MACHINING OF “FREEFORM” BIOLOGICAL SURFACES ON AN ADVANCED 7-AXIS CNC POLISHING MACHINE

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Abstract:

Oesteo-arthritis is the progressive degeneration of the natural cartilage tissue which plays a critical part in the load bearing function of hip and knee joints. Solutions to the problems caused by this tissue breakdown are administration of anti-inflammatory drugs or more normally and especially in advanced cases is the replacement of all or part of the joint with artificial joints. Worldwide, the total number of implant procedures is around 800,000. Today the life expectancy of such systems is 5-15 years. The manufacturing route utilises a 7 axis CNC Zeeko polishing machine to polish freeform knee joint surfaces to the required form and finish. The paper discusses the process constraints and optimal settings and the surface generation process.

Keywords: ***Hips, Knees, CNC polishing, freeform surfaces***

1 INTRODUCTION

The thrust of much recent research in the field of hip and knee replacements has been to use a hard on hard bearing couple of metal on metal or ceramic on ceramic [1]. To enable this combination extremely low surface roughness’ and excellent conformance of the part is necessary. This can be achieved in the case of hips though with some difficulty. For knee systems the use of hard on hard bearings has up till now been precluded by the need to obtain the conformance and roughness constraints on the effectively free form knee surfaces In the present work an advanced 7-axis CNC polishing machine developed by Zeeko Ltd. is being used to develop a polishing and freeform correction process to obtain these excellent conformances and surface finishes with an overall goal of increasing the lifetime of the replacement knee joints through facilitating the use of “hard on hard” bearing couples.

1.1 The Zeeko Machine

The machine uniquely uses an inflated bulged polymer polishing head as the lap medium in combination with water based polishing slurries. The inflated head can be adjusted to vary the polished spot size. Novell precessions control software allows the polishing head to polish off axis whilst maintaining close form control. For free form surfaces the head is driven by a new generation of intelligent software and is capable of moving in multiple axes, the adaptive polishing head allows components to be manufactured to a precision of $\lambda/4$ [2].

Fig. 1: Zeeko IRP200 Polishing Machine

The key features of the Zeeko polishing Machine are; an adaptive pressure-tool tuned automatically to local surface errors. Precession ability allows multi-directional lapping for excellent texture where the resulting tool footprint is Gaussian-like with no sharp central zero velocity artefact. The result is a polished surface corrected form, and excellent texture demonstrating no directional properties.

Fig. 2: Inflated bulged polymer head design

1.2 Machine Parameters of Zeeko IRP 200 7-axis CNC robotic polisher

To achieve the polishing accuracies and surfaces textures there are several machine parameters that need to be adjusted to achieve optimum performance on the work piece. The settings of these parameters will vary dependant on the form and material of the workpiece. These parameters are outlined in the next sections of the paper.

1.2.1 H-axis head speed

This parameter relates to the speed of rotation of the H-axis (tool) of the CNC machine. The axis can be either rotated clockwise or anti-clockwise but for the present tests this was kept constant in the anti-clockwise direction and only the speed was changed. The speed of the H-axis is measured in revolutions per minute (RPM)

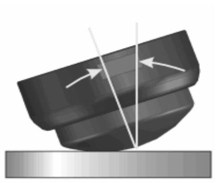
Fig. 3: H-Axis Head Speed

1.2.2 H-axis head pressure

This parameter is related to the pressure behind the polish head bonnet on the H-axis (tool) of the CNC machine. The head is supplied by a constant pressure which inflates the bonnet into a spherical shape on which the polishing media is attached. The pressure was measured in Bar.

Fig. 4: H-Axis head pressure

1.2.3 Precess Angle



This parameter is related to the angle at which the centre line of the bonnet and the 90 degree perpendicular between part and bonnet intersect. The unit of measure is degrees.

Fig. 5: Precess Angle

1.2.4 X-Y Spacing

This parameter is a combination of two separate machine factors but was grouped together for the Taguchi experiment. In the case of the X spacing this depicts the spacing between “polishing” points of the raster polish across the horizontal of the part being polished. In the Y case it also determines spacing between “polishing” points but this time in the vertical of the part being polished. Both X and Y spacing are measured in millimetres (mm).

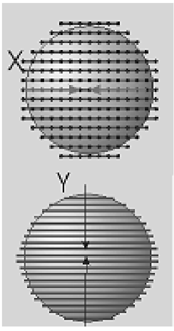
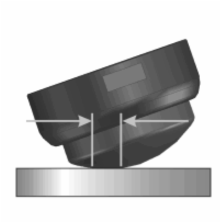


Fig. 6: X-Y Spacing of data points

1.2.5 Spot Size



This parameter is determined by the size of the spot that is created when the surface of the polishing head (bonnet) comes in contact with the surface to be polished. The spot is measured in millimetres (mm).

Fig. 7: X-Y Spacing of data points

1.2.6 Precess Positions

This factor determines how many positional changes the tool makes for each tool path. The value can either be 1, 2 or 4 precesses and increasing this helps to give a uniform material removal that improves surface texture due to avoiding the zero velocity point of the polishing bonnet. The tool can also be used in a pole down position where there is a zero degree precess angle that mimics current lapping techniques.

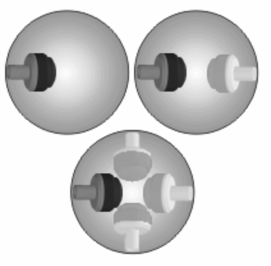


Fig. 8: Precess Positions

1.3 Taguchi Optimisation of the Polishing Process

The purpose of using Taguchi analysis was to optimise the roughing/polishing process for the biocompatible metals used by using a minimum of trials.

Previous tests [3] were carried out on a plano piece of 316L stainless steel, using one precess position for precess angles of 5, 10 and 15 degrees as well as a pole down polish, H-axis head speeds of 500, 1000, 1500 and 2000 RPM, H-axis head pressures of 0.5, 1, 1.5 and 2 bar, X-Y spacings of 0.1, 0.2, 0.3 and 0.4mm and spot sizes of 6, 8, 10 and 12mm. An L16b orthogonal array with 16 tests was run three times for an average set of results.

1.3.1 Taguchi results

Table 1 Summary of Taguchi Test Results

Parameter	Consideration		
	Stability, Predictability and reduction of errors	Best Result	Best Result on Process Time
H-axis head speed (RPM)	1500- 2000	2000	2000
H-axis head pressure (Bar)	0.5 – 1	0.5	0.5
Precess Angle (Degrees)	0 (Pole Down) – 5	10	15
X-Y Spacing (mm)	0.1 – 0.2	0.2	0.2
Spot Size (mm)	8 - 10	12	10
Process Time (approx. minutes)	20	28	11.5

From Table 1, and using a process time of 28 minutes, the best result of Sa = 27.1nm were obtained as measured on a white light interferometer (4mm x 4mm). The most repeatable and predictable result gave a surface finish of 30nm took and average process time of 20 minutes although looking at process time for manufacturing purposes a result of 34.6nm was achieved in a more realistic time of 11.5 minutes. These optimal conditions were used throughout as a base surface preparation prior to final polishing.

2 METROLOGY OF FREEFORM SURFACES

A freeform surface can be defined as one that deviates significantly from a rotationally-symmetric form; this therefore includes parts that are off-axis sections of rotationally-symmetric aspheric parents, such as off-axis paraboloids, hyperboloids, etc. Using this definition is relevant as the challenges of producing off-axis and generalized free-form parts so as prosthetic knee joint replacements are vary similar [2]. There are several problems related to freeform metrology these include suitable reference artefacts to calibrate the metrology equipment and the difficulty of some freeform surfaces having no axis of symmetry, creating problems of fixing a reference location for surface geometry measurements especially those related to co-ordinate metrology.

The National Physics Laboratory UK have a current Engineering measurement program which is identifying these current problems and looking at solutions [4]. Development of the proposed freeform national measurement facilities and the truly freeform verification standards will permit both rapid characterisation and provision of measurement traceability for commercial complex-freeform measuring systems, thus supporting the UK's engineering fraternity in the rapidly growing field of advanced freeform machining [5]. Table 2 summarises the advantages and disadvantages of the metrology equipment available to the present authors.

2.1 Metrology equipment

Table 2: Metrology equipment summary

Metrology Equipment	Advantages	Disadvantages
White Light Interferometer	Easy functionality, quick repeatable measurements and good representation of surface texture.	Restriction on measurement areas (7mm x 7mm flat surface and 0.25mm x 0.25mm curved surfaces used in most implants)
Diamond Stylus Surface Profiler	Larger surface area measurements, excellent for form measurements and material removal.	Long measurement times. Possible specimen damage, contamination
High precision CMM	Ability to scan surface from a CAD model particularly useful for freeform biological surfaces.	Limitations on resolution uncertainty of measurements and difficulty of referencing axis.

Table 2 shows the metrology equipment available for measuring the form texture and finish of freeform surfaces

3 COBALT CHROME PIN ON DISC TESTING

Well before clinical testing can take place in the design or manufacture of Total Hip Replacement (THR) or Total Knee Replacement (TKR). The material to be used needs to be thoroughly tested for its wear and bio-compatibility. Preliminary wear screening is usually carried out using a pin on plate wear test rig. A schematic of such a test set up is shown in figure 9. This test piece is used an initial demonstrator for the present polishing technology.

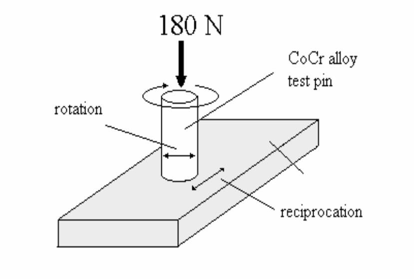


Fig. 9: Schematic setup of pin on plate wear rig

3.1 Cobalt chrome pin design

The design for the cobalt chrome pin component used for pin on plate wear testing can be seen in figure 3. The pin is of cylindrical shape with a diameter of 20mm and a spherical surface with a radius of curvature of 25mm at one end and a location keyway on the outside diameter.

Fig. 10: Images of pin for wear testing

4 INITIAL TRIALS ON COBALT CHROME KNEE REPLACEMENT

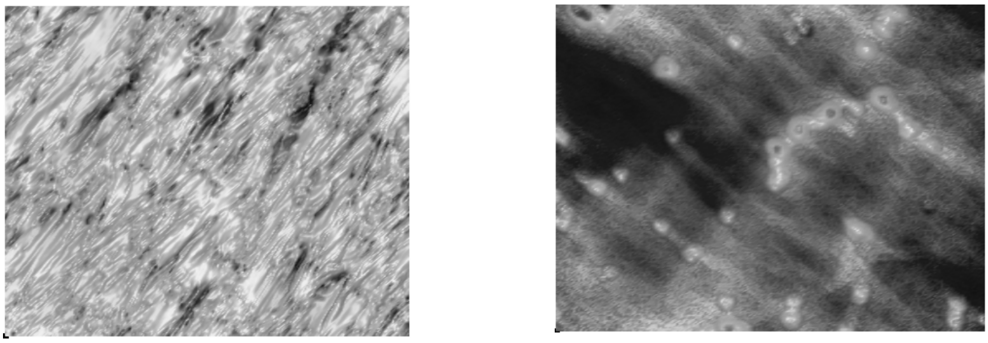
RhinoCAD 3D was used to create a test polishing area on a semi finished CoCr knee component and the following stages were used to implement the test polishing area. The process started with importing a CAD model of the whole knee component, then a series of steps including trimming, centring, contouring and finally creating an offset Non Uniform Rational B-Spline (NURBS) surface was carried out. This was then imported into the specialised ZeeCAD software to generate a tool path for the polishing of the test area. The ZeeCAD software was used to create a CNC polishing program for a single condile on the knee surface to be polished. The process involves probing with the tool for non-linear corrections in tooling and fixturing, outlining the parameters defined in section 1.2 and creating a tool path that is feed into the CNC controller. When selecting the parameters the results from the Taguchi testing were taken into consideration. The rest of this paper discusses the results obtained from both the cobalt chrome pin polishing and the initial knee component test polishing.

5 RESULTS OF POLISHING

With the generation of the CNC programs and consequent tool paths polishing trials on the cobalt chrome pins and the initial cobalt chrome knee component could be conducted.

5.1 Cobalt chrome pin polishing

Seven stages of polishing were used for the cobalt chrome pins. The stages ranged from a 120 grit roughing stage with a nickel bonded diamond polishing pad to a final polishing stage using a 3000 grit resin bonded diamond cloth. The slurry medium for each stage was recycled tap water. Figure 11 shows interferometer images of after the first roughing stage with a surface finish of Sa = 345nm and an image of the final pole down polish with a surface finish Sa = 2.8nm.



Pre polish Sa = 345 nm 0.25x0.25mm

Post polish Sa= 2.8nm 0.25x0.25mm

Fig. 11: White light interferometer images of cobalt chrome pin polishing process

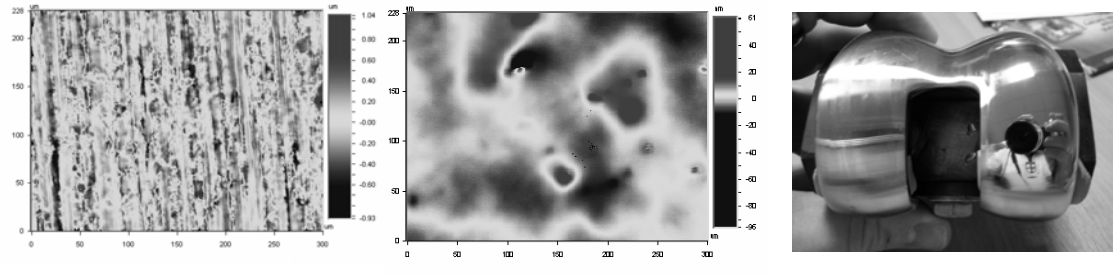
Table 3 shows a summary of repeatability machine polish tests (MP) and a comparison with hand polished pins (HP). It is considered the variation in the machine polished results is caused by edge effects on the pins. The results show that for the machine polished pins the roughness obtained was within the bounds considered acceptable for these types of surfaces [6].

Table 3: Summary or repeatability on surface finish of cobalt chrome pins.

	Interferometric Surface Measurement, Surface Roughness Sa/nm					
Pin Number	Quadrant A	Quadrant B	Crown	Quadrant C	Quadrant D	Average
HP1	20.1	27.1	17.2	36.3	24.1	25.1886
HP2	17.8	13.6	19.2	36.8	24.1	22.269
HP3	12.6	40.4	15.1	16.5	18.1	20.5364
MP1	3.2	3.8	2.8	3.3	4.6	3.5426
MP2	17.7	5.8	10.0	10.7	11.2	11.0816
MP3	23.1	7.8	10.3	11.7	15.5	13.6758

5.1 Cobalt chrome knee replacement polishing

The surface a part finished cobalt chrome knee component was prepared to a 1200 grit hand polish. Two stages of polishing were used. A roughing stage using a 600 grit nickel bonded diamond cloth and a polishing run using a 3000 grit resin bonded diamond cloth. Figure 12 shows (a) interferometer images of before the roughing stage with a surface roughness Sa = 175.8nm (0.25mm x 0.25mm) and Figure 12 (b) an image of the final pole down polish with a surface roughness Sa = 9.7nm (0.25mm x 0.25mm). Again the slurry medium used was recycled tap water. The image shows distinctive peaks caused by hard and pronounced carbides in the matrix of the material. It is considered that the used of colloidal silica as the slurry medium could aid in the reduction of these peaks by enhancing the chemical element of the polishing process. Figure 12(c) shows an optical image of the polished cobalt chrome knee component. The left of the component shows the dull 1200 grit pre polish surface and the on the right of the component shows the mirror finished condile machine polished on the Zeeko 7-axis CNC machine.

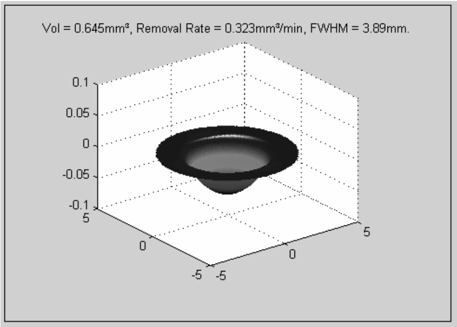


(a) Sa = 344.8nm (b) Sa = 2.8nm (c)

Fig. 12: Interferometer images of cobalt chrome knee polishing process (0.25 x0.25mm) (a, b) and optical image of polished knee condile section (c)

5.2 Cobalt chrome pin corrective polishing

With the success of the polishing results of the cobalt chrome pins the next stage of progress would be to correct the cobalt chrome pins form. Precessions 3D a unique software created by Zeeko Ltd will be used to correct the form errors induced from the pre-polish machining process.



The software uses a pre determined material removal mechanism called an influence function. An example is shown in Figure 13 which is a uniform Gaussian shape with no sharp central velocity. The volume of removal, coupled with the time the tool dwelled on the sample is used by the software to calculate tool dwell times over the pin surfaces small form deviations, removing sufficient material to correct the form to the desired level.

Figure 13 Example of an influence function

Polishing medium supplied by Sia Abrasives made from a non woven alumina oxide was tested. An early unsuccessful attempt of a nickel bonded diamond cloth, which after examination under an Scanning Electron Microscope (Figure 14) showed evidence of a chemical reaction similar to that witnessed in research carried out by Evans et al [7] on chemical aspects of tool wear in diamond turning.

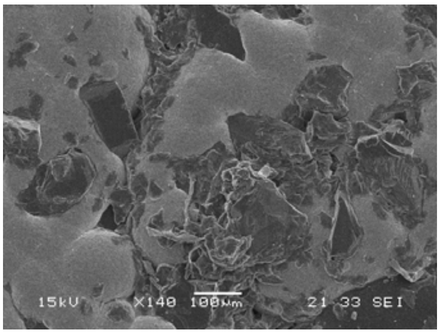


Figure 14 SEM of Nickel bonded diamond cloth after influence function generation.

5.2.1 Influence function testing

To analyse the effectiveness and repeatability of material removal a set of tests to generate four influence functions were devised. Identical machine parameters were used for the tests carried out on flat samples of cobalt chrome with matching material properties as that of the pins. The results were measured in 2D on a diamond stylus profiler. The tests carried out with the nickel bonded diamond medium produced non stable material removal and decreasing influence function depths making them unsuitable for the corrective polishing process (Figure 15). Whereas the same tests with the non woven medium produced very stable uniform material removal with negligible decreases in influence function depths proving very suitable for the corrective polishing process (Figure 15).

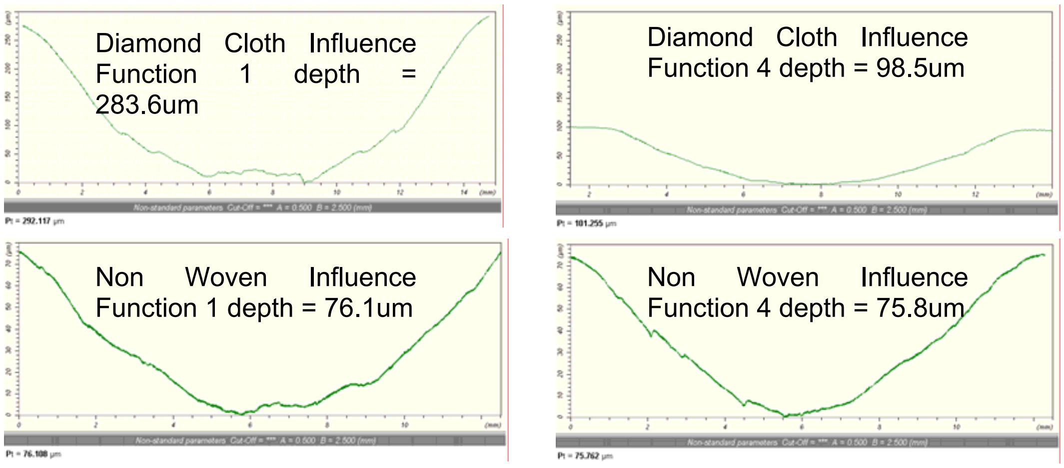


Figure 15 Examples of influence function test variations

6 CONCLUSIONS

The present work has shown initial results as to the applicability of the Zeeko IPR 200 polishing system for the manufacture of orthopaedic "freeform" knee joints in particular the system has shown the ability to generate nanoscale surface topography. In addition the machine seems capable of manufacturing freeform surfaces as defined to be biologically compatible with knee joint movement requiring high levels of conformance which could facilitate the development of hard on hard knee joints.

7 ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the EPSRC, and the advice of Mr. Paul Bills of Huddersfield University and the team of technical staff at Zeeko Ltd.

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