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Research on control method for machining non-cylinder pin hole of piston*

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Abstract: The control method for machining non-cylinder pin hole of piston was studied systematically. A new method was presented by embedding giant magnetostrictive material (GMM) into the tool bar proper position. The model is established to characterize the relation between control current of coil and deformation of tool rod. A series of tests on deformation of giant magnetostrictive tool bar were done and the results validated the feasibility of the principle. The methods of measuring magnetostrictive coefficient of rare earth GMM were analyzed. The measuring device with the bias field and prestress was designed. A series of experiments were done to test magnetostrictive coefficient. Experimental results supplied accurate characteristic parameter for designing application device of GMM. The constitution of the developed control system made up of displacement detection and temperature detection for thermal deformation compensation was also introduced. The developed machine tool for boring the non-cylinder pin hole of piston has the micron order accuracy. This control method can be applied to other areas for machining precision or complex parts.

Key words: Giant magnetostrictive material (GMM), Piston, Non-cylinder pin hole, Control method
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INTRODUCTION

With the development of engine power and rotational speed, the load of pin hole of piston is more and more heavy. By analyzing the load of common cylindrical pin hole, the load of each part of the pin hole is asymmetric when the engine is working. The stress of inner side is the most and that of the outer side is the least. So, to improve engine performance, people reduce the stress concentration of the inner side of the pin hole by changing the geometric shape and improve stress distribution to lengthen the engine life. This non-columniform pin hole is called "non-cylinder pin hole" (Suhara *et al*., 1996; Wu and Wu, 1994). There are many methods for machining non-cylinder pin hole of piston, such as lever tool rod machining, eccentric tool rod machining, eccentric spindle machining and profiling or boring machining (Weng and Weng, 1998; Hu *et al*., 1999; Lu, 1999; Xu *et al*., 1999). All these methods need to use mechanical part and profiling, so there are many disadvantages, such as complex structure, high manufacturing accuracy, easy to wear and difficulty in guaranteeing the process precision. Therefore, in accordance with the present situation of non-cylinder pin hole of piston, a new method for controlling tool distortion based on a new type of function material giant magnetostrictive material (GMM) is presented. The control principle and implement for machining non-cylinder pin hole are mainly studied in this paper.

MACHINING PRINCIPLE

Magnetostrictive principle

In magnetic field, some materials will be extended or shortened along the magnetic direction. This phenomenon is called magnetostrictive effect.

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The reason is that ferromagnetic or ferrimagnetic material will cause spontaneous magnetization to form magnetic domain below the Courier point. In each magnetic domain, crystal lattice deforms in the direction of magnetization intensity. When applying external field, the randomly oriented magnetic domain rotates so that its magnetization direction corresponds with the direction of the external field and these materials show macroeffect, which extends or shortens along the external field. The value of magnetostriction is calculated by magnetostrictive coefficient λ.

Machining principle

The structure of tapered pin hole, shown in Fig.1 of an inverse taper with small size outside and large size inside with diameter difference of 0.01~0.04 mm generally. Since the difficulty of machining tapered pin hole of piston is the two tapered parts, the system must have the ability to produce a micro-radial feed between boring tool and workpiece when the boring tool cuts the pinhole's inner side. A control method of bending the tool rod is adopted in this system, e.g., when machining tapered parts, the tool rod produces a micro-bending distortion step by step to make the cutting radius of the boring tool achieve a corresponding tiny increment ΔR. To make the tool rod bend, the magnetostrictive distortion characteristic of GMM is used. The GMM is embedded into the proper position of the tool rod (Fig.1). The structure of the non-cylinder is shown in Fig.2. The tool rod will produce corresponding bending distortion with the stretching or shortening of GMM when the peripheral magnetic field changes. Since the changes of magnetic field can be controlled by changing coil current, so the tool rod's bending distortion can be realized by coil current.

The increment of radius of boring tool ΔR has functional relation with coil current I. First, the relation between ΔR and ΔL (extension of GMM) is discussed. As a result of the distortion of GMM, a tiny turning angle θ is produced in boring rod (Fig.2).

$$L_1=L\sin\theta, \quad L_2=R\cos\theta,$$
$$\Delta R=L_1+L_2-R=L\sin\theta+R\cos\theta-R. \tag{1}$$

For a very little θ, $\sin\theta=\theta$, $\cos\theta=1$. So

$$\Delta R=L\theta, \tag{2}$$

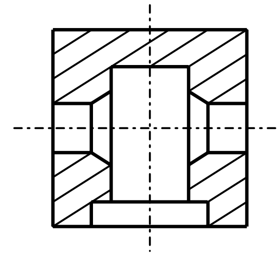

Fig.1 Structure of non-cylinder pin hole of piston

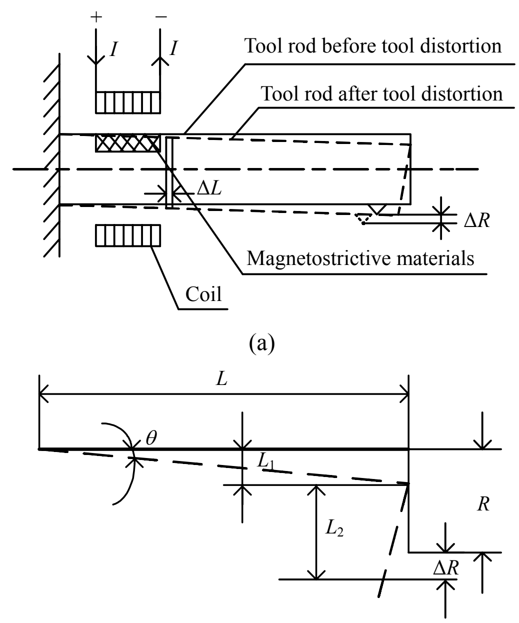

Fig.2 Distortion principle of the GMM tool rod
(a) The embedded GMM tool rod; (b) A tiny turning angle θ of the rod

where θ is proportional to ΔL approximately.

$$\theta=K\Delta L,$$

where K is the scale coefficient, so

$$\Delta R=KL\Delta L. \tag{3}$$

Secondly, for the electrified spiral with tight wind, the relation between its internal magnetic density H and the current I is:

$$H=\mu I,$$

where μ is permeability.

The value of magnetostriction is calculated by magnetostrictive coefficient $\lambda=\Delta L/L'$, where L' is the length of GMM. The relation between λ and magnetic density H is only decided by the characteristic of GMM, described as:

$$\lambda=F(H).$$

So

$$\Delta L=\lambda L'=L'F(H). \quad (4)$$

Deducing from Eq.(3) and Eq.(4), the relational expression between the increment of boring tool ΔR radius and coil current I is:

$$\Delta R=KLL'F(H),\ H=\mu I. \quad (5)$$

From the distortion principle of GMM tool rod and analysis on distortion, the relation between its control current and tool rod distortion is stable as long as the control current of the drive coil is so high that the tool rod can produce enough distortion of pin hole machining, so the purpose of using distortion of giant magnetostrictive tool rod to machine non-cylinder pin hole can be realized.

EXPERIMENT AND ANALYSIS

The following distortion experiment and analysis validate the feasibility of the control principle of machining non-cylinder pin hole fully.

(1) A series of experiments were done to verify whether the tool rod distortion is enough to meet the need of machining non-cylinder pin hole or not. The results are shown in Table 1 showing that the increment of the boring tool cutting radius ΔR can reach 28 μm when the coil current I reaches 2 A. Since the difference between big end and small end of tapered pin hole Δ is usually less than 28 μm, so the tool rod distortion is enough to meet the need of machining non-cylinder pin hole.

(2) Whether the relation between the increment of the boring tool cutting radius ΔR and coil current I is steady or not. Since the relation between the elongating value and magnetic density is decided by the material characteristics under the condition of definitive coil parameters, the relation between ΔR and I is steady theoretically. Many of experiments have been done proving that the relation curve of ΔR-I has very good consistency and that a good linear range exists. This result provides reliable basis for realizing the system. Fig.3 shows the relation curve of ΔR-I, which is comprised of the three segments below:

(1) From 0 to 0.5 A, ΔR offsets inversely with the increment of the current and returns to zero when I rises to about 0.4 A, then it offsets forward. In practical application, this segment should be truncated.

(2) When I rises from 0.5 A to 1.4 A (E~F segment), ΔR increases linearly between ΔR and I. In practical system, this segment is the working segment.

(3) After I rises to 1.4 A, the linear relation becomes bad.

Table 1 Relation between control current of coil and deformation of tool rod

I (A)	ΔR_1 (μm)	ΔR_2 (μm)	ΔR_3 (μm)
0	0	0	0
0.2	−2.0	−2.1	−2.1
0.4	0.7	0.6	0.7
0.6	3.1	3.2	3.2
0.8	7.2	7.1	7.2
1.0	11.9	11.7	12.1
1.2	16.4	16.3	16.6
1.4	20.7	20.3	20.6
1.6	24.1	23.7	24.0
1.8	26.5	26.5	26.6
2.0	28.7	28.8	28.7

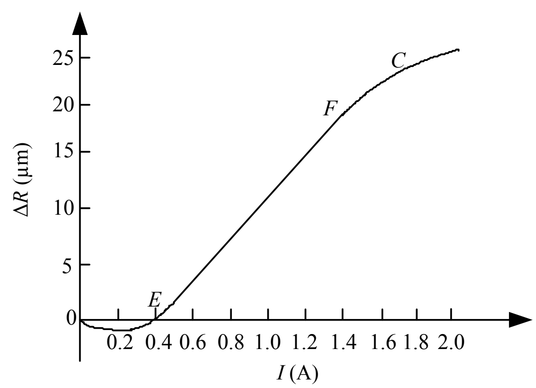

Fig.3 Experiment result between control current and deformation of tool rod

The control of machining tapered pin hole is realized by using the linear range of ΔR-I and the measured quantity of distortion can meet the actual demand of machining control. The increment of cutting radius of boring tool can be enlarged only some mathematical treatments on C segment (Fig.3). According to the control principle of machining and the results of experiments, this method has many advantages compared to the traditional control of mechanical profiling, such as simple structure, less influence on mechanically-driven, high precision and low cost with minimal amount of GMM.

MEASURING OF MAGNETOSTRICTIVE COEFFICIENT

Methods of measuring magnetostrictive coefficient

Deep research on GMM showed that in addition to external factor, like work condition, characteristic parameters are more influenced by internal factors, such as chemical composition, phase composition, impurity composition, grain structure and orientation, which depend on technology and the environment of material preparation. A great difference exists though in the same group of production. So tests on the performance of GMM must be done before using the materials to ensure rationality of design and utilizing their excellent functions. Based on GMM, methods of measuring magnetostrictive coefficient are discussed and a series of experiments were done.

From the point of engineering application, magnetostrictive coefficient λ is the important characteristic parameter of GMM and is the base of design and calculation of key factors which decide performance of application devices. There are two methods of measuring magnetostrictive coefficient:

(1) Strain gauge method.

The definition of strain ε in mechanics is the same as that of magnetostrictive coefficient λ, so λ can be tested by strain gauge. Strain gauge is applied on the surface of test sample, and then strain capacity is recorded with strain instrument and oscilloscope under low magnetic field excitation and other different conditions. To improve the measuring accuracy, strain gauge can be applied on multiple parts of the test sample and the average can be obtained by strain instrument (Liu, 1979).

(2) Displacement method.

The main method of measuring magnetostrictive coefficient is resistance strain method. Displacement transducer or digital micron meter also can be used in measuring with relevant equation but can be easily generated (Wan *et al*., 2002; Xia *et al*., 1999). The dilatation value of magnetostrictive materials is measured by $\lambda=\Delta l/l$. Since distortion value is on micron level, the accuracy of displacement transducer must be very high, with the accuracy and resolution of displacement transducer having much to do with the measuring results.

Design of measurement device

From the above discussion, strain gauge method is used to measure magnetostrictive coefficient λ. The device for measuring rare earth GMM is shown in Fig.4 composed of drive, prestressing, bias field, measure force, displacement and strain. The test rod ($TbDyFe_2$) size is 60 mm in length and 8 mm in diameter. The GMM rod is properly prestressed by a combined device, which includes beam, crutch, nut, spring and crown bar, and the pre-stress can be displayed by digital dynamometer at the bottom of device. Fixing device made by base plate, pallet, crutch, beam and nut, must have good rigidity to reduce stress deformation as much possible. The closed magnetic loop, made of soft iron, can reduce most leakage magnetic flux. The extension is measured by electric eddy current displacement transducer placed on beam, and the disc on crown bar not only bears and transfers the stress of the spring, but acts as the detection object of the displacement transducer (Benatar and Flatau, 2005).

Current feedback power amplifier, which produces driving magnetic field, supplies exciting current to the main coil and DC regulated power supplies

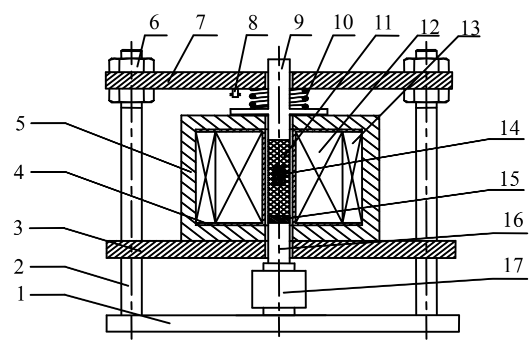

Fig.4 Skeleton drawing of measurement device for magnetostrictive coefficient
1: Base plate; 2: Crutch; 3: Pallet; 4: Shell; 5: Magnetic loop made of soft iron; 6: Nut gasket; 7: Beam; 8: Displacement transducer; 9: Crown bar; 10: Spring; 11: GMM rod; 12: Main excitation coil; 13: Offset coil; 14: Strain gauge; 15: Hall transducer; 16: Dowel steel; 17: Dynamometer

bias current. Not considering coil induced current, magnetic field strength varies linearly with input current approximately. So changing coil current can control magnetic field strength. The schematic diagram of the measurement system is shown in Fig.5. Magnetic induction of rare earth GMM rod is detected by Hall transducer. Then relative permeability, driving magnetic field strength and the relation between input current and magnetic field strength can also be obtained.

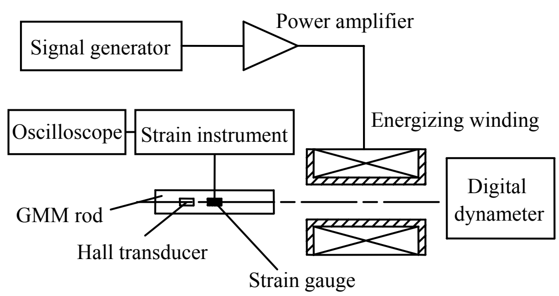

Fig.5 Schematic diagram of test system

Results of measuring magnetostrictive coefficient

A series of experiments were done to test axial magnetostrictive coefficient of homemade rare earth GMM with the results being the same under the same conditions. The experimental error can be controlled within 5%. Under low magnetic field excitation, the magnetostrictive coefficient has a certain change with prestress but the change is not obvious with the bias field. When prestress is 503 N and bias magnetic field strength is 39.8 kA/m, the maximum magnetostrictive coefficient could be up to 1100×10^{-6} in linear area at 45 °C and saturation magnetostrictive coefficient could reach 1800×10^{-6}. Fig.6 shows how magnetostrictive coefficient changes with driving magnetic field strength and experimental data are shown in Table 2.

Table 2 Magnetostricitive coefficient of homemade rare earth GMM

H (kA/m)	λ ($\times10^{-6}$)	H (kA/m)	λ ($\times10^{-6}$)
0.1	31	0.9	1268
0.2	50	1.0	1327
0.3	324	1.5	1528
0.4	624	2.0	1657
0.5	843	2.5	1715
0.6	1000	3.0	1753
0.7	1125	3.5	1772
0.8	1203	4.0	1779

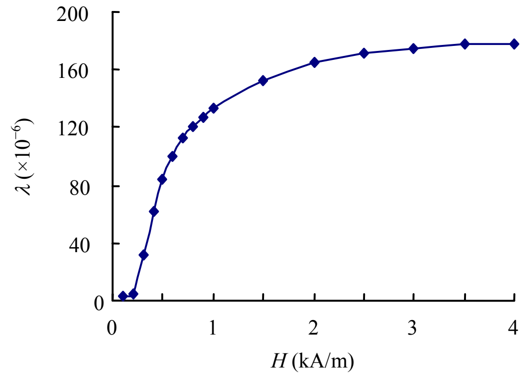

Fig.6 Experimental results between magnetic field strength and magnetostrictive coefficient

CONTROL SYSTEM

Based on the above control principle and considering the strict requirement for axiality of pin hole and verticality of piston axial cord, the control system is made by special boring machine used for machining tapered pin hole. The main control task of the system is to measure the axial position of the workpiece, supply stable and adjustable current to drive coil and change the GMM magnetic field, then a radial amount of feed varying linearly with the workpiece's axial position is attained. The relation between control current and axial displacement is shown in Fig.7. To guarantee the strict synchronization between increment of the boring tool cutting radius and the machine's axial feed movement, inductosyns are fixed on the slide carriage and bed. With the position detection signal of inductosyns being sent to control system through digimatic gauge,

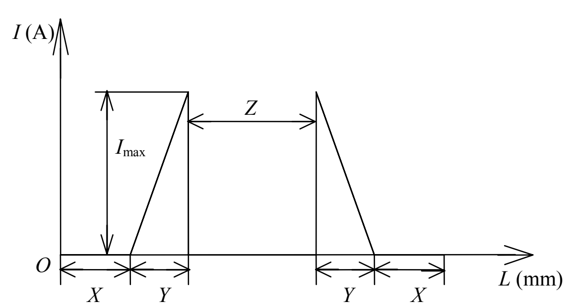

Fig.7 Relation between control current and axial position of non-cylinder pin hole

X: Cylindrical length of tapered pin hole; Y: Taper length of tapered pin hole; Z: distance between two tapered pin holes on two sides of piston; I_{max}: Maximal value of coil current, which is decided by Δ of taper pin hole the whole system will work harmoniously. Moreover, considering that the tool rod easily generates heat deformation after long run, temperature-detecting subsystem is configured to allow for thermal compensation (Pérez-Aparicio and Sosa, 2004; Calkins *et al*., 2000).

The control system shown in Fig.8 includes main control system, constant-current source driving subsystem, axial position detecting subsystem and temperature detecting subsystem.

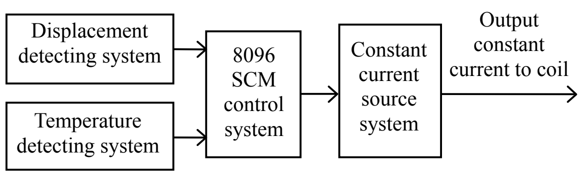

Fig.8 Main modules of control system

When machining the pin hole of tapered piston, the boring rod which is fixed on spindle, rotating with high speed, deformed. The piston, fixed on a small saddle, moves along longitudinal direction. The control system controls the output of the constant-current based on the axial position of the saddle measured by inductosyn. When the saddle moves to the non-tapered part as shown in Fig.7, constant-current output is zero. The GMM boring rod had no distortion and the diamond boring tool located at the end of the deformed boring rod and borings cylindrical hole. When saddle moved to the tapered part, the GMM boring rod distorted gradually and the diamond boring tool generated radial feed step by step to complete the machining of the non-cylinder pin hole. The products have reached micron-level, which meet the machining quantity requirement of enterprises.

CONCLUSION

The non-cylinder pin hole of piston not only reduces stress concentration of the inner side and improves stress distribution, but also optimizes the piston's heat load. So it is valuable for high efficiency engine and has become an import direction of development of the international piston industry. This paper, which makes use of distortion characteristics of GMM, develops the control system of machining non-cylinder pin hole and resolving successfully the actual question of machining non-cylinder pin hole in enterprise. The idea based on GMM distortion control can be applied to the areas of precise or complex mechanical machining control.

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