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Tool deflection model and profile error control in helix path contour grinding

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ABSTRACT

Because of finite stiffness of grinding system, grinding force will cause the tool deflection (the difference between actual cutting depth and nominal cutting depth). During helix path contour grinding, the grinding condition are variable at different grinding point which will bring forward different tool deflection and result in dimensional errors. This paper presents an error analysis model during multi-pass grinding, which can predict the accumulation process of surface profile error induced by tool deflection. It establishes the relationship between profile error and grinding parameters. The estimation method of key model parameters is described in the proposed model through series of experiments. According to the error analysis model, we can implement the varied feed rate and varied cutting depth method for compensating the profile error. The grinding experimentation and compensation grinding verifies the validity of error analysis model and effectiveness of compensation method, and the profile error reduced by 82.1% comparing with grinding process without compensation.

Contents

1. Introduction

During helix path contour grinding of brittle materials, the grinding force between wheel and workpiece induces material removal. Because the grinding system has not infinite stiffness, grinding force will cause the tool deflection. The deflection

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Nomenclature

$\widehat{d_c}$	actual cutting depth (mm)
$\widehat{R_t}$	wheel radius (mm)
$\widehat{\Delta S}$	cutting area of cross-sectional (mm^2)
L	spiral pitch of helix path (mm)
$\widehat{v_r}$	tangential speed due to the workpiece rotation (mm/min)
r	radial position of the grinding point (mm)
V	removal volumetric of material (mm^3)
$\widehat{v_c}$	cross feed rate (mm/min)
Ω_w	rotation speed of workpiece (rpm)
t	grinding time (min)
K_p	Preston coefficient (mm^2/N)
F	normal grinding force (N)
Ω_t	rotation speed of grinding tool (rpm)
d_{co}	nominal cutting depth (mm)
v_s	relative speed between grinding wheel and workpiece (mm/min)
T	tool deflection (mm)
K_m	cutting stiffness (N/mm)
$d_c(r, n)$	actual cutting depth at position r after nth pass (mm)
$T(r, n)$	tool deflection at position r after nth pass (mm)
n	the number of grinding pass
K_d	non-dimensional parameter
C_v	constant depending on varied feed rate compensation (mm)
r_m	half aperture of workpiece (mm)
v_{co}	feed rate during constant feed rate grinding (mm/min)
C_d	constant depending on varied cutting depth compensation (mm)
d_{cc}	nominal cutting depth during varied cutting depth grinding (mm)

influences by the elastic deformation of wheel and workpiece, the clamping rigidity of workpiece, the finite rigidity of motion axes and so on [1–4]. Moreover since grinding force is a function of grinding parameters [5–7], the amount of force/deflection will vary with different position on the workpiece for helix path grinding, which will result in dimensional errors [8–12]. At the same time, tool deflection brings forward several problems, such as low grinding accuracy and material removal rate, low surface quality and strength degradation due to accumulation of cutting depth in multi-pass grinding [13–17].

It is an effective method for decreasing profile error induced by tool deflection through increasing the static and dynamic stiffness of the grinding system [17,18]. The cost of hardware improvements normally increases exponentially as the grinding precision increasing. So establishing on error analysis model and then developing corresponding compensation method for the surface contour grinding process will be an effective method to enhance grinding precision.

Profile error induced by tool deflection is a universal problem in milling process of curved geometries, and many correlative studying are carried out [3,4,19,20]. The variation amount and direction of cutting force result in profile error along machined path [3,19]. In order to estimate the profile error in various cutting modes, the cutting force and the tool deflection models were established [4,20]. But there is a big difference between milling and grinding process, we need establish a model suitable for grinding process.

In order to analyze the chatter during multi-pass grinding, Li has studied the relationship between grinding force and tool deflection [21], but the profile error has not been mentioned. Huang has developed a discrete system model and an in-process sensing technique to address the partial removal and precision control problems [22,23], but it is improper to guide the precision improvement during contour grinding. A method for in-process manipulation of cutting depth or feed rate to improve the grinding precision was developed by Hekman based on the predicted tool deflection from the modeled compliance and the measured cutting force [24,25]. Due to need real-time measurement of cutting force, the application situation is limited. Tang has proposed a mathematic model to predict the accumulated error between the nominal cutting depth and actual cutting depth in multi-pass surface grinding, and studied the relationship between accumulated error and grinding parameters [26]. The above-mentioned literatures can offer useful reference for the studying in this paper, but further work should be implemented.

The objective of this study is to develop a mathematic model to predict the accumulation process of profile error in surface contour grinding based on the analysis of grinding system and material removal process. According to the error analysis model, varied cutting depth method [24–26] and varied feed rate method [25] for compensating profile error are proposed, which can provide further understanding for the profile error induced by tool deflection and improve grinding precision.

2. Multi-pass grinding model

2.1. Characteristic description of grinding process

Contour grinding process often requires multiple passes grinding to remove grinding mark and subsurface damage leaving by the former grinding process. Single-point contour grinding can be used to generate plane, spherical and aspherical optical surfaces. In contour grinding, a rotating grinding wheel moves simultaneously in two orthogonal directions X and Z axis, and the workpiece rotates around the corresponding rotation axis. The grinding process is just like in the Fig. 1.

The cutting depth $\widehat{d_c}$ and the wheel radius $\widehat{R_t}$ determine the contact arc length $\widehat{AB}$, and the cutting area of cross-sectional $\widehat{\Delta S} \approx Ld_c$ is shown in Fig. 1b. From the geometry relationship, the volumetric removal rate of material will be the product of $\widehat{\Delta S}$ and $\widehat{v_r}$, and it can be donated by Eq. (1).

$$\frac{dV}{dt} = \widehat{\Delta S} v_r \approx L d_c 2\pi r \Omega_w \tag{1}$$

where $\widehat{d_c}$ is the actual cutting depth, $L = BC$ is the spiral pitch of helix path (it is decided by cross feed rate $\widehat{v_c}$ and rotation speed Ω_w of workpiece), r is the radial position of the grinding point on the workpiece. The speed $\widehat{v_r}$ is the tangential speed due to the workpiece rotation ($v_r = 2\pi r \Omega_w$).

On the other hand, the relationship between the load and material removal rate is described by Preston for loose abrasive lapping [27], as follows:

$$\frac{dV}{dt} = K_p F v_s \tag{2}$$

where K_p is the Preston coefficient, F is the normal grinding force and v_s is the relative speed between the grinding wheel and workpiece in grinding point. The Preston coefficient depends on many factors such as the workpiece properties, tool condition and