, followed by tool offset (22.68%), head speed (6.26%) and precess angle (4.44%).

2.4 Confirmatory experiment

Table 7: The results of confirmatory experiment

Before polishing(nm)	After polishing(nm)	S.R. ratio(%)	Estimated reduction ratio(%)
24	7	70.8	64

To investigate the reliability of the Taguchi experimental results, a confirmatory experiment was conducted under the optimal factor level combination acquired from the Taguchi trials. The corresponding results are given in table 7. It is observed that a slight discrepancy exists between the estimated ratio and surface roughness improvement ratio. Fig.7 shows 3D maps of the specimen measured by CCI before and after confirmatory experiments.

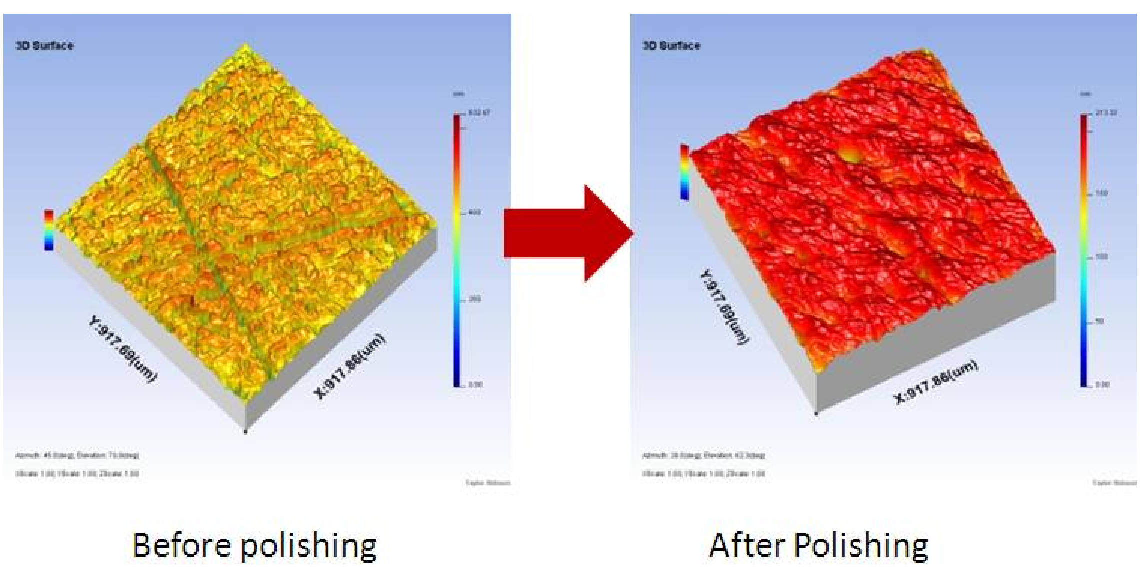

Fig. 7: 3D map measured by CCI before and after polishing under the optimal condition

3. Conclusions

This study investigated the parameter optimization of the bonnet polishing of a CoCr alloy. The experimental design was based on Taguchi method which four parameters (precess angle, tool offset, tool pressure, and head speed) with three levels were chosen to design an L9 array.

9 runs were carried out. The main effects of S/N ratio show that the optimal condition for CoCr polishing is 5degs of precess angle, 800rpm of head speed, 0.2mm of tool offset and 1.5 bar of tool pressure. The ANOVA results indicate that the greatest contribution for surface roughness is tool pressure, accounting for 48.84%, followed by tool offset (22.68%), head speed (6.26%) and precess angle (4.44%). A confirmatory experiment has verified the reliability of the optimal condition with only a slight discrepancy. These parameters have been used to confirm the results and provide the basis for the finishing processes to be implemented in corrective polishing of orthopaedic bearing surface.

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