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Crown Shaping Technique of Bearing Raceway by Electrochemical Mechanical Machining

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A new Electrochemical Mechanical Machining (ECMM) technique for bearing crown raceway finishing was proposed in this paper. A theoretical model for the crown shaping was also put forward to simulate the workpiece crown shaping process. The research emphasis is on controlling the raceway crown shape. The comparison between the calculated results and experimental results was carried out to verify the proposed model. It was found that the difference between the predicted values and real ones are less than 10%. By ECMM, the surface roughness of bearing raceway was reduced from *Ra*0.58 μm to *Ra*0.03 μm in 1-4 min, and the desired crown shape has been obtained at the same time. This paper exploit a new way for the crown shaping and superfinishing of bearing raceway.

Keywords: Bearing Raceway; Crown Shape; Surface Quality; Electrochemical Mechanical Machining

1. INTRODUCTION

Recent failure mechanism analysis shows that the high stress concentration often exists on both sides of the rollers-raceway interface, when a roller bearing is in a loaded state [1-3]. Poplawski et al. [4] have analyzed four roller profiles in cylindrical roller bearing for stress and life. It was found that the stress concentration of edge loading on the flat roller profile caused life reduced as much as 98%. The crown shape of roller or the raceway profile which is proposed in present design and fabrication criterion can reduce stress concentration significantly on the edge of the roller, improve lubricating property, lower working temperature, decrease the noise from vibration effect and prolong the bearing working lifetime. The pressure distribution on different profile raceway is shown in Fig. 1. The problem of the contact generator correction, ensuring constant pressure distribution along the generator, was first discussed by Lundberg [5], and a logarithmic correction profile was proposed. As it was impossible to put the logarithmic correction into practice, different types of correction of simpler shape were used, such as arch correction and revised arch correction, as shown in Fig. 2.

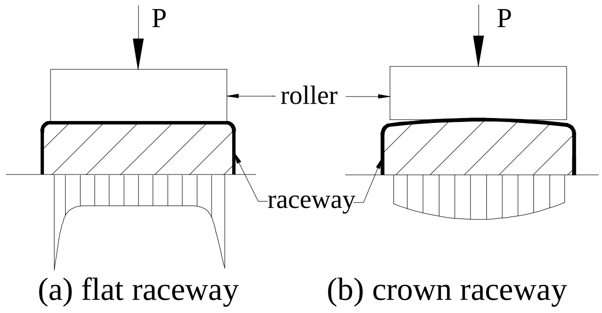
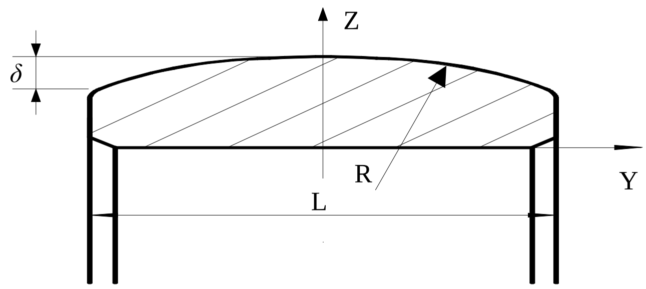


Figure 1. Pressure distribution on raceway P-load



δ - crown height; L - width of raceway; R - the radii of raceway profile

Figure 2. Arch correction profile of raceway

Most of cases, a bearing crown raceway is ground using a formed grinding wheel with sharpener, or, tilted axis grinding. Usually, the finished product raceway crown height (δ) as shown in Fig. 2 is between 5-10 μm, which is hardly controlled by conventional grinding. The surface quality of bearing raceway has an important influence on the performance and vibration of the bearing [6, 7]. Generally, after grinding, the bearing raceway is finished with a hone to improve the surface quality. The conventional bearing finishing methods are using several steps to improve surface quality resulting in high product cost and low efficiency. In addition, grinding wheels and hones are worn easily, leading to the surface quality unstable. The final surface roughness by conventional processing is larger than *Ra*0.05 μm. Therefore, an advanced and economic solution to control the crown shape and to obtain a better surface quality of bearing raceway is necessary.

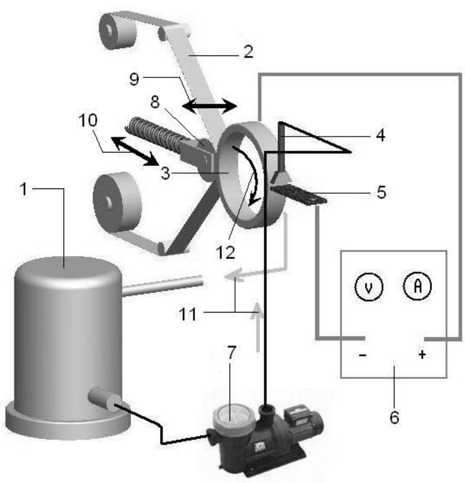
Electrochemical machining (ECM) is an effective method of machining high-strength, heat-resistant alloys which are extremely difficult to cut by other established methods [8, 9]. Current applications of ECM range from large-scale deburring and polishing of metallic parts to etching on micron scales in the processing of semiconductor devices. ECM processes are also adopted in the aerospace, die and mold, and electronic industries for shaping and finishing operations [10]. The experimental results of Mileham et al. [11] showed that the quality of the machined surface was influenced by processing parameters. Acharya et al. [12] compared ECM with traditional machining, and concluded the greater profit and higher quality can be obtained by ECM than that of traditional machining.

Generally, many researchers pay more attentions to analysis of stress distribution on those special profiles of bearing and ECM application [13, 14]. Purcar et al. [15, 16] established a 3D prediction model for ECM, but is too complex to control and still in the simulation stage. Kozak [9] and Riggs [17] constructed a mathematical model for ECM and forecasted workpiece shape, but the model entails an excessive number of assumed conditions. A neural network model was used by Parthiban [18] Pang [19] to predict anode shape, however, the neural network requires a lengthy training time and continues to present over-fitting and under-fitting problems. Jain and Pandey [20, 21] demonstrate the application of the finite element method for 2D computation of the removal rate. Their model incorporated the effects of simultaneous changes in the electrolyte flow velocity and temperature rise. Bhattacharyya et al. [22] used a simulated cut-and-try procedure to predict cathode shape in ECM. Few reports deal with the bearing crown raceway processing by ECM.

Applying ECM to bearing raceway processing, the emphasis is put on controlling the crown processing, the ideal surface roughness of workpiece and the desired crown shape.

In this paper, a new Electrochemical Mechanical Machining (ECMM) technique for bearing crown raceway finishing was proposed. The paper is structured as follows: firstly, the basic mechanism of ECMM is introduced. Secondly, a mathematical model used to describe the profile generated of the crown shape of bearing raceway is proposed. Thirdly, the numerical simulation according to the model is presented. Fourthly, the experiments are conducted to verify the model. The comparison between the calculated results and experimental results is discussed. The conclusions are given in the final section.

2. BASIC MECHANISM OF ECMM



1 - electrolyte tank; 2 - abrasive belt; 3 - workpiece (anode); 4 - electrolyte nozzle; 5 - tool (cathode); 6 - DC power supply; 7 - pump; 8 - contact wheel; 9 - belt oscillation; 10 - pressure regulation; 11 - electrolyte flow; 12 - workpiece rotation

Figure 3. The structure of experimental equipment of ECMM

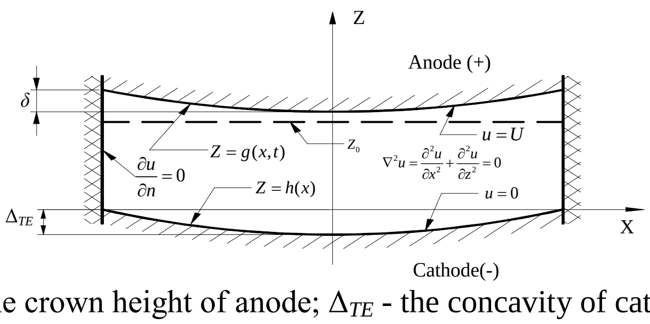
ECMM is a compound finishing technology with both electrochemical machining (ECM) and mechanical polishing. ECMM is an anodic dissolution and polishing process where the workpiece and the tool are used as the anode and the cathode respectively. The electrolyte is pumped into the interelectrode gap. When an electric current is applied between the electrodes, the anode (workpiece) is dissolved locally. In ECMM, the mechanical polishing is introduced to remove the anode passive film formed on the surface of workpiece by electrochemical reaction, which prevent the anode from further resolving. As electrochemical and mechanical alternately processing, the material at the peak point on the surface will be removed gradually, and the smooth surface can be obtained.According to Faraday's Law of electrolysis, the unbalance of interelectrode gap and the unbalance distribution of electric field lead to the unbalance of current density distribution, resulting in the nonuniform material removal of anode. During processing, the shape of the generated workpiece is approximately a negative mirror image of that of the tool. Therefore, the desired crown shape anode can be obtained by a concave cathode.

The structure of experimental equipment is illustrated in Fig. 3.

In processing, the bearing inner ring adopted as the anode, rotates along with the spindle. The tool is designed as the cathode which keeps static. Electrodes are connected to DC power supply. When an electric current is passed through the electrolyte flowing within the interelectrode gap, the bearing raceway is eroded accordance with Faraday's Law of electrolysis. The electrolyte tank is used for storing and depositing the electrolyte. The abrasive belt is adopted as a flexible mechanical polishing tool which can match the change of the workpiece surface profile. It is pushed on the raceway by elastic contact wheel and oscillated in axial, which is in favor of the uniformity of the mechanical polishing on the raceway surface.

3. MODELING OF ECMM CROWN SHAPING

According to Faraday's Law, the electric field affects the removal of anode. The electrolyte is ejected in the perpendicular direction to the electric field plane. The processing is lightly affected by the temperature and the bubbles because the electrolyte flows shortly and uniformly in the interelectrode gap. The flow field is supposed to be stable. The removal of anode by ECMM only attributes to the electric field. Fig. 4 shows the model of raceway crown shaping.



δ - the crown height of anode; Δ_{TE} - the concavity of cathode

Figure 4. The model of shaping crown raceway

The shape of cathode is constant in processing. It can be expressed as $Z = h(x)$. The anode shape can be expressed as a function about position and time, $Z = g(x, t)$. $Z = Z_0$ is the initial shape of anode, which is flat. The starting time of processing can be expressed as t_0, t_i is a certain time during the processing and t_n is the ultimate time. So the curve of $Z = g(x, t)$ presents the shape of anode at t time.

The shape of anode at t_i can be expressed as

$$Z\big|_{t=t_i} = Z\big|_{t=t_{i-1}} + \Delta Z = Z\big|_{t=t_{i-1}} + \eta\omega\kappa \cdot \Delta t \cdot \frac{\partial u}{\partial n} \qquad (1)$$

where κ is the electrolyte conductivity, ω is the electrochemical equivalent of the metal, u is the interelectrode voltage and η is the current efficiency, Δz is the changing shape of anode, $\partial u/\partial n$ is the electric potential gradient and $u = u(z, x)$, then,

$$g(x,t_i) = g(x,t_{i-1}) + \eta\omega\kappa \cdot \Delta t(u'_z(z,x) + u'_x(z,x) + u'_z(z,x) \cdot g'_x(x,t_{i-1})) \qquad (2)$$

The shape of anode at ultimate time t_n can be expressed as

$$g(x,t_n) = g(x,t_0) + \eta\omega\kappa \cdot \Delta t \cdot \sum_{i=1}^{n}(u'_z(z,x) + u'_x(z,x) + u'_z(z,x) \cdot g'_x(x,t_{i-1})) \qquad (3)$$

The distribution equation of interelectrode voltage (u) can be expressed as Laplace's equation:

$$\nabla^2 u = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} = 0 \quad (4)$$

Boundary conditions of Eq. (4) can be expressed as:

$$\begin{cases} u = 0 & \text{on the surface of cathode} \\ u = U & \text{on the surface of anode} \\ \dfrac{\partial u}{\partial n} = 0 & \text{on the surface of insulation wall} \end{cases} \qquad (5)$$

It can be seen that the changing shape of anode $g(x, t)$ in Eq. (3) depends on the electric field distribution (u) and the processing time (t). During the processing, the shape of anode is changed, which leads to the change of the electric field distribution, so it is difficult to solve Eq. (3). Because the interelectrode gap is less than width of workpiece in this paper, the electric field distribution and the current density can be assumed to be uniform, and the curvic current line is replaced by straight-line between the electrodes. The changes of κ, ω and η are ignored due to the assumption of flow field. According to Ohm's Law, the relation between the interelectrode voltage (u) and the approximate length of current line is established as follows:

$$\delta_t = g(x,t) - h(x) \qquad (6)$$

$$i = \kappa \frac{u}{\delta_t} \qquad (7)$$

$$\Delta z = v_a \cdot \Delta t = \eta\omega\kappa \frac{u}{\delta_t} \cdot \Delta t \qquad (8)$$

where, v_a is the removing speed of anode.

During the bearing raceway processing, the cathode is fixed and the workpiece rotates. According to Faraday's Law, in the first lap of rotating at time t_i, the shape of anode can be expressed as:

$$\begin{aligned} g(x,t_i) &= g(x,t_{i-1}) + u\eta\omega\kappa \cdot \Delta t \big/ (g(x,t_{i-1}) - h(x)) \\ &= g(x,t_{i-1}) + u\eta\omega\kappa \cdot \Delta t \big/ \delta_{t_{i-1}} \end{aligned} \qquad (9)$$

where, Δt is the electrochemical reaction time in one circle, δ_t is the interelectrode gap at time t_{i-1}.

After n circles of rotating, the shape of anode at t_n can be expressed as:

$$\begin{aligned} g(x,t_n) &= g(x,t_{n-1}) + u\eta\omega\kappa \cdot \Delta t \big/ \delta_{t_{n-1}} \\ &= g(x,t_0) + \sum_{i=0}^{n-1} u\eta\omega\kappa \cdot \Delta t \big/ \delta_{t_{i-1}} \end{aligned} \qquad (10)$$

According to Eq. (10), the final shape of anode has relationship with the machining time (t), and the cathode shape, $h(x)$.

4. NUMERICAL SIMULATION

From Eq. (10), it is found that if the parameters of interelectrode voltage (u), electrolyte conductivity (κ), electrochemical equivalent of the metal (ω), the current efficiency (η), and initial anode shape, ($g(x, t_0)$), are fixed, the shape of cathode ($h(x)$), and the time of processing (t), are the key variables influencing the shape of anode.

4.1 Determination of Fixed Parameters

The aim of bearing raceway ECMM is to obtain a smooth surface and a crown shape raceway. If the fixed parameters are chosen to meet the requirement of surface quality, the desired crown shape can be obtained by controlling variable parameters, the shape of cathode $h(x)$ and the time of processing (t). Consequently, the desired crown shape and a good surface quality of the bearing raceway can be obtained at the same time.

In order to access the appropriate fixed parameters for a good surface of raceway, a series of polishing experiments are conducted according to experimental conditions of ECMM listed in Table 1 to determine the optimum parameters range for the good surface quality. The chemical composition of bearing steel is given in Table 2.

Table 1. Conditions of ECMM experiment

Workpiece (anode)	Tool (cathode)	Main parameters	Others
Materials: bearing steel	Materials: Cu	Initial interelectrode gap δ: 0.1 - 0.8 mm	Main components of Electrolyte: 10% - 30% $NaNO_3$ + additive
Size: Φ60mm × 26mm	Processing area: 26mm × 5mm	Workpiece rotating speed n : 100 - 800 r·min^{-1}	Electrolyte flow rate q: 0.1 - 1 m^3·h^{-1}
Initial surface: Ra 0.58 μm flat raceway HRC 60		Interelectrode voltage u: 10 - 30 v Processing time t: 1 - 5 min Grit size ω: 5 -10 μm	

Table 2. Chemical composition of bearing steel

Element	C	Si	Mn	Cr	Mo	P	S	Cu	Al	O	Fe
wt.%	0.93-1.05	0.15-0.35	0.25-0.45	1.35-1.60	≤0.1	≤0.025	≤0.015	≤0.30	≤0.05	≤0.0015	Others

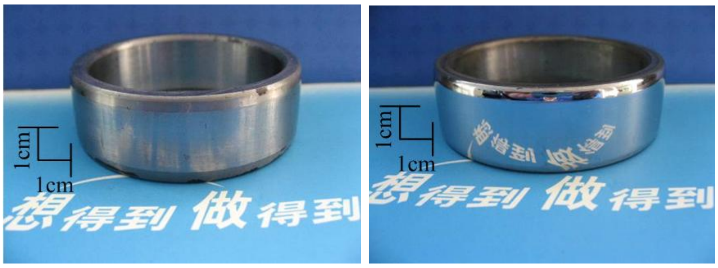
The experiments were performed on the device as shown in Fig. 3. The different values of parameters were employed for determining the influence of parameters on the surface quality by ECMM. A good surface quality has been achieved owing to the optimum parameters applied in previous polishing experiments [23]. The range of optimum parameters for a good surface quality by ECMM is listed in Table 3.

Table 3. The optimum parameters range of raceway surface polishing

Interelectrode voltage u (V)	Interelectrode gap δ_0 (mm)	Grit size ω (μm)	Workpiece rotating speed n (rpm)	Processing time t (min)
15-25	0.1-0.6	5-7	150-600	1-4

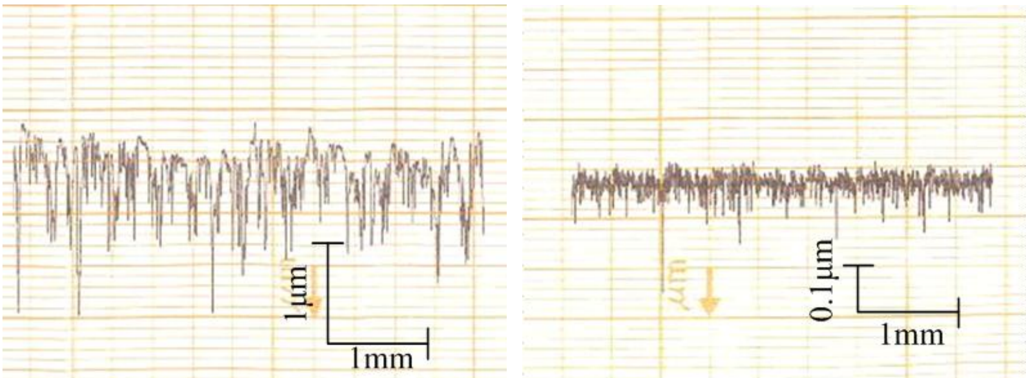
Based on the analysis of experimental results, main influential parameters on the surface quality are initial gap (δ_0), processing time (t), interelectrode voltage (u), workpiece rotating speed (n) and grit size (ω). The parameters of electrolyte conductivity (κ), electrochemical equivalent of the metal (ω) and the current efficiency (η) are steady when the electrolyte and the material of anode are chosen.

Both Fig. 5 and Figure 6 exhibit the bearing raceway before and after ECMM. Obviously, the surface quality in Fig. 5(b) has been improved significantly compared with that in Fig. 5(a). From Fig. 6, it can be observed that the surface quality *Ra*0.58 μm measured before ECMM was reduced to *Ra*0.029 μm after ECMM. It indicates that proper parameter setting can result in a bright and smooth surface in ECMM.



(a) before ECMM (b) after ECMM

Figure 5. Bearing raceway surface before and after ECMM



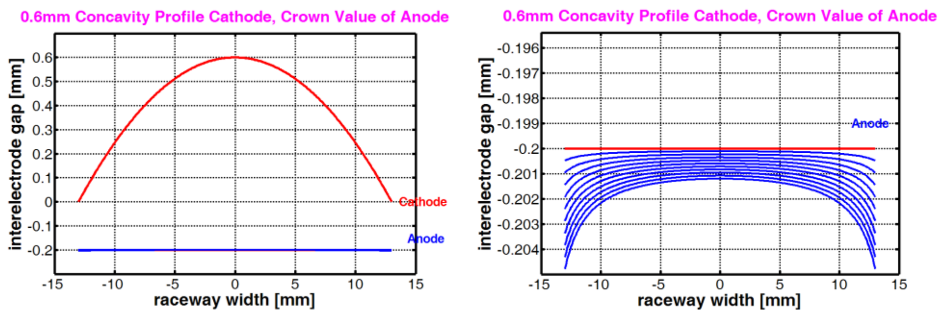
(a) before ECMM (*Ra* 0.58 μm) (b) after ECMM (*Ra* 0.029 μm)

Figure 6. Roughness of bearing raceway surface

4.2 Numerical Simulation and Discussion

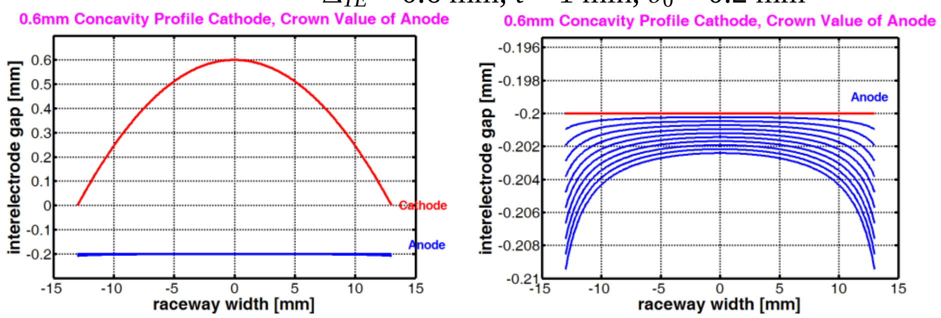
Table 4. The conditions for simulation and crown shaping experiments

Interelectrode voltage u (V)	Interelectrode gap δ_0 (mm)	Processing time t (min)	Cathode		Workpiece rotate speed n (rpm)
			profile	Concavity Δ_{TE} (mm)	
25	0.2	1, 2, 3, 4	concave end	0.8, 0.6, 0.2	150



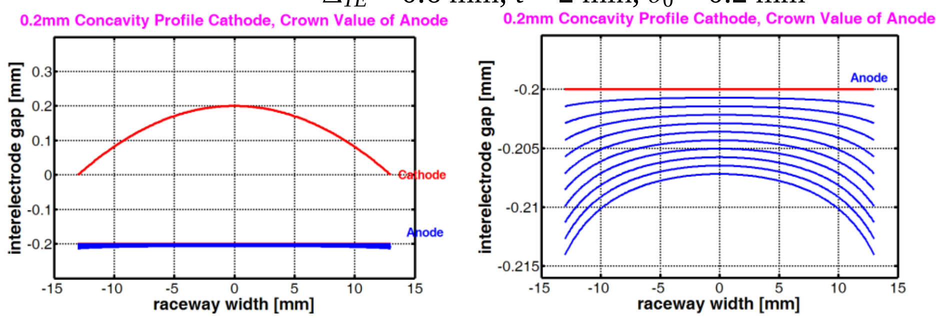
(a) (b)

Δ_{TE} = 0.6 mm, t = 1 min, δ_0 = 0.2 mm



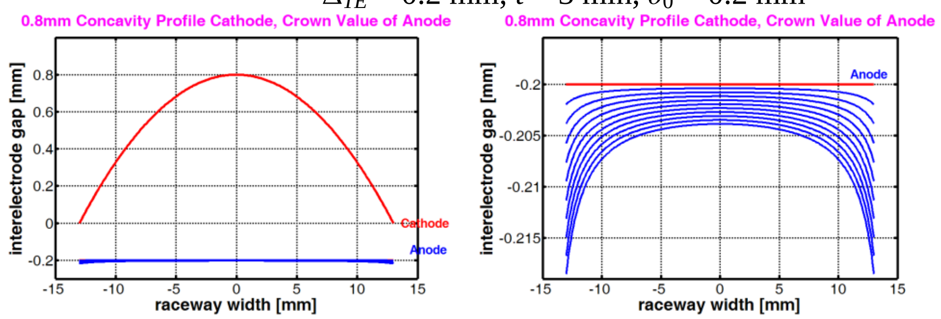
(c) (d)

Δ_{TE} = 0.6 mm, t = 2 min, δ_0 = 0.2 mm



(e) (f)

Δ_{TE} = 0.2 mm, t = 3 min, δ_0 = 0.2 mm



(g) (h)

Δ_{TE} = 0.8 mm, t = 4 min, δ_0 = 0.2 mm
(a), (c), (e), (g) overall view of the simulation
(b), (d), (f), (h) details of the anode shaping

Figure 7. Crown profile simulated of workpiece with different concavity profile

When the fixed parameters determined by the polishing experiments are applied as the known values in Eq. (10), processing time (t) is taken as variable parameter to calculate the theoretic anode shape with different concave shape of cathode. After simulating the processing, the profile of the crown shaping is obtained.

The conditions for the crown shaping simulation are listed in Table 4.

Shape curves simulated of the anode are shown in Fig. 7.

The changing shapes of anode in processing are shown in Fig. 7 at each time step. In simulation, a concave end sheet is chosen as the cathode, a bearing ring with flat raceway as the anode. The shape of cathode ($h(x)$) depends on the concavity of cathode (Δ_{TE}). The processing time (t) and the shape of cathode ($h(x)$) are considered as controlling variable.

From Fig. 7, it is found that the generated profile of anode with the same initial flat raceway changes with the changing of cathode concavity (Δ_{TE}) and the processing time (t). The anode shape ($g(x, t)$) trends to agree with the profile of cathode.

Comparing Fig. 7(b) and Fig. 7(d), as the processing time continues, the removal of anode increases, and the higher crown height can be obtained. Because the same cathode is used for the processing, the anode shapes are similar.

In Fig. 7(d) and Fig. 7(f), the smaller curvature of anode profile is generated by the smaller concavity of the cathode profile. Although the increasing of processing time is helpful to generate the more removal of anode, the crown height of anode profile is decided by the curvature of cathode profile.

In Fig. 7(h), the maximum concavity of cathode profile is applied, and the obvious nonuniform removal of anode is attributed to the large gap between the anode and the cathode. The more nonuniform removal occurs on the anode, the larger crown height is obtained.

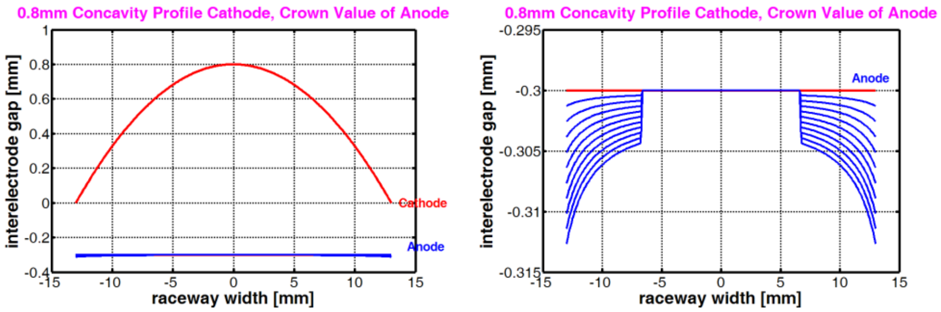
The results of simulation in Figure 7 show that the curvature of crown profile of anode has close relation with the cathode shape, and the removal of anode is affected by the processing time (t). Combined effect of the cathode shape and the processing time determines the desired crown shape of anode.

Curves of simulated processing are tabularized in
Table **5**.

Table 5. Numerical description of simulation processing data (see Fig. 7)

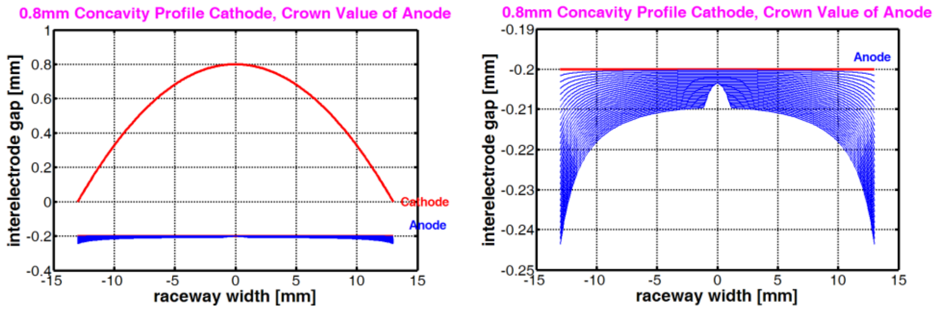
Figure number		Fig. 7(a, b)	Fig. 7(c, d)	Fig. 7(e, f)	Fig. 7(g, h)
Processing time (min)		1	2	3	4
Concavity of cathode (mm)		0.6	0.6	0.2	0.8
Interelectrode gap (mm)	min	-0.2048	-0.2095	-0.2141	-0.21853
	max	-0.2012	-0.2024	-0.2072	-0.2039
	mean	-0.2018	-0.2037	-0.2089	-0.2062
Crown height of anode (mm)		0.0036	0.0071	0.0069	0.01463

The simulated discontinuity surface of the anode as shown in Fig. 8 is the overcut situation in ECMM because of the improper variables setting.



(a) (b)

Δ_{TE} = 0.8 mm, t = 4 min, δ_0 = 0.3 mm



(c) (d)

Δ_{TE} = 0.8 mm, t = 10 min, δ_0 = 0.2 mm
(a) , (c) overall view of simulation of anode and cathode
(b) , (d) details of corresponding anode shaping

Figure 8. Simulation of the discontinuity surface with overcut of anode

In Fig. 8(a), (b), the initial flat profile in the middle region of anode is kept steady without changing during the simulation, which leads to the discontinuous surface of anode.

In Fig. 8(c), (d), at the beginning of simulation, the removal of anode rises with the increasing of the machining time. When the machining time exceeds a certain time, in the middle region of anode, the anode stops removing and the discontinuity surface occurs again.

The discontinuity surface of raceway leads to a new stress concentration when the bearing is loaded. Therefore, the overcut can be avoided by simulation.

In fact, the variables of the processing time (t) and the cathode shape ($h(x)$) affect the anode shape via the interelectrode gap (δ).

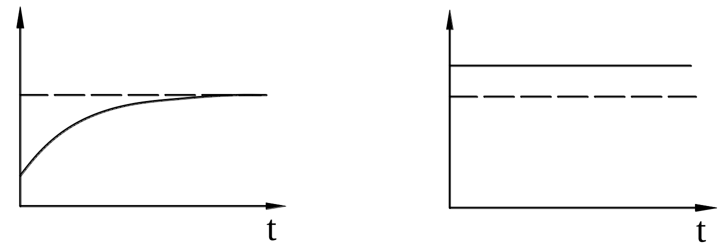
The interelectrode gap (δ) has two changing trends during ECMM processing:

- If δ is smaller than the equilibrium gap, the anode can be removed. The interelectrode gap increases up to the final equilibrium gap;
- If δ is greater than the equilibrium gap, the anode reaches steady-state. The interelectrode gap is invariant.

The steady state is a situation which indicates the electrochemical reaction between electrodes has been stable and the anode surface reaches a steady-state shape. The steady state is also called the equilibrium state, in which the interelectrode gap gets the equilibrium gap.

In ECMM, the anode will not be removed any more in the equilibrium state.

The changes of δ on machining time are illustrated in Fig. 9. Where, δ_0 is initial gap, δ_{eq} is equilibrium gap.



(a) δ_0 is smaller than δ_{eq} (b) δ_0 is greater than δ_{eq}

Figure 9. Variation of interelectrode gap with machining time

In bearing raceway crown shaping by ECMM, the initial interelectrode gap (δ_0) is nonuniform because of the concavity of cathode.

On some locations where the maximum initial gap between the electrodes is greater than the equilibrium gap, the anode will keep the initial anode shape without any removal, and others keep on dissolving, which results in the overcut on the anode. It is shown in Fig. 8(a), (b). When the proper initial interelectrode gap is set, the interelectrode gap increases as the processing time increases. If the crown shaping by ECMM continues for a sufficient long time, the gap will reach the equilibrium gap in the end. Similarly, the overcut of the anode occurs unless the processing is stopped in time. It is illustrated in Fig. 8(c), (d).

Since the overcut is considered as the failure of bearing raceway crown shaping, the variable parameters of processing time (t) and the cathode concavity (Δ_{TE}) should be restricted as followed:

$$\delta_{0\max} < \delta_{eq} \qquad (11)$$

and, $\delta_{0\max} = \Delta_{TE} + \delta_0$, that is,

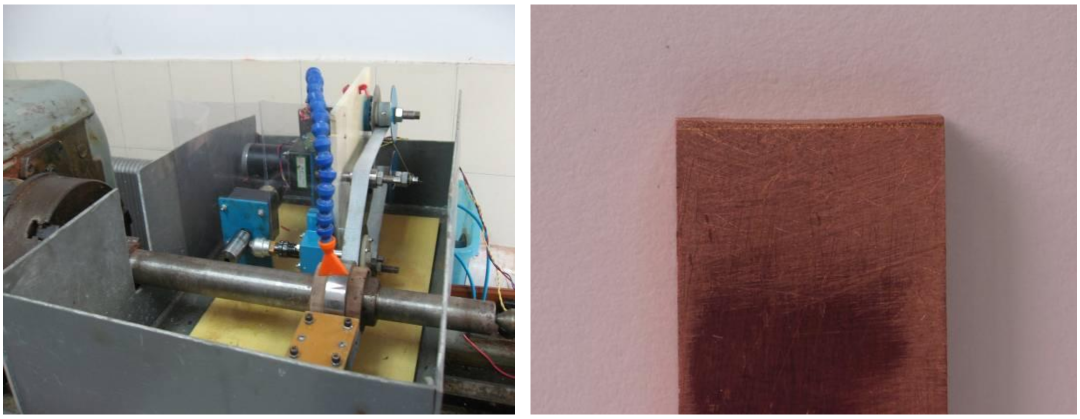
$$\Delta_{TE} < \delta_{eq} - \delta_0 \quad (12)$$

$$t_{\max} \le t_{eq} \qquad (13)$$

where, $\delta_{0\max}$ is the maximum initial interelectrode gap, Δ_{TE} is the concavity of cathode, $t_{\max}$ is the maximum processing time, t_{eq} is the processing time when the anode reaches the equilibrium state.

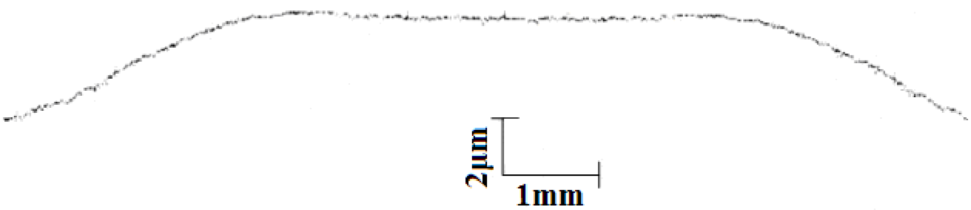
5. EXPERIMENTAL RESULTS OF CROWN SHAPING AND DISCUSSION

In order to verify the accuracy of theoretical model, crown shaping experiments are carried out under the same conditions of simulation, which are listed in Table 4. The processing time and the shape of cathode are considered as controlling variable. The processing time (*t*) is changed from 1 to 4 min, three types of concave cathode (Δ_{TE}=0.2mm, 0.6mm and 0.8mm) are employed in the shaping experiments. The experimental setup and crown cathode are shown in Fig. 10. The crown profile of raceway is measured by Surfcorder SE-3H. The measured contours of anode processed are shown in Fig. 11. The experimental results and theoretical calculation results are listed in Table 6.

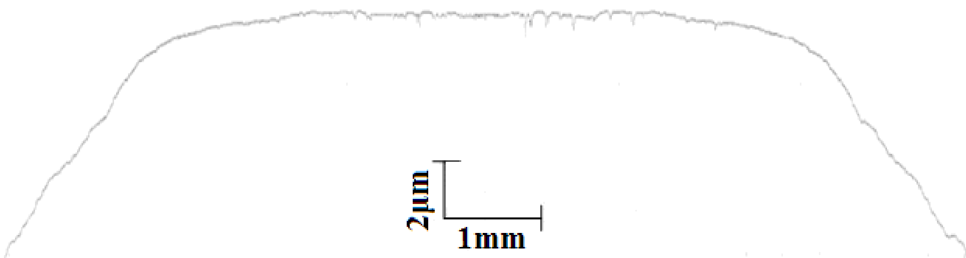


(a) experimental setup (b) crown cathode

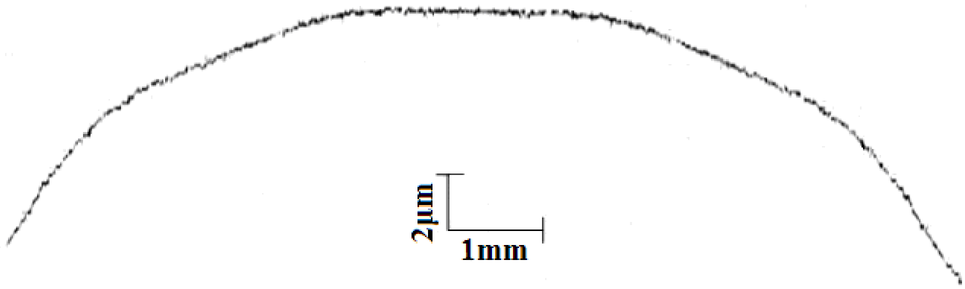
Figure 10. Photograph of experimental setup and crown cathode



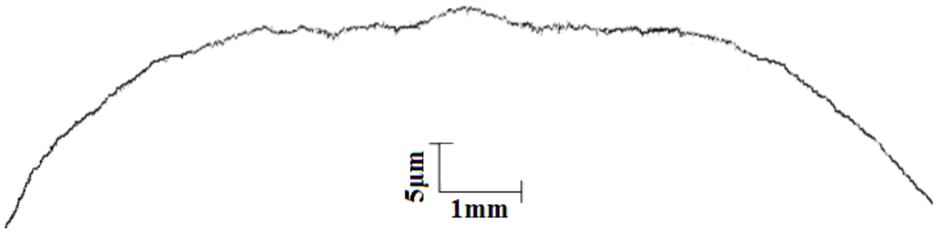
(a) Δ_{TE} = 0.6 mm, T = 1 min, δ_0 = 0.2 mm



(b) Δ_{TE} = 0.6 mm, T = 2 min, δ_0 = 0.2 mm



(c) Δ_{TE} = 0.2 mm, T = 3 min, δ_0 = 0.2 mm



(d) Δ_{TE} = 0.8 mm, T = 4 min, δ_0 = 0.2 mm

Figure 11. Crown profile measured of raceway by ECMM

Table 6. Comparison of experimental and theoretical results of crown shaping by ECMM

Processing time t (min)	Concavity of cathode (mm)	Theoretical results (μm)	Experimental results (μm)	Relative Errors %	Surface roughness *Ra* (μm)
1	0.6	3.6	4.2	16.7	0.030
2	0.6	7.1	8.3	16.9	0.029
3	0.2	6.9	8.1	17.4	0.031
4	0.8	14.63	17.4	18.9	0.038

Analyzing Fig. 11 and Table 6, it can be seen that the profile of workpiece surface has been crowned owing to the nonuniform material removal of the anode. The generated profile of anode changes with the changing of cathode concavity and the processing time. The anode shape trends to agree with the profile of cathode.

To compare with Fig. 11(a) and Fig. 11(b), with the times continues, the higher crown height can be obtained, and the similar anode shapes also can be obtained because of the same cathode is used. Fig. 11(c) indicated that the smaller curvature of anode profile is generated by the smaller concavity of the cathode profile compared with Fig. 11(b). The crown height of anode profile is decided by the curvature of cathode profile. In Fig. 11(d), the obvious nonuniform removal of anode is attributed to the large gap between the anode and the cathode. The more nonuniform removal occurs on the anode, the larger crown height is obtained.

Comparing the results, the experimental results are different from the theoretical calculation values due to the measurement errors and processing errors. The error between numerical simulation and real experimental is less than 20%. The changing of crown shape agrees well with that of model.

The numerical simulation can predict the crown shape. Using the model of crown shaping, the processing parameters can be chosen according to the desired crown shape in advance, which can effectively reduce the production cost, control the accuracy of crown shaping and avoid processing failure.

6. CONCLUSIONS

In this paper, a compound process named ECMM was proposed to generate the crown shape of bearing; a theoretical model has been developed to describe the relationship of the profile of bearing and machining parameters.

The model has been verified by experiments. The difference between the experimental results and the theoretical ones is less than 10%. To avoid the over cut in ECMM, the equilibrium gap was taken as a constrain to determine the initial gap and the processing time. Based on the simulate results, the maximum initial gap and the machining time should be less than the time when the gap reaches the equilibrium state. The machining conditions were determined by those for the desired surface quality. The crown shape is controlled by the machining time. Therefore, the required crown shape and the surface quality of bearing could be obtained simultaneously. Experimental results show that the surface roughness of bearing can be reduced form *Ra*0.58 μm to *Ra*0.03 μm in 1-4 minutes.

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References

1. I.A. Zverev, I.U. Eun, C.M. Lee, *Int J Adv Manuf Technol*, 21(2003) 10
2. S. Neagu-Ventzel, S. Cioc, I. Marinescu, *Wear*, 260(2006)1061
3. A. Selvaraj, R. Marappan, *Int J Adv Manuf Technol*, 53 (2011) 5
4. J.V. Poplawski, S.M. Peters, E.V. Zaretsky, *Tribol Trans,* 44(2001) 417
5. H. Krzemiński-Freda, B. Warda, *Wear,* 192(1996)29
6. R.S. Sayles, S.Y. Poon, *Precis Eng*, 3(1981)137
7. H. Huang, H.P. Wang, *Int J Adv Manuf Technol*, 12(1996)37
8. Y.J. Seo, *Microelectron Eng*, 88(2011)46
9. J. Kozak, M. Chuchro, A. Ruszaj, K. Karbowski, *J Master Process Technol*, 107(2000)283
10. J.A. McGeough, Principles of Electrochemical Machining, Chapman and Hall, London (1974).
11. A.R. Mileham, S.J. Harvey, K.J. Stout, *Wear,* 109(1986)207
12. B.G. Acharya, V.K. Jain, J.L. Batra, *Precis Eng*, 8(1986)88
13. R. Mahdavinejad, M. Hatami, *J Mater Process Technol*, 202(2008)307
14. S.H. Ju, T.L. Horng, K.C. Cha, Proceedings of the Institution of Mechanical Engineers, 214(2000)147

15. M. Purcar, A. Dorochenko, L. Bortels, J. Deconinck, B.Van den Bossche, *J Mater Process Technol*, 203(2008)58
16. M. Purcar, L. Bortels, B. Van den Bossche, J. Deconinck, *J Mater Process Technol*, 149(2004)472
17. J.B. Riggs, R.H. Muller, C.W. Tobias, *Electrochim Acta*, 26(1981)961
18. T. Parthiban, R. Ravi, N. Kalaiselvi, *Electrochem Acta*, 53(2007)1877
19. G.B. Pang, W.J. Xu, X.B. Zhai, J.J. Zhou, *Lect Notes Comput Sci*, 3174(2004)262
20. V.K. Jain, P.C. Pandey, *J Eng Ind*, 103(1981)183
21. V.K. Jain, P.C. Pandey, *Prec Eng*, 103(1980)23
22. S. Bhattacharyya, A. Ghosh, A.K. Mallik, *J Mater Process Technol*, 66(1997)146
23. B. Tao, X.Y. Wang, H.Z. Zhen, W.J. Xu, *Advanced Materials Research*, 24-25(2007)361