EFFECTS OF ANISOTROPY OF FRICTION MATERIAL ON PROPERTIES OF ULTRASONIC MOTOR

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Abstract Three kinds of friction materials of USM with different fiber orientation were developed. A experimental research was carried out on a simulated tester of USM. A simple contact model for describing the contact mechanics between stator and rotor of a traveling wave USM is presented. Using FEM, effects of anisotropy of friction material on contact state of stator and rotor are simulated numerically. The action of fiber orientation of friction material on properties of USM were studied. The results show that the friction material with higher tangential elastic modulus and fiber orientation paralleling with sliding direction is beneficial to improvement of USM performances. The measured results agreed with simulated ones.

1 INTRODUCTION

Ultrasonic motor (USM) is drived by frictional force. In order to enhance drive efficiency and extend useful life, a thin layer of friction material is glued on the rotor surface of USM. Therefore, the performances of the friction material affect the output properties and useful life. To choose the friction material is one of the key technology of USM[1]. Some researchers [2] thought that friction material of USM may have higher tangential elastic modulus and lower normal elastic modulus. Ishii [3] et al obtained experimentally that wear of the friction material with long fiber parallel to both sliding surface and sliding direction was smaller. Recently, the results calculated by Storck and Wallaschek [4] shown that the friction material with higher tangential elastic deformation was suitable for USM, that is, the friction material with higher tangential elastic modulus was better. These results are contradictious each other. Obviously, it shown that no theoretical guidance is currently available to choose the best friction material [5]. Indeed, the elastic modulus and anisotropy of friction material affect obviously contact state between stator and rotor of USM. The contact state affects directly the properties of USM [6]. In order to provide a theoretical guide for designing friction material, the purpose of this research is that investigates influences of anisotropy of friction material on properties of USM.

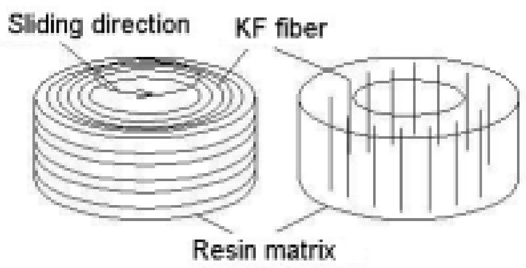
2. EXPERIMENTAL METHODS AND MATERIALS

Test rig

All experiments are carried on a simulated tester friction properties of USM in literature [6]. The stator of simulated USM is chosen from that of a B_{13} mode disc traveling wave ultrasonic motor[7]. Its outer and inner diameter are 40 mm and 14 mm respectively. Average diameter of circumference of stator's tooth is 25 mm. Height of stator's tooth is 4.5 mm. Thickness of PZT disc is 1 mm. Exciting voltage of stator is V_{pp}=100V. the preload between stator and rotor is 21 N. The outer and inner diameter and thickness of friction material are 36 mm, 18 mm and 2 mm respectively.

Sample preparation

Phenolic resin and Kevlar fiber are used as binder and reinforced material respectively. Two kinds of anisotropic friction materials are developed with continuous long fiber. One is that fiber is parallel to sliding direction. Another is that fiber is perpendicular to sliding direction. As shown in figure 1. Their names are PK3 and PK2 respectively. Two kinds of isotropic friction materials are developed with 3 mm ~ 5 mm short fiber and pure resin. Their name are PK1 and PK0 respectively. The performances of these samples are shown in table 1.



a）PK3 *b*）PK2

Figure 1 Fiber orientation of friction materials

Table 1 Performances of friction materials

Sample No.	PK0	PK1	PK2	PK3
Fiber content, wt%	0	45	45	45
Elastic modulus* $E_{//}$	0.24	1.8	1.5	6.56
Elastic modulus* $E_{\perp}$	0.24	1.8	6.56	1.5
Rock hardness, HRM	50	81	71	95
Friction coefficient, *f*	0.44	0.35	0.16	0.32

* $E_{//}$ and $E_{\perp}$ represent that elastic modulus are parallel to and perpendicular to sliding direction respectively.

3. CALCULATED MODEL

FEM contact model

Materials of stator and rotor are shown in table 2. While the stator vibrates at ultrasonic frequency, there are three wave peaks on tooth surface of stator[7]. They contact with the friction material of rotor simultaneously and are symmetrical about 120^o. The distribution of contact stresses on every wave peak is same. A wave length is chosen as analytical area. The FEM contact model is shown in figure 2. Suppose that wave surface of traveling wave in stator is rigid body. Because elastic modulus and Poisson ratio of PZT ceramic are approximate to that of stator material, it is simplified as same material as the stator. Friction material is linear and elastic material and its deformation varies with the wave surface of stator. The matrix of rotor is rigid body. Friction material combines firmly with the matrix of rotor and effects of gluing layer are neglected. Because the tooth's width of stator at radial is much less than the wavelength, the contact problem between stator and rotor is simplified as a plane contact problem with friction. Suppose that stator contacting with rotor is equal to quasi-static state, effects of elastic modulus of friction material on contact state of stator and rotor are researched by ADINA FEM software.

Solved area and conditions

In figure 2, the teeth of stator are supposed as rod rigid body and every tooth is divided into 3 elements. Original displacements in *Y* direction and *Z* direction are given respectively as following equations [6]

Z direction $$w = A_s \sin(\frac{2\pi}{\lambda}(y+\frac{\lambda}{4})) + h + \delta_c \qquad (1)$$

Y direction $$\upsilon = y - (h+\delta_c)A_s\frac{2\pi}{\lambda}\cos[\frac{2\pi}{\lambda}(y+\frac{\lambda}{4})] \qquad (2)$$

Where A_s is the amplitude of stator, A_s=1.5um. h_c is the tooth height of stator, h_c=4.5mm. δ_c is the thickness of neutral layer, δ_c=1.2mm. λ is the wavelength of traveling wave, λ=26.2mm. Total preload between stator and rotor is 21 N. the single contact peak is F_{cz}=7 N. In order to simulate the contact state of stalling, suppose that the load in *Y* direction is F_{cy}=1.616 N. Calculated boundary conditions are given in figure 2.

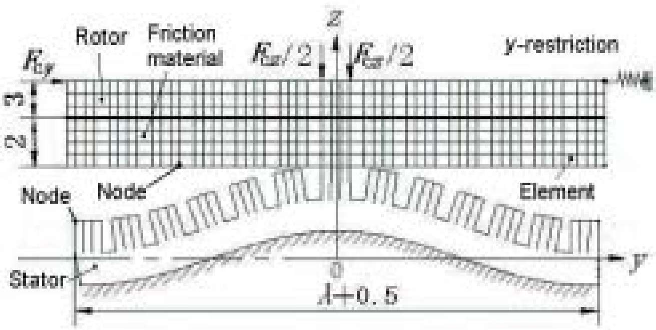


Figure 2 FEM contact model between stator and rotor

Elastic sliding deformation work of contact

In this paper, contact deformation work W_y is defined as the algebraic total of product of every surface node's pressure and their surface displacement in *y* direction in contact region. The W_y describes indirectly one part of loss power from elastic sliding in contact region. The W_y is related to the elastic modulus, friction coefficient and hardness of friction material.

Table 2 Materials of stator and rotor

Element	rotor	Stator	Piezoelectric ceramic
materials	LY12	LY12	PZT4
Elastic modulus	70.0	70.0	73.0
Density ρ/(g·cm^{-3})	2.7	2.7	7.6
Poisson ratio μ	0.33	0.33	0.38

4. RESULTS AND DISCUSSIONS

Experimental results

Drive properties of USM with different friction materials are measured, as shown in table 3. Load power P_f is calculated with following formula

$$P_f = \frac{M_f \times n_f}{K_p} \qquad (3)$$

Where M_f and N_f are load torque and load speed respectively. K_p is a constant coefficient, $K_p = 9.55\times10^3$.

Performances of friction material affect the contact state between state and rotor and properties of USM. From table 1 and 3, the elastic modulus of reinforced isotropic friction material PK1 with short KF is very approximate to that at a certain direction of anisotropic friction material PK2 and PK3. Comparing PK2 with PK1, fixing elastic modulus $E_{//}$, no load speed of USM increases with the increase of elastic modulus $E_{\perp}$, but load power and stalling torque decrease with that. The reason why P_f and M_d decrease is that when the $E_{\perp}$ increases, the contact deformation between stator and friction material decreases and geometric sliding decreases, and then the n_0 increases, but when the contact deformation decreases, frictional drive force decrease, particularly, friction coefficient of PK2 is smaller, the frictional drive force decreases obviously. Comparing PK3 with PK1, fixing the $E_{\perp}$, no load speed and load power and stalling torque increase with the increase of the $E_{//}$. The reason is that when the $E_{\perp}$ is fixed, contact deformation between stator and friction material hardly changes and that when the $E_{//}$ decreases, the loss power generated by elastic deformation at sliding direction may decrease, the transfer efficiency of friction drive and no load speed may increase, particularly, friction coefficient of PK3 is approximate to that of PK1, which makes P_f and M_d increase.

Table 3 Drive properties of friction material

Sample No.	PK0	PK1	PK2	PK3
Load torque M_f, 10^{-3} N • m	6.25	6.25	6.25	6.25
Load speed n_f, r/min	90	142	130	155
Load power P_f, 10^{-5} KW	2.4	3.7	3.4	4.1
Stalling torque M_d, 10^{-2} N • m	1.38	2.70	1.13	2.81
No load speed n_0, r/min	140	190	195	198

Simulated calculations

From the contact model in figure 2, effects of anisotropic friction material on contact state between stator and rotor are simulated numerically. Calculated results are shown in table 4. From table 4, if the elastic modulus $E_{\perp}$ is fixed at 1.48 GPa and the elastic modulus $E_{//}$ increases from 1.48 GPa to 6.56 GPa, the contact deformation work W_y decreases by 39.2 %. The result shows that the elastic sliding loss power at sliding direction decreases and the transfer efficiency of USM increases. The theoretic analysis agrees with the experimental results.

Table 4 Contact deformance work ($\times 10^{-7}$ N.m)

Elastic modulus $E_{\perp}$, GPa	Elastic modulus $E_{//}$, GPa			
	0.5	1.48	6.56	7.0
0.5	0.22* (5.02)	0.15 (5.27)	—	—
1.48	0.25 (2.7)	0.15 (2.35)	0.09 (2.19)	—
6.56	—	0.09 (0.99)	—	—
7.0	—	—	—	0.08 (0.69)

* （）Numberes in bracket are the contact deformance work at normal direction

The conclusion that anisotropic friction material with higher elastic modulus parallel to sliding direction improves drive properties of USM is reached. However, anisotropy of friction material affects its friction properties. When to increase the $E_{\perp}$ and the $E_{//}$ of friction material, it is necessary to keep its friction coefficient from changing or decreasing. When to use the reinforced friction material with fiber parallel to sliding direction and higher friction coefficient, drive properties of USM become better, when to use the reinforced friction material with fiber perpendicular to sliding direction, that of USM become worse. The elastic modulus $E_{//}$ is in relationship with the elastic modulus $E_{\perp}$. When the $E_{//}$ increases, the $E_{\perp}$ must be controlled in certain optimum value, so that the contact deformation between stator and rotor is most reasonable. In order to obtain bigger friction drive force, the deformation at *Y* direction is smaller, drive properties of USM are better. If the $E_{//}$ is smaller, the elastic sliding in Y direction is larger, loss power and wear of friction material increase. Therefore, it is beneficial to apply anisotropic friction material to USM in order to improve its drive properties.

5. CONCLUSIONS

A method is proposed to estimate the effects of anisotropy of friction material on drive properties of USM. The anisotropic friction material that it is reinforced with fiber parallel to sliding direction and that its tangential elastic modulus is larger makes output performances of USM good. The results have been confirmed by experimental investigation and theoretical analysis.

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