Applied Thermal Engineering 86 (2015) 251–268

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Simulation and experimental study on the thermally induced deformations of high-speed spindle system

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HIGHLIGHTS

- A systematic modeling method of spindle thermal characteristics is proposed.
- A systematic characterization and modeling method of TCR is proposed.
- TCR modeling is based on morphological characterization and mechanical properties.
- TCR and bearing stiffness have a notable impact on spindle's thermal characteristic.
- The algorithm select contact angle as iteration variable to improve convergence.

ARTICLE INFO

Article history:
Received 8 October 2014
Accepted 20 April 2015
Available online 5 May 2015

Keywords:
High-speed spindle
Finite element analysis
Temperature field
Thermal errors
Thermal contact resistance
Fractal theory

ABSTRACT

In order to avoid the degeneration of high-speed spindle's machining accuracy in actual machining caused by the uneven distribution of temperature field at the design stage, a three-dimensional (3D) finite element analysis (FEA) model, which considered the combined influence of thermal contact resistance (TCR) and bearing stiffness on the accuracy of simulation results, was proposed to conduct transient thermal-structure interactive analysis of motorized spindles. And the method to calculate the boundary conditions used in the FEM model were discussed in detail, such as the heat loads, convective heat transfer, TCR and bearing stiffness. Based on the quasi-static mechanics analysis of rolling bearing, the transfer relationships among multiple variables in the equilibrium equation set of bearings were analyzed. Newton–Raphson algorithm, which regarded the contact angle as the iteration variable, was proposed to calculate the heat power and stiffness of bearings and improve the convergence of the algorithm, and the termination criteria of contact angle's searching trial calculation was proposed to improve the accuracy of the algorithm. The Weierstrass–Mandelbrot (W–M) function in fractal geometry was used to characterize the rough surface morphology of bearing rings. The fractal parameters were identified by the power spectrum method, and a contact deformation model of asperities was developed to calculate the contact parameters used in the TCR modeling. Then, the predictive model for TCR, which considered the combined effect of the morphology of bearing rings and the contact deformation of asperities, was proposed. Thermal equilibrium experiments were conducted to demonstrate the validity of the model. The results showed that the FEA model can accurately simulate the temperature field and thermal deformation of the spindle system and that the FEA model was much more accurate than the traditional thermal model of the high-speed spindle system which ignored TCR and bearing stiffness.

1. Introduction

It is the lifelong pursuit for researchers to improve the CNC machine tool's machining accuracy. And the error of machine tools can be divided into three categories: geometric, thermal and cutting force-induced errors. Among all these errors, thermal induced errors account for more than 50% of the total error of a machine tool [1]. Moreover, motorized spindle is a core component of machine

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http://dx.doi.org/10.1016/j.applthermaleng.2015.04.064
1359-4311/

tools. However, this compact structure combing the built-in motor and high-speed bearings introduces a large amount of heat into the high-speed spindle system. Besides, the heat dissipation condition is poor, the material properties of the components are different and the structure of the spindle system is complex. The interactive influence of such factors as heat source's location and intensity, heat dissipation condition, material properties and structure may produce complex thermal characteristics. For example, the uneven distribution of internal and external heat sources causes elastic thermal deformation of spindle's components, resulting in geometric and shape errors of the machined workpieces. Therefore, it is essential to study the thermal characteristics of high-speed spindles to avoid the degeneration of CNC machine tool's machining accuracy.

The numerical analysis method has been used to analyze the distribution of the temperature field and variation of thermal deformation of machine tools in recent years. Bossmanns and Tu [2] characterized the heat generation, heat transfer and heat sinks of high-speed spindles based on finite difference method (FDM). Lin et al. [3] presented an integrated model to study various thermo–mechanical–dynamic spindle behaviors at high speeds. The finite element method (FEM) was applied to improve the thermal characteristics and machining accuracy of the spindle bearing system by Kyung et al. [4]. Mori et al. [5] used FEM to optimize the structure of a headstock of NC lathes and minimize the thermal deformation of the spindle's center line. Zhao et al. [6] simulated the temperature field and thermal errors of the spindle under the actions of thermal loads and heat dissipation. Creighton [7] and Chen [8] analyzed the variation of temperature field and thermal errors of machine tools based on FEM to improve the machining accuracy of machine tools. The heat generation and heat transfer were regarded as the important boundary conditions for thermal analysis in the models mentioned above. However, the influence of TCR and bearing stiffness were ignored in the above models because the difference between the heat transfers of continuum and joint surface and the influence of bearing stiffness on thermal deformation were not identified. Zahedi [9] and Uhlmann [10] developed bearing spindle's thermodynamic models taking TCR into consideration. However, TCR was regarded as an empirical constant and the combined effect of the rough surface morphology and contact deformation of asperities on TCR was not considered in their models. In fact, it is unreasonable because the strongly nonlinear relationship between TCR and such factors as rough surface morphology, contact area, interface pressure, contact deformation modes and material properties. Namely, TCR is a complex interdisciplinary problem, including geometry, mechanical and thermal sub-problems. Moreover, the basis for TCR modeling is the characterization of rough surface morphology and the core of a TCR analysis is its mechanical issue.

The statistical and experimental methods were used to characterize the morphology of rough surfaces [11,12]. However, the statistical method [11] was sensitive to the sampling length and resolution of the measuring instrument when the disorder, nonstationary random and self-affinity features of rough surfaces were characterized. And the method based on experiments [12] had its own disadvantages, such as the poor generality, worse adaptability and some uncertainties. When any one among such factors as material, mean roughness and the contact pressure change, the experiment has to be redesigned to identify the empirical constants in the correlations. Therefore, it is essential to propose a new kind of characterization method which is independent of the sampling length and the resolution of the measuring instruments and can reflect the inherent properties of rough surfaces.

The deformation of the asperities of the rough surfaces is difficult to be predicted according to the traditional elastic and plastic deformation laws, in which the Hertz contact theory [13] is commonly used. However, the traditional elastic and plastic deformation laws only considered the macrocontact problem of rough surfaces. As is known to all, the rough surface consists of various scales of asperities. However, the microcontact problem of asperities was ignored. And the deformation of the asperities has a significant effect on the actual contact area of two contacting rough surfaces which directly determined the value of the TCR. Moreover, three modes of deformation: elastic, elastic–plastic and plastic deformations occur when two rough surfaces are in contact with each other. However, the traditional contact mechanics models ignored the entire deformation process of asperities. Therefore, it is necessary to propose a new contact mechanics model to consider the entire deformation process of asperities.

On the other hand, the influence of bearing's stiffness on thermal deformation of the spindle system was ignored. In fact, bearing's axial and radial stiffness has great effect on the thermal deformation of the spindle system, and hence the bearing's stiffness should be considered. However, the convergence and accuracy of the traditional Newton–Raphson algorithm, which is used to calculate the stiffness and heat generation of bearings, was poor [14]. Therefore, it is essential to analyze the transfer relationship among variables in the balance equation set of bearings. Moreover, the iteration variable should be selected reasonably and the searching area of the iteration variable should be reduced to improve the convergence and accuracy of the algorithm.

The framework of this paper is as follows. Section 2 proposed the FEA model which considered such boundary conditions as heat powers of the built-in motor and bearings, convective heat transfer coefficients, TCR and bearing stiffness. Besides, the calculation methods of boundary conditions were discussed in detail. Based on the quasi-static mechanics analysis on rolling bearings, the transfer relationships among multiple variables were analyzed and the contact angle was selected as the iteration variable to improve the convergence and accuracy, and the searching area of the contact angle was reduced by half to accelerate the convergence rate. Then, Newton–Raphson algorithm was applied to calculate the heat power and stiffness of bearings. The heat power of the built-in motor was calculated based on the efficiency analysis. The fluid's flow state was determined by Reynolds number, and the convective heat transfer coefficients of the spindle's different components were calculated based on Nusselt number. A geometry–mechanical–thermal predictive model for TCR was proposed to consider the combined effect the morphology of bearing rings and contact deformation of asperities. The Weierstrass–Mandelbrot function in fractal geometry was applied to characterize bearing ring surfaces, and a contact mechanics model, taking three deformation modes of elastic, elastic–plastic and plastic into account, was established. Section 3 introduced the experimental setup and measuring principles and conducted thermal equilibrium experiments to demonstrate the validity of the model. Section 4 presented the simulation results. Section 5 compared the simulation and experiment results. And the results showed that the FEA model can accurately simulate the temperature fields and thermal deformation of the spindle system from the cold to thermal equilibrium states and that the FEA model was much more accurate than the traditional one which ignores TCR and bearing stiffness. Section 6 presented the conclusions obtained from the above analysis.