International Journal of Machine Tools & Manufacture 89 (2015) 110–123

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

The estimation of cutting forces and specific force coefficients during finishing ball end milling of inclined surfaces

Szymon Wojciechowski *

Poznan University of Technology, Piotrowo 3, Poznan 60-965, Poland

ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form
12 October 2014
Accepted 27 October 2014
Available online 15 November 2014

Keywords:
Ball end milling
Cutting forces
Specific force coefficients
Surface inclination
Run out

ABSTRACT

The majority of cutting force models applied for the ball end milling process includes only the influence of cutting parameters (e.g. feedrate, depth of cut, cutting speed) and estimates forces on the basis of coefficients calibrated during slot milling. Furthermore, the radial run out phenomenon is predominantly not considered in these models. However this approach can induce excessive force estimation errors, especially during finishing ball end milling of sculptured surfaces. In addition, most of cutting force models is formulated for the ball end milling process with axial depths of cut exceeding 0.5 mm and thus, they are not oriented directly to the finishing processes. Therefore, this paper proposes an accurate cutting force model applied for the finishing ball end milling, which includes also the influence of surface inclination and cutter's run out. As part of this work the new method of specific force coefficients calibration has been also developed. This approach is based on the calibration during ball end milling with various surface inclinations and the application of instantaneous force signals as an input data. Furthermore, the analysis of specific force coefficients in function of feed per tooth, cutting speed and surface inclination angle was also presented. In order to determine geometrical elements of cut precisely, the radial run out was considered in equations applied for the calculation of sectional area of cut and active length of cutting edge. Research revealed that cutter's run out and surface inclination angle have significant influence on the cutting forces, both in the quantitative and qualitative aspect. The formulated model enables cutting force estimation in the wide range of cutting parameters, assuring relative error's values below 16%. Furthermore, the consideration of cutter's radial run out phenomenon in the developed model enables the reduction of model's relative error by the 7% in relation to the model excluding radial run out.

1. Introduction

Nowadays, high speed machining (HSM) of curvilinear surfaces using ball end mills is the subject of a lot of research [1]. The HSM technology is being widely used in many fields of industry, i.e. in production of drop forging dies and casting molds made from hardened steel [2], or in aerospace industry in manufacturing of wing parts made from aluminum alloys and composites [3]. Ball end milling of complex surfaces is very often conducted as the finishing process (with axial depth of cut, a_p, lower than 0.3 mm and radial depth of cut, a_e, lower than 0.5 mm) and thus requires the obtainment of high tolerances and low surface roughness of the machined surface. However the variation of ball end mill inclination against the work piece (defined by surface inclination angle α) significantly affects cutting forces [4] and thus surface texture [5]. From the previous research [6,7] it is resulting that the most undesirable is plain cutting with surface inclination angle $\alpha=0°$, because cutting speed near cutter's free end is close to zero. Thereupon, work material is not being cut but is ploughed and exposed to large elasto-plastic deformations. This ploughing mechanism can induce excessive forces on the cutter, which can lead to cutter's chipping, as well as surface roughness deterioration. The problem of elasto-plastic deformation of work material during ball end milling was insightfully investigated by the Tuysuz et al. [8].

The excessive cutting force values can also induce tool's deflections which form dimensional errors. Lopez de Lacalle et al. [9] used the model of the cantilever beam to calculate the static deflection of the tool during the high speed ball end milling with various cutting conditions. This deflection model was applied to the estimation of dimensional errors. The research revealed that the 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

* Fax: +48 61 6652200.
E-mail address: sjwojciechowski@o2.pl

http://dx.doi.org/10.1016/j.ijmachtools.2014.10.006
0890-6955/

related to the modal parameters of the spindle-toolholder-milling tool system and variable force signals. However, the research [9] was the starting point to the work [10], related to the optimization of toolpath during ball end milling, in order to minimize dimensional errors. The main aim of work [10] was to use the predicted cutting forces' values as a decision criterion for the best selection of toolpaths. The similar approach was proposed by Lazoglu et al. [11], who used the minimum cost connection (force minimal) optimized toolpaths. Results revealed that the optimum path can achieve almost 60% less mean force.

Above deliberations show that reliable prediction of milling forces is significant for the simulation of the process' physical and technological effects. According to Ehmann [12] and Jayaram [13], cutting force models can be classified into two ground groups: analytical and mechanistic. Analytical methods are usually including thermomechanical phenomena occurring in cutting process and modeling physical mechanisms during work piece decohesion process, e.g. slip stress and strain via intense plastic deformation [14]. Mechanistic models assume that cutting forces are proportional to the cross-sectional area of cut and so called specific cutting force coefficients [15]. These mechanistic models can be classified into two groups. In the first one, the effects of shearing mechanism due to the chip generating process on the tool's rake face and effects of ploughing mechanisms on the flank face are expressed as the one specific force coefficient for each cutting force component [16,17]. In the second model, developed by Lee and Altintas [18], the shearing and ploughing effects are characterized separately by the respective specific shear and edge force coefficients. This model is able to predict the cutting forces in roughing processes with acceptable accuracy. However, the machining of curvilinear surfaces and finishing process are not presented in the paper. The approach proposed by Lee and Altintas [18] was employed by many other authors. For reference, during the ball end milling of sculptured surfaces in Al7075-T6 aluminum alloy and AISI H13 (52 HRC) tool steel [19], as well as for the five-axis ball end milling of impeller made of Al7075 [20]. Models employed by these authors reveal good accuracy however their validation was carried out during semi-finishing process, with axial depths of cut, a_p, higher than 0.3 mm. Furthermore, the cutter's radial run out was not included in these approaches.

The quantitative accuracy of the cutting force model depends mainly on the specific force coefficients' calibration. In the literature, two methods for calculation of these coefficients are known, namely: oblique transformation from the orthogonal cutting tests, and calibration of coefficients conducted on milling operation. The first approach requires small number of experiments, but has a limited accuracy for the low immersion cutting and finishing processes. The latter, is more accurate for the tools with complex geometry, however it requires large number of tests in order to determine the cutting constants. Nevertheless, Gonzalo et al. [21] proposed a different approach to obtain the specific coefficients. Their method is inexpensive because determines coefficients directly from FEM models, without any experimental cutting tests. However, it has been so far validated only for the slot milling with the cylindrical end mill.

From the literature it can be seen that for the particular cutting tool and work piece, the edge specific coefficients are independent on cutting parameters and assumed as the constant values, while the shear specific coefficients are dependent only on the axial position of the cutting edge elements [19,22]. Nevertheless the work [23], revealed that during the slot milling of titanium and aluminum alloys, the shear coefficients can be also independent on the cutting conditions (cutting speed, axial depth of cut and feed per tooth). In the numerous researches of the ball end milling process, the specific force coefficients are calibrated on the basis of the averaged force signals, during slot milling, i.e. in case when feed motion vector is perpendicular to the tool's rotational axis and working angle is equaled to π. However, during the finishing ball end milling with variable surface inclination, the working angles are lower than π, and thus the calibration coefficients estimated for the slot milling process are not valid [24]. Above mentioned simplifications can significantly reduce the accuracy of cutting force prediction. Additionally, during the finishing milling, cutter's run out can have also the significant influence on the instantaneous maximal forces per consecutive teeth. From the previous research [25] it is resulting that during finishing ball end milling of hardened steel the discrepancies between the maximal forces generated for the consecutive teeth can exceed 40%. This means that the run out should be taken into account during the finishing ball end milling, however literature survey reveals, that only the few models [4,26] include this phenomenon. In addition, the run out is considered only in the expressions of uncut chip thickness. However during ball end milling of inclined surfaces, its value affects also active length of cutting edge, and thus have direct influence on cutting forces (mainly edge forces).

Literature survey reveals, that ball end milling process was acutely investigated. Nevertheless, problems of cutting force modeling in finishing conditions are still insufficiently examined. These investigations should focus also on the accurate specific force coefficients' estimation, which includes the variation of cutting mechanics for different surface inclinations, as well as on the consideration of ball end mill's run out in the expressions of the geometrical elements of cut (uncut chip thickness and uncut chip width). Therefore, this paper proposes an accurate cutting force model applied for the finishing ball end milling. This model includes cutting conditions, surface inclination angle and cutter's run out. The run out is considered in equations applied for the calculation of sectional area of cut and active length of cutting edge. The specific force coefficients are determined with the application of the developed method. This approach is based on the calibration during ball end milling with various surface inclinations and the application of instantaneous force signals as an input data. The proposed model is validated experimentally, during finishing ball end milling of hardened 55NiCrMoV6 steel in the wide range of cutting parameters.

2. Mechanistic cutting force model

In order to determine cutting forces, mechanistic cutting force model, developed by Lee and Altintas [18] is applied. In this model, a set of curvilinear coordinate system normal to the ball envelope is used to specify the resultant force acting on the i-th infinitesimal segment of the cutting edge. Fig. 1 depicts cutting forces acting on the cutter and tool's coordinates for a ball end mill.

The elemental tangential dF_{tj}, radial dF_{rj}, and axial dF_{aj} forces acting on the j-th tooth, are expressed by:

$$dF_{tj} = K_{te} dl_j + K_{tc} dA_{zj} \tag{1a}$$

$$dF_{rj} = K_{re} dl_j + K_{rc} dA_{zj} \tag{1b}$$

$$dF_{aj} = K_{ae} dl_j + K_{ac} dA_{zj} \tag{1c}$$

where K_{te}, K_{re}, and K_{ae} are the edge specific coefficients [N/mm],
K_{tc}, K_{rc}, and K_{ac} are the shear specific coefficients [N/mm^2],
dl_j is the infinitesimal length of cutting edge [mm],
A_{zj} is the cross sectional area of cut [mm^2].

In order to calculate cutting forces acting on i-th infinitesimal segment of the cutting edge, it is necessary to determine cross