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Original Research Article

Modeling of cutter displacements during ball end milling of inclined surfaces

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ARTICLE INFO

Article history:
Received 19 February 2015
Accepted 28 June 2015
Available online 1 August 2015

Keywords:
Ball end milling
Dynamics
Run out

ABSTRACT

This work concentrates on the modeling of cutter's displacements during ball end milling with various surface inclinations. The cutter's displacements (vibrations) model including: tool's geometry, cutting conditions, surface inclination angle, run out and tool's deflections (induced by the cutting forces) was proposed. Subsequently, this model was validated empirically during the milling tests with various feed per tooth (f_z), depth of cut (a_p) and surface inclination angle (α) values. Experiments were carried out with the application of laser displacement sensor and force dynamometer. The research revealed that cutter's displacements are strongly affected by the cutter's run out and surface inclination. This observation is also confirmed by the developed model.

1. Introduction

Ball end milling process of the curvilinear surfaces is very often conducted in the finishing conditions, that is, with axial depth of cut, a_p, lower than 0.3 mm and radial depth of cut, a_e, lower than 0.5 mm. For the above-mentioned applications manufacturing tolerances are very narrow, usually within the range 0.05–0.1 mm for stamping dies and less than 0.04 mm for injection molds made of hardened steels [1]. However, the measured form errors in the machined curvilinear surfaces very often exceed 100 μm [2]. Thus, the problem of the quality improvement in the complex surfaces needs extensive studies.

Many of researches related to the machined surface's texture focuses primarily on the influence of the cutting parameters [3]. Nevertheless, the machined surface's quality can be also affected by the other phenomena occurring during cutting, e.g. tool wear [4], burr formation at the edges of the work material [5], machined surface temperature [6] or process stability [7]. Another important source of the problems related to the surface's texture formation is cutter's displacement (vibrations). These displacements are mainly caused by the cutting and centrifugal forces, which induce tool's deflections, but also by the geometrical errors of the spindle–toolholder–milling tool system (e.g. static run out).

The numerous of works are focused on estimation of the tool's displacements on the basis of models which assume solely deflections induced by the cutting forces. As an example, Budak [8] estimated end mill's deflections on the basis of the cantilever and segmented beam models. Subsequently, this model was applied to the estimation of form errors during the peripheral milling of a plate made out of titanium Ti6Al4. Similar approaches were also adopted by Kim

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http://dx.doi.org/10.1016/j.acme.2015.06.008
1644-9665/

et al. [2] and López de Lacalle et al. [9], which were concentrated on the estimation of form and dimensional errors during the ball end milling of KP4M material in semi-finishing conditions and high speed ball end milling of hardened SKD 61 steels. The research results presented in the both works have revealed that errors obtained in the machined surfaces are affected by the machining strategies and surface inclination angles.

Nevertheless, deflection model based on a cantilever beam is not very accurate, but it can be useful to have an aim on the dimensional error's values in machining of complex surfaces. The moderate accuracy of this model can be attributed to the consideration of static deflections, instead of dynamical ones, which in turn are related to the modal parameters of the spindle–tool system and variable force signals. Therefore, the second model is based on the dynamical deflections, which are calculated on the basis of differential motion equation. As an example, Insperger et al. [10] estimated tool's deflections with the application of the standard 2 degrees of freedom oscillator. The model was applied to the assessment of the surface location errors (SLE) during the end milling of AlMgSi alloy in the semi-finishing conditions. The similar approach was presented by Twardowski et al. [11] to the estimation of surface roughness during high speed end milling of hardened X155CrVMo12-1 steel. Furthermore, the differential motion equation model was also applied to the estimation of the work piece's deflection during low radial immersion milling [12] and the surface roughness estimation of the thin wall milling [13]. With reference to the ball end mills, the dynamical deflection model was employed to the estimation of tool tip displacement during semi-finishing of sculptured surface made of CK45 carbon steel [14] and simulation of stability lobe for a ball end milling of titanium Ti6Al4V [15]. Nonetheless, the comparison of the modeled and measured tool's displacements was not presented in these works.

The dynamical deflection model is valid mainly for the machining processes with relatively large cross sectional area of cut values (e.g. roughing, semi-roughing), or/and for the machining with the slender tools. However, during finishing processes or machining with the application of the rigid tools, the geometrical errors of the spindle–toolholder–milling tool system have also the significant meaning. According to Sun and Guo [16] the static run out can significantly affect cutter's sweep surface during five-axis flank milling, and thus machined surface's quality. Additionally, the previous researches [17,18], related to the finishing end milling of the hardened 55NiCrMoV6 steel have revealed that milling tool's working part displacements measured by the laser vibrometer were affected both by the deflections induced by cutting forces and cutter's static radial run out.

From the literature survey presented above, it can be seen that problem of ball end mill displacements' estimation during machining is investigated unsatisfactorily, and thus needs further studies. The researches should focus on model's formulation, which includes the effect of cutter's deflection and run out phenomenon simultaneously, as well as the variation of surface inclination during milling of curvilinear surfaces. Furthermore, the reliable comparison of the modeled and measured tool's displacements should be also presented. Consequently, in this paper, the ball end mill's displacements model is proposed. This approach includes both deflections induced by the dynamical cutting forces and cutter's static radial run out, and thus it can be applied for the diversified milling operations, e.g. finishing or roughing. Subsequently, the developed model will be validated empirically with the application of laser displacement sensor, during the milling tests with various feed per tooth, axial depth of cut and surface inclination angle values.

2. Ball end mill's displacement model

The work presented in this paper focuses on the modeling and measurements of the ball end mill's instantaneous displacement $y(t)$, in the direction perpendicular to the tool's rotational axis and collinear to the feed motion vector (Fig. 1). In accordance to the previous researches [1,19], this direction has direct influence on the cutter's displacement y_e, which is perpendicular to the machined surface, and thus affects the surface texture formation (e.g. surface roughness or surface location errors). In this study, the end milling tool's working part displacements model, described in [18] is adopted. This model assumes that cutter's instantaneous displacements are caused by the geometrical errors of the spindle–toolholder–milling tool system y_r and tool's deflections y_d, induced by the variable cutting forces (Fig. 2).

The total tool's instantaneous displacement can be expressed by the following equation:

$$y(t) = y_r(t) + y_d(t) \tag{1}$$

The value of tool's displacement y_r is usually related to the static radial run out e_r, which can be induced by the tool itself (wear, asymmetry, insert setting, dynamic imbalance and thermal deformation) or the offset between the position of tool's rotation axis and spindle's rotation axis. The consequence is a tool rotation around the spindle axis with an eccentricity, which induces cutter displacements.

The instantaneous displacement y_r for the ball end mill, related to the static radial run out e_r can be calculated from the expression:

$$y_r(t) = -(e_r)\cdot\sin\left(\frac{\pi\cdot n\cdot t}{30} - \frac{\psi_{l1}+\psi_{l2}}{2} + \delta\right) \tag{2}$$

where: ψ_{l1}, ψ_{l2} are the initial and final lag angles [rad], δ is the radial run out's angle [rad], e_r is the static radial run out

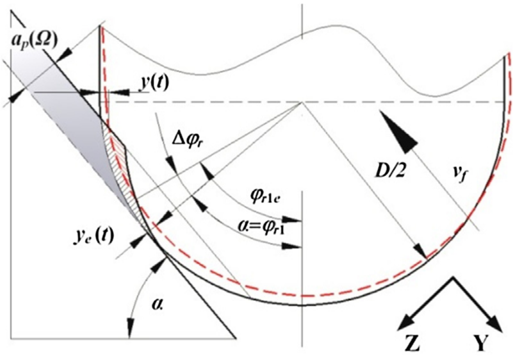

Fig. 1 – Instantaneous cutter's displacements: $y(t)$ and $y_e(t)$ during ball end milling with surface inclination ($\alpha > 0$).