Experimental investigation and analytical modelling of the effects of process parameters on material removal rate for bonnet polishing of cobalt chrome alloy

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ABSTRACT

Cobalt chrome alloys are the most extensively used material in the field of total hip and total knee implants, both of which need highly accurate form and low surface roughness for longevity in vivo. In order to achieve the desired form, it is extremely important to understand how process parameters of the final finishing process affect the material removal rate. This paper reports a modified Preston equation model combining process parameters to allow prediction of the material removal rate during bonnet polishing of a medical grade cobalt chrome alloy. The model created is based on experiments which were carried out on a bonnet polishing machine to investigate the effects of process parameters, including precess angle, head speed, tool offset and tool pressure, on material removal rate. The characteristic of material removal is termed influence function and assessed in terms of width, maximal depth and material removal rate. Experimental results show that the width of the influence function increases significantly with the increase of the precess angle and the tool offset; the depth of the influence function increases with the increase of the head speed; increases first and then decrease with the increase of the tool offset; the material removal rate increases with the increase of the precess angle non-linearly, with the increase of the head speed linearly, and increases first then decreases with the increase of the tool offset because of the bonnet distortion; the tool pressure has a slight effect on the influence function. The proposed model has been verified experimentally by using different Preston coefficients from literature. The close values of the experimental data and predicted data indicate that the model is viable when applied to the prediction of the material removal rate in bonnet polishing.

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1. Introduction

Conventional polishing of bearing surfaces for artificial joints is usually carried out by semi-automated polishing or in some instances manual polishing, both of which are labour-intensive and time consuming. To minimise the processing time and improve the surface quality, a technique of computer numerical control (CNC) known as bonnet polishing has been applied to such polishing tasks in the present study. Bonnet polishing, originally developed by Walker and co-workers [1], was primarily developed for polishing optical materials used in large optical devices such as telescopes. Aspheres and freeform optical surfaces have been processed using the bonnet polishing technology [2], but it represents a new and attractive option when applied to the manufacture and finishing of the bearing surfaces of prosthetic hip or knee implants. In such devices form control of the bearing surface is a critical determinant of implant life [3]. To achieve the desired form, it is of paramount importance to understand how the various machining parameters affect the ability to achieve optimal form to facilitate the extended lifespan of implants. The material removal rate (MRR) is clearly a fundamental element in optimising the machining. It is therefore non-trivial to establish the link between the MRR and machine process parameters.

The MRR has been widely investigated in various polishing processes. The earliest investigation was carried out by Preston [4] who proposed the well-known Preston equation which assumes that the MRR is proportional to the contact pressure, and the relative velocity:

$$MRR = K \times P \times V$$  \hspace{1cm} (1)

where $K$ is the Preston coefficient, including the effects of abrasive size and material, slurry concentration, workpiece material, polishing cloths/pads, etc.; $P$ is the contact pressure between the polishing tool and the workpiece; $V$ represents the velocity of the polishing tool relative to the workpiece.
The Preston equation is widely accepted and has become the basis of the subsequently proposed MRR models. Buijs and Houten [5] presented an MRR model by incorporating Young’s modulus, hardness and fracture toughness in lapping of glass. Compared with Preston equation, this model only investigated the Preston coefficient instead of wholly changing the modes of contact pressure and relative velocity. Matsuo et al. [6] proposed a modified Preston’s equation by substituting frictional force for polishing pressure. This model created the connection of frictional force with MRR, indicating that the material removal in polishing process was achieved by polishing force rather than contact pressure, which was contributed to a better understanding of the material removal mechanism. Another model similar to Matsuo’s was developed by Shorey [7]. Shorey’s model described the MRR using the shear stress to replace the pressure or the frictional force. The above models confirmed that the MRR was linearly proportional to the contact pressure and the relative velocity but other researchers, such as Wang et al. [8], presented another approach. Wang et al. proposed a revised model by introducing the exponents to the contact pressure and the relative velocity. The limit of Wang’s model was that it needed a huge amount of experimental data to ascertain the exponents for the contact pressure and relative velocity, which would be costly in terms of time and machining effort. Cheung et al. [9] proposed an MRR model based on the assumption of Gaussian distribution of the contact pressure in bonnet polishing. However, the present authors found that the Gaussian shape of the influence function was created by the precession mode polishing (i.e. revolving the polishing tool around the normal of the workpiece) rather than by a genuine Gaussian distribution of the contact pressure as shown in Fig. 1 (the left influence function polished in precession mode is Gaussian shape, the right one polished in static mode is not Gaussian shape).

As can be seen, all the models based on the Preston equation described above only consider the contact pressure and the relative velocity. However, there are many other factors that may affect the MRR for different polishing processes. When considering the bonnet polishing, the main process parameters which potentially affect the MRR include precess angle, head speed, tool offset and tool pressure. Therefore, the current models are unsuitable to be used to predict the MRR in a bonnet polishing process which becomes the key motivation of this work. The aim of the present study is to empirically establish the link between the MRR and the process parameters based on the Preston equation and experimental data.

2. Experimental setup

In the present study, the workpiece material applied throughout was a medical grade cobalt chrome (CoCr) alloy, the most commonly used biomaterial for artificial implants. The polishing medium was GR35 polyurethane polishing pad with 3 μm alumina slurry whose specific gravity was 1.025. The samples were 23 mm diameter and 8 mm height cylindrical CoCr alloy. In this investigation, the precession mode, in which the inclined rotating polishing tool is rotating slowly around the normal of the workpiece, was used to polish the influence function (IF) so that the created IF was Gaussian shape.

The experiments were carried out on a typical 7-axis bonnet polishing machine, Zeeko IRP200 (Fig. 2). This machine uses a rotating bulged bonnet with internal pressure as the polishing tool. The bonnet is flexible and covered with a polishing cloth/pad. The inflated bonnet can conform to the variable curvature of the curved surface of the component during the polishing process. An outstanding feature of this machine is that it has a higher polishing efficiency as well as the ability to generate smooth surface textures [10]. Bonnet polishing predominantly depends on the following four process parameters: precess angle α, head speed ω, tool offset d and tool pressure tp (Fig. 2).

3. The effects of process parameters

This section investigates the characteristics of material removal through polishing different IFs by varying the values of the process parameters. The IF can be defined as a dimple produced by rotating the polishing tool on a fixed location of the workpiece surface for a fixed set of machine parameters [11]. When one parameter was studied, the values of other parameters were kept constant as in Table 1. After polishing, the 3D maps of the IF were measured by

Fig. 1. Influence function polished by different modes.

Fig. 2. Experimental setup and process parameters.
a Somicronic Surface 3D profiling instrument. The width and the maximal depth of the IF were extracted to investigate the effects of the process parameters (Fig. 3). The volumetric MRRs were calculated by the Zeeko Precession software using the metrological data measured by the Somicronic instrument.

### 3.1. The effect of the precess angle

The precess angle is the angle between the centre line of the bonnet and the normal of the workpiece surface (Fig. 2). In this section the precess angle was increased from 5° to 30° in increments of 5°. Other parameters were kept constant and are given in Table 1. The measurement results indicate that all IFs are rotationally symmetrical and comply broadly with a Gaussian shape. In this study, both the width and maximal depth of the IF and the MRR increase with increasing precess angle (Fig. 4). This set of experiments indicates that the precess angle is one of the main parameters affecting the MRR and the resulting width and maximal depth of the IF.

### 3.2. The effect of the head speed

According to the Preston equation, the MRR is proportional to the polishing speed. A higher speed will always result in more material removal in a given period of time. In bonnet polishing, the polishing speed is the radial velocity of bonnet rotation (Fig. 2). This investigation tries to confirm that the relationship of the head speed and the MRR is applicable to bonnet polishing of CoCr. The experimental conditions are given in Table 1. The head speeds ranged from 300 rpm to 1800 rpm in increments of 300 rpm. Fig. 5 shows the effect of the head speed on the IF and the MRR. As given in Fig. 5(a), with the increase of the head speed, the width of the IF only changes slightly while the maximal depth increases significantly. The linear relationship of the MRR and the head speed indicates that in bonnet polishing the MRR is still in agreement with the Preston equation (Fig. 5(c)).

### 3.3. The effect of the tool offset

The tool offset is the deformation depth of the bonnet when it contacts the surface of the workpiece during polishing (Fig. 2). Obviously, different tool offsets generate different contacting areas during the polishing process. The contacting zone holds the abrasives which remove the material of the workpiece during the polishing process. Therefore, when the tool offset varies, the width of the IF should change as well. However, how much tool offset affects the IF needs to be investigated. In this investigation, tool offset increased from 0.1 mm to 0.6 mm in increments of 0.1 mm while other experimental conditions remained unchanged and are given in Table 1. Fig. 6 shows the measurement results of the IF and the MRR. The width of the IF increases greatly with the increase of the tool offset. The maximal depth of the IF increases when the tool offset increases from 0.1 mm to 0.2 mm. The maximal depth decreases sharply when the tool offset is greater than 0.2 mm. The measurement results also display that when the tool offset is less than 0.3 mm, the IF is broadly Gaussian in shape, but when the tool offset increases to 0.6 mm, the IF becomes more Gaussian in shape.

### Table 1

<table>
<thead>
<tr>
<th>Precess angle</th>
<th>Head speed</th>
<th>Tool offset</th>
<th>Tool pressure</th>
<th>Dwell time</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>1200 rpm</td>
<td>0.15 mm</td>
<td>1 bar</td>
<td>300 s</td>
</tr>
</tbody>
</table>

![Fig. 3. 3D influence function and 2D profile through centre.](image1)

(a) The effect of the precess angle on the width of the IF

(b) The effect of the precess angle on the depth of the IF

(c) The effect of the precess angle on the MRR

![Fig. 4. The effect of the precess angle on the width and depth of the influence function (IF) and the material removal rate (MRR).](image2)
offset is greater than 0.4 mm, the IF deforms corresponding to the distortion of the bonnet tool (Fig. 7). This phenomenon is harmful for deterministic polishing and must be avoided. Fig. 6(c) shows that the MRR increases significantly with the increase of the tool offset from 0.1 mm to 0.4 mm, and slightly decreases afterwards. The results indicate for a given set of abrasives and workpiece material that there is an upper limit of the MRR to the tool offset.

3.4. The effect of the tool pressure

Tool pressure in bonnet polishing is not the contacting pressure on the workpiece. It relates to the “hardness” of the polishing tool. If the tool offset is constant, an increase of tool pressure will result in an increase of contacting pressure and vice versa. Hence in bonnet polishing, the contacting pressure relates to both the tool offset and tool pressure. The tool offset was kept constant as 0.15 mm in this investigation and the tool pressure was changed from 0.4 bar to 2.0 bar in increments of 0.4 bar. Other polishing parameters are given in Table 1.

Fig. 5. The effect of the head speed on the width and depth of the influence function (IF) and the material removal rate (MRR).

Fig. 6. The effect of the tool offset on the width and depth of the influence function (IF) and the material removal rate (MRR).

Fig. 8 shows how the IF and the MRR vary with the tool pressure. It can be seen that both the width and the maximal depth of the IF remain fairly constant with the increase of tool pressure. Fig. 8(c) shows the effects of the tool pressure on the MRR. The MRR changes slightly with the increase of the tool pressure compared to other process parameters. This indicates that if the precess angle, the head speed and the tool offset are kept constant, the tool pressure has only a small effect on the MRR.

4. Material removal rate modelling

This section will use the above-mentioned experimental data to create a material removal rate model based on the Preston equation. The authors will use the theory of contact mechanics to build the links of process parameters to the contact pressure P first and then apply kinematics theory to establish the relationship of process parameters and the relative velocity V.
4.1. Contact pressure $P$

In this research, the polishing tool is made up of part of a hollow spherical rubber tool covered with a polyurethane polishing pad. When the polishing tool comes into contact with the workpiece, it can be considered as an elastic deformable sphere pressed against a rigid flat (Fig. 9). As shown in Fig. 9, when the polishing tool contacts the workpiece, the radius of the contact area $r$ can be calculated by Eq. (2) according to the Hertz solution [12].

$$r = \sqrt{Rd}$$

(2)

where $R$ is the radius of the polishing tool and $d$ is the depth of the tool offset. However, Eq. (2) is only suitable for ideal elastic contact. In this case, because the bonnet is fixed to a duralumin frame, the radius of the contact area is also highly affected by the precess angle $\alpha$ (Fig. 4) and slightly affected by the head speed $\omega$ (Fig. 5) and the tool pressure $F_{t}$ (Fig. 8). In order to simplify the model, the authors ignore the slight effects of the head speed and the tool pressure on the width of the IF, therefore, Eq. (2) can be modified as:

$$r = P_{d}(\alpha) \times \sqrt{Rd}$$

(3)

where $P_{d}(\alpha)$ represents the effect of the precess angle and can be deduced by regression analysis using the experimental data of Figs. 4 and 6.

$$P_{d}(\alpha) = -2 \times 10^{-6} \alpha^{4} + 5 \times 10^{-5} \alpha^{3} + 0.002 \alpha^{2} - 0.016 \alpha + 0.777$$

(R$^{2}$ = 0.999)

(4)

Therefore, the contact area $A$ can be expressed as:

$$A = \pi r^{2} = \pi P_{d}^{2}(\alpha)Rd$$

(5)

Again, according to the Hertz solution when the polishing tool contacts the workpiece, the contact load $F$ is given as:

$$F = \frac{4}{3} ER^{1/2} d^{3/2}$$

(6)

where $E$ is the Hertz elastic modulus and can be defined as:

$$E = \left( \frac{1 - \nu_{1}^{2}}{E_{1}} + \frac{1 - \nu_{2}^{2}}{E_{2}} \right)^{-1}$$

(7)

where $E_{1}$, $E_{2}$, $\nu_{1}$, $\nu_{2}$ are Young’s moduli and Poisson’s ratios of the polishing tool and the workpiece, respectively. As described in Section 3.3, when the tool offset increases, the bonnet polishing tool exhibits a warping phenomenon. The onset of warping $d_{c}$ can be calculated by:

$$d_{c} = \left( \frac{\pi mH}{2E} \right)^{2} R$$

(8)

where $H$ is the hardness of the polishing tool related to the tool pressure and $m$ is the hardness coefficient. The onset of warping is depending on the tool pressure.

Substituting Eq. (8) into Eq. (6), gives:

$$F = \frac{2}{3} \pi mHRd^{3/2} d_{c}^{3/2}$$

(9)
Therefore the contact pressure $P$ between the polishing tool and the workpiece is derived as:

$$ P = \frac{F}{A} = \frac{(2/3)\pi mHd(3/2)d_c^{-1/2}}{\pi P_0^2(\alpha)d} = \frac{2}{3}mHd^{1/2}P_0^{-2}(\alpha)d_c^{-1/2} \quad (10) $$

If the radius of the polishing tool is 20 mm, when the tool pressure is greater than 1.5 bar, $d_c = 0.2$ mm; when the tool pressure is less than 1.5 bar, $d_c = 0.3$ mm.

4.2. Relative Velocity $V$

Fig. 9 schematically shows the details of the velocity distribution of a random point $A(a, b)$ ($a^2 + b^2 \leq r^2$) in the contact area when the polishing tool is rotating with the speed of $\omega$. As shown in Fig. 10, $O$ is the centre of the polishing tool, $O'$ is the centre of contact area, $OQ$ is the centre line of the polishing tool and $Q$ is in the contact area. Therefore,

$$ |OQ| = \frac{R - d}{\cos \alpha} \quad (11) $$

Then,

$$ |OQ'| = |OQ| \sin \alpha = (R - d) \tan \alpha \quad (12) $$

and

$$ |QN| = (R - d) \tan \alpha + a \quad (13) $$

We can obtain,

$$ |MN| = |QN| \cos \alpha = [(R - d) \tan \alpha + a] \cos \alpha \quad (14) $$

So in the triangle $\triangle MNA$,

$$ |MN|^2 + |NA|^2 = |MA|^2 \quad (15) $$

So,

$$ |MA| = \sqrt{a^2 \cos^2 \alpha + 2a(R - d) \sin \alpha \cdot \cos \alpha + (R - d)^2 \sin^2 \alpha + b^2} \quad (16) $$

Therefore, the relative velocity $V$ can be expressed as follows:

$$ V = \omega \cdot |MA| = \omega \cdot \sqrt{a^2 \cos^2 \alpha + 2a(R - d) \sin \alpha \cdot \cos \alpha + (R - d)^2 \sin^2 \alpha + b^2} \quad (17) $$

When $a = 0$, $b = 0$, the average of the contact area is:

$$ V = \omega \cdot (R - d) \cdot \sin \alpha \quad (18) $$

During polishing process, the polishing tool moves in precession mode which means it is rotating as well as revolving around $OO'$ with the speed of $\omega'$. However, $\omega'$ is very slow compared to $\omega$. The effect of $\omega'$ on the MRR can be neglected. $\omega'$ only affects the shape of the influence function, creating the rotationally symmetrical Gaussian shape.

So the Preston equation can be rewritten as:

$$ MRR = KP \cdot V = \frac{2}{3}KmHd^{1/2}P_0^{-2}(\alpha)d_c^{1/2} \cdot (R - d) \cdot \sin \alpha \quad (19) $$

As shown in Fig. 8, the effect of the tool pressure on the width and maximal depth of the IF, and on the MRR is very small. Hence, $mH$ in Eq. (19) can be considered as a constant and combined into the Preston coefficient $K$. Therefore, the final MRR model can be expressed as:

$$ MRR = \frac{2}{3}K \cdot \frac{\omega}{\text{term1}} \cdot \frac{d^{1/2}}{\text{term2}} \cdot \frac{d_c^{1/2}}{\text{term3}} \cdot \frac{(R - d)}{\text{term4}} \cdot \sin \alpha \quad (20) $$

In Eq. (20), term 1 represents the modified Preston coefficient, including the effects of abrasive size and material, slurry concentration, workpiece material, polishing cloths/pads and tool pressure. The value of $K$ can be determined experimentally.

Term 2 describes the effect of the head speed, which indicates the MRR is proportional to the head speed and is in agreement with experimental results as well as the Preston equation.

Term 3 depicts the effect of tool offset on the MRR. When the tool pressure is less than 1.5 bar, $d_c = 0.3$ mm, which means the value of the tool offset should not be greater than 0.3 mm; when the tool pressure is greater than 1.5 bar, $d_c = 0.2$ mm, which indicates that in this case the value of the tool offset $d$ should not be greater than 0.2 mm.

Term 4 gives the effects of the precess angle on the MRR. As can be seen in Eq. (20), the MRR increases non-linearly with the increase of precess angle, which is in agreement with the experimental results.
5. Verification of the model

In order to confirm the viability of the created model, four sets of experiments were performed to verify the role of precess angle, head speed, tool offset and tool pressure respectively. The machine settings are shown in Table 2. The polishing medium was a GR35 polishing pad with 1 µm diamond slurry whose specific gravity was 1.024. The workpieces were 23 mm diameter and 8 mm high cylinders of CoCr alloy, of the same material as used in Section 3. The Preston coefficient calculated from the above polishing medium and workpiece material is shown in Table 3. To further verify the model, other Preston coefficients for polishing optics and metallic materials are taken from literature and given in Table 3. The experimental results and the calculated results based on the proposed model using different Preston coefficients are given in Fig. 10. As illustrated in Fig. 10, the trends of predicted data are well in agreement with the experimental data, which would imply the created model can be used within this range of machine settings to predict the MRR in bonnet polishing of CoCr alloys. In Fig. 10(d), the increase of MRR is thought to result from the decrease of $d_c$ due to the tool pressure exceeding 1.5 bar.

6. Discussion and conclusions

This paper has investigated the influence of process parameters on the influence function during bonnet polishing of a medical grade CoCr alloy. Experimental results show that all IFs polished in precession mode are near Gaussian shape; the width of the IF increases with the increase of both precess angle and tool offset; the depth of the IF increases significantly with the increase of the head speed, increases first and then decreases with the increase of the tool offset. The MRR increases with the increase of the precess angle non-linearly, with the increase of the head speed linearly, and increases first then decreases with the increase of the tool offset because of the bonnet distortion. The tool pressure only has a slight effect on both IF and MRR; however, the tool pressure can affect the optimal depth of the tool offset; if the tool pressure is less than 1.5 bar, the tool offset should be less than 0.3 mm; if the tool pressure is greater than 1.5 bar, the tool offset should be less than 0.2 mm.

The authors believe that the reason why the precess angle greatly affects the width of the IF is the increase of contact area.
between the polishing tool and the workpiece. Although the bonnet is a part of spherical rubber, the contact areas in position 1 and position 2 are different if the tool offset is the same because the bonnet is fixed by a duralumin framework (Fig. 11). The increase of the MRR in this case is caused by both the increase of the contact area and the relative velocity (Fig. 12). This is different from the conclusion obtained by Walker et al. [10], who considered the change of precess angle only affecting the relative velocity. As shown in Fig. 12 and Eq. (18), when the precess angle \( \alpha = 0 \), the relative velocity is 0; when the precess angle \( \alpha \neq 0 \), the increase of \( \alpha \) will lead to the increase of relative velocity. Therefore, the variation of the precess angle is essentially the change of the relative velocity. When the precess angle and tool offset are fixed, the increase of the head speed can result in a great increase in the MRR and the depth of the IF, and a slight increase of the width of the IF. This is in agreement with Walker et al. [10]. When the precess angle and the head speed are fixed, the increase of the tool offset will lead to the increase of the contact area and hence to an increase of the width of the IF and the MRR. The investigation results show that the effect of the tool pressure on both IF and MRR is very moderate. However, the impact of the tool offset and the tool pressure on the IF should be noted to avoid the warping of the bonnet which can give rise to a protrusion in the centre of the IF.

Based on the experimental results, an MRR model which takes into account the process parameters of bonnet polishing has been created. This model results from the traditional Preston equation, but uses the Hertz solution to calculate the contact pressure and kinematics theory to obtain the relative velocity. The created MRR model is a function of the process parameters. This model has been verified experimentally. The predicted data are in good agreement with the experimental data, which indicates that the created model can be used to calculate the MRR in bonnet polishing over the range of process parameters considered. Although this model is based on the CoCr alloy polishing, it can also be applied to the bonnet polishing of other materials such as stainless steel, copper, ceramics or optical materials, etc. Compared with other models, the primary advantage of this model is that it can be easily used once the Preston coefficient is determined experimentally. Generally, the Preston coefficient is constant when the experimental conditions are constant. Therefore, the Preston coefficient can be obtained from a few experiments only.

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