Available online at www.sciencedirect.com
SCIENCE DIRECT
International Journal of Machine Tools & Manufacture 46 (2006) 1892–1900
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE
DESIGN, RESEARCH AND APPLICATION
www.elsevier.com/locate/ijmactool

A study of dynamic stresses in micro-drills under high-speed machining

Pei Yongchen, Tan Qingchang, Yang Zhaojun*

Institute of Mechanical Science and Engineering, Jilin University, Nan-ling Campus, Changchun, 130025, PR China

Received 22 March 2005; received in revised form 20 October 2005; accepted 28 October 2005
Available online 9 December 2005

Abstract

In this paper, a dynamic model of micro-drill-spindle system is developed using the Timoshenko beam element from the rotor dynamics to study dynamic stresses of micro-drills. The model includes effects of eccentricity of the spindle-clamp-drill system, the axial drilling force, the system rotational inertia, the gyroscopic moment, and bearings of micro-hole drilling machines on bending deformation of micro-drills during machining. After the model is verified using the published work, effects of the clamped length of micro-drills, the bearing stiffness and damping, the spindle speed, the system eccentricity, and the axial drilling force on dynamic stresses of micro-drills are analyzed using the model.

Keywords: Rotor dynamics; Micro-drills; Dynamic stress

1. Introduction

The application of micro-holes is increasing with the development of astronavigation, electronic industry, and medical apparatus. Many instruments being miniaturized and lightened, which often require machining holes with both high accuracy and small diameters. Small holes usually are machined in industry using drills. High-speed drilling is an economic method to machine micro-holes with good accuracy, and is suitable for machining many kinds of workpiece materials.

Spindle speeds of micro-hole drilling machines are $(1\text{–}12)\times 10^4$ r/min and micro-drill diameters less than 1 mm. The micro-drills break easy during machining since their diameters are small and it is difficult to detect the drill wear [1]. Now, there are two ways to deal the problem. The first is that the vibration drilling and the work monitoring are used to improve and control the machining process [2], preventing micro-drills from breaking. The second is that turning precision and rotating stability of the drilling system, which includes the drilling machine spindle, the drill clamp and the micro-drill, are increased to decrease dynamic stresses in micro-drills. In order to improve turning precision of the drilling system, dynamic properties of the drilling system have been analyzed under high-speed drilling in three stages: when a micro-drill does not contact a workpiece, when it just contacts a workpiece, and when it penetrates a workpiece respectively.

For dynamic properties of the drilling system, Ref. [2] studied transverse displacement of a micro-drill tip when it just contacted a workpiece, but this work did not consider effect of dynamic properties of the drilling system on the drilling process. Ref. [3] established a dynamic model of micro-drill-spindle system with finite element methods. The model considered the effects of micro-drill shear deformation, rotational inertia, gyroscopic moment, drill screw slots, and spindle speed on dynamic properties of the drilling system. Ref. [4] developed three boundary conditions for wandering motion of micro-drills when a micro-drill did not contact, just contacted, and penetrated a workpiece. Ref. [5] studied a special instrument to monitor axial force and torque of micro-drill machining, to enable suitable tool change times to be predicted.

However, the above work did not study effects of micro-drill bending, eccentricity of the drilling system, and the spindle speed on stresses of micro-drills. Effects of the bending and eccentricity on the stresses cannot be analyzed using the axial drilling force and drilling torque measured in Ref. [5]. This is because the measured axial force and

*Corresponding author. Tel./fax: +86 431 5095757.
E-mail address: yzj@jlu.edu.cn (Y. Zhaojun).

0890-6955/$ - see front matter
doi:10.1016/j.ijmachtools.2005.10.017

Nomenclature

A	cross-sectional area of a shaft element
A_i	cross-sectional area of various shaft segments
A_1	cross-sectional area of the checked shaft
C	the bearing damping
c_x, c_y	the bearing damping coefficient in x- and y-directions
E	the Young's modulus
e_x, e_y	eccentricities of an element centroid with respect to the turning axis in x-and y-directions
d^e	diameter of a shaft element
G	the Shear modulus
L	length of a shaft element
L_c	length of the checked shaft
L_1	span between the two bearings
L_2	length from drill tip to the bearing positioned down
L_1/L_2	cantilever ratio of the drilling system
I	inertia moment of a shaft element
I_1	inertia moment of the checked shaft
I_d	quadrate moment of the shaft per unit length
I_p	quadrate-polar moment of the shaft per unit length
k	Shear coefficient of the material
k_x, k_y	the bearing stiffness in x- and y-directions
J_i	polar inertia moment of various shaft segments
P	axial drilling force
r	radius of the checked shaft
s	axial position from an element end, seeing Fig. 2
T	drilling torque
T^e	kinetic energy of a shaft element
t	time
U^e	potential energy of a shaft element
x, y	the deformed displacements of the drilling system in x- and y-directions
x_b, y_b	displacements from the bending deformation in x- and y-directions
x_s, y_s	displacements due to shear deformation caused by the bending in x- and y-directions
$x_c, y_c, \dot{x}_c, \dot{y}_c$	displacements and velocities of the bearing center in x- and y-directions
ρ	mass density of the material
θ_x, θ_y	angle displacements in x- and y-directions
Ω	the spindle speed
ω	the natural frequency
$\bar{\omega}$	dimensionless form of the natural frequency
σ_{ca}	the calculated stress
σ_q^e and τ_q^e	bending and shear stresses of a shaft element from the bending
δW^b	virtual work produced by the bearing force
δW^e	virtual work produced by centrifugal force of an element
$[C_1^e]$	damping matrix of a shaft element
$\{F_{1_{sin}}^e\}$ and $\{F_{1_{cos}}^e\}$	the generalized force vectors of a shaft element
$[K_1^e]$	stiffness matrix of a shaft element
$[K_{p1}^e]$	an element stiffness matrix due to the axial drilling force
$[M_1^e]$	mass matrix of a shaft element
$\{N\}, \{N_\theta\}$	vectors of the shape functions
$\{q_u^e\}, \{q_v^e\}$	the generalized displacement vectors of any element nodes in x- and y-directions
$\{\ddot{q}_u\}, \{\dot{q}_u\}, \{q_u\}$	acceleration, velocity, and displacement vectors of all element nodes of the drilling system in x-direction
$\{\ddot{q}_v\}, \{\dot{q}_v\}, \{q_v\}$	accelerate, velocity, and displacement vectors of all element nodes of the drilling system in y-direction
$\{A\}$	amplitude vector of the bending deformation at any position of the spindle-drill system
$[C]$	matrix of the system damping
$\{F_{sin}\}$ and $\{F_{cos}\}$	vectors of the generalized forces of the system
$[K]$	stiffness matrix of the system
$[K_p]$	the system stiffness matrix due to the axial drilling force
$[M]$	mass matrix of the system
$\{Q\}$	the system generalized forces in the complex form
$\{z\}$	the system generalized displacements in the complex form

torque relate to forces acting on cutting part of micro-drills, and do not contain the effects of the bending and eccentricity. Since the stiffness of micro-drills is small and there is eccentricity in the drilling system, bending deformation of micro-drills will take place due to the axial drilling force and the eccentricity. The high rotational speed of the drilling system increases the amplitude of bending deformation. The bending deformation increases the stress on micro-drills and the stress cannot be analyzed using the measured axial drilling force and torque.

In this work, a dynamic model of the drilling system is developed using the Timoshenko beam element from the rotor dynamics theory. The model contains effects of the drilling system eccentricity, the drilling axial force, the rotational inertia, the gyroscopic moment and the spindle bearings on bending deformation of micro-drills during drilling. The model was verified by the results in published work. Relationships between the bend deformation amplitude of the drills and the clamped length of the drills, stiffness and damping of the bearings, the spindle speed, the eccentricity, and axial drilling force are determined by analyzing the model. From this relationship, stresses on the weakest section are studied using the measured drilling axial force and torque.