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Analytical model of milling forces based on time-variant sculptured shear surface

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ABSTRACT

A concept of sculptured shear surface was proposed in this study. The sculptured shear surface is determined by helix structure and movement of milling tool. The area of sculptured shear surface is time variant during milling processes. The projected area of sculptured shear surface in three directions determines the milling forces in three directions respectively. The analytical model of milling forces based on sculptured shear surface is build and this analytical model is verified by the milling experiments. Finally the effect of cutting tool geometrical parameters (helix angle and rake angle) and milling parameters (axial depth of cut, radial depth of cut, feed rate per tooth) on milling forces is analyzed by proposed milling force model.

1. Introduction

The research on cutting forces of machining process is necessary and can generate further insight into cutting temperature, tool life, surface finish, and other machinability properties. There are mainly three methods to predict the cutting forces: empirical/semi-empirical methods, finite element methods and analytical methods.

Empirical methods include some statistical relationship models between the cutting forces and cutting parameters, such as exponential model, second order model and so on [1]. The contribution of every item to the cutting forces is different, which results in the coefficient of every item is different. A large amount of experiments are performed to get the cutting forces and then the data is used to fit the coefficient of every considered item [2]. In semi-empirical methods, the analytical models of uncut chip thickness are built, and then the relationship between uncut chip thickness and cutting forces are built [3]. The cutting forces are considered to be proportional to the uncut chip thickness under certain cutting conditions and the ratios were called force component coefficients [4]. These coefficients can be gained from a lot of experiments and the cutting force components are approximated. Further researches showed the relationship between cutting force and chip thickness to be an exponential function. The force coefficients agree with the polynomial model including the cutting process parameters [5]. Beside the force component coefficients, some other coefficients called edge coefficients were proposed in the cutting force model, which make cutting forces model better agreed with the experimental results [6]. The empirical or semi-empirical methods, however sophisticated, are useful in practice process but they are limited to the fixed machine tool, cutting tool and cutting conditions. The predictions of force largely depend on the reliability of the empirical cutting force coefficients, which are gained from a large number of experiments in different cutting conditions. Because the physical meanings of force coefficients are undefined, this kind of model is difficult to reflect the physical process truly and it is difficult to be used widely.

Finite element method (FEM) was more and more popular in the processes simulation from the 1980s onward. FEM is an important tool to study the complex thermo-mechanical phenomenon of cutting process, which is difficult to investigate by experimental measurement. It is used to calculate cutting forces [7], cutting temperature [8] and stress distribution [9], or research the tool design methods and select the optimum cutting conditions [10]; even predict the tool wear process [11] and the residual stresses in the machined layer [12]. Some commercial FEM codes, like ABAQUS [13], DEFORM [14], AdvantEdge [15] are available to use to simulate the cutting processes. The simulated results by finite element methods could be accurate in the predicting of cutting forces as soon as the material model [16], friction model

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[17], heat transfer model [18]and numerical approach [19] is reasonable. However, the prediction of cutting forces is time consuming and the commercial FEM software is too expensive to use widely in the industry.

The above two methods for the prediction of cutting forces are difficult to build the nature and direct relationship between cutting forces and cutting process parameters, including machining parameters, geometrical parameters of cutting tool and so on. Analytical models of cutting forces considers the analysis in the cutting processes, including the materials deformation, flow, contact action and so on. It is generally considered that the source of resultant cutting forces are shearing and friction in the cutting processes [20]. The components of cutting force are derived as projection of the resultant cutting force. The friction forces can be considered as the function of shear forces and friction angle. The shear force is approximately expressed as the product of shear area and shear stress. The friction, shear area and shear stress models are required to solve the cutting forces. Many analytical models of orthogonal cutting were developed, like “card model”, “shear angle model” [21], “slip line model” [22], “thermo-stress coupled model” [23] and so on. But in some complex cutting processes, like milling, the shear plane or zone is not a plane, but a curved surface due to complex tool structure and tool movement. Generally the differential elements are obtained by slicing the milling tool along helical cutting edge. It could be considered as orthogonal cutting condition for every discrete element. The milling forces are integrated axially along the sliced differential elements from the bottom of the flute towards the final axial depth of cut. More prediction of cutting forces of complex operations and tool cutting could be performed by the above analytical method [24]. However, the accuracy of the milling force prediction strongly depends on the size of differential elements. The height of differential elements in the axial direction should be small enough to avoid the prediction error of cutting forces. Moreover, it is difficult to analyze the continual and dynamic change of cutting forces due to removal of workpiece materials.

In this study, a concept of sculptured shear surface was proposed. The sculptured shear surface is determined by helix structure and movement of milling tool. The area of sculptured shear surface is time variant during milling processes. The projected area of sculptured shear surface in three directions determines the milling forces in three directions respectively. The analytical model of milling forces based on sculptured shear surface is build and this analytical model is verified by the milling experiments. Finally the effect of cutting tool geometrical parameters (helix angle and rake angle) and milling parameters (axial depth of cut, radial depth of cut, feed rate per tooth) on milling forces is analyzed by proposed milling force model.

2. Milling force model based on sculptured shear surface

2.1. Orthogonal cutting forces system

The cutting forces [25] and velocity system [26] acting in the orthogonal cutting are discussed in many researches, as Fig. 1 shown. The equation of shear force F_s, resultant force R, friction force f and normal pressure N are respectively:

$$F_s = \tau_s \cdot h \cdot a_w / \sin\varphi \tag{1}$$

$$R = F_s / \cos(\varphi + \beta_\alpha - \alpha) \tag{2}$$

$$F_c = \tau_s \cdot h \cdot a_w \cdot \cos(\beta_\alpha - \alpha) / \sin\varphi / \cos(\varphi + \beta_\alpha - \alpha) \tag{3}$$

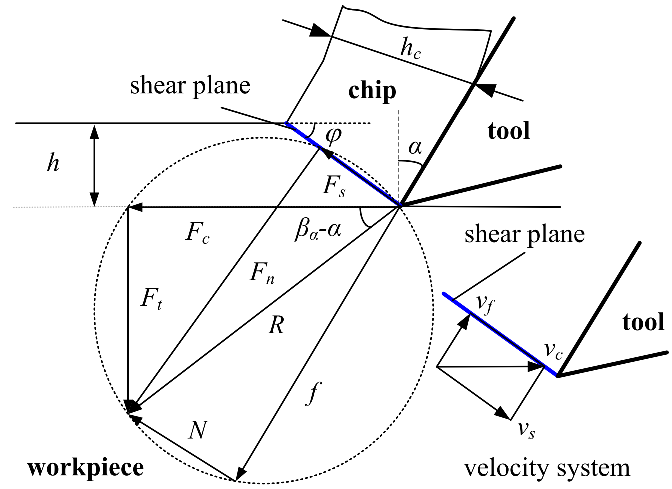

Fig. 1. Orthogonal cutting forces and velocity system.

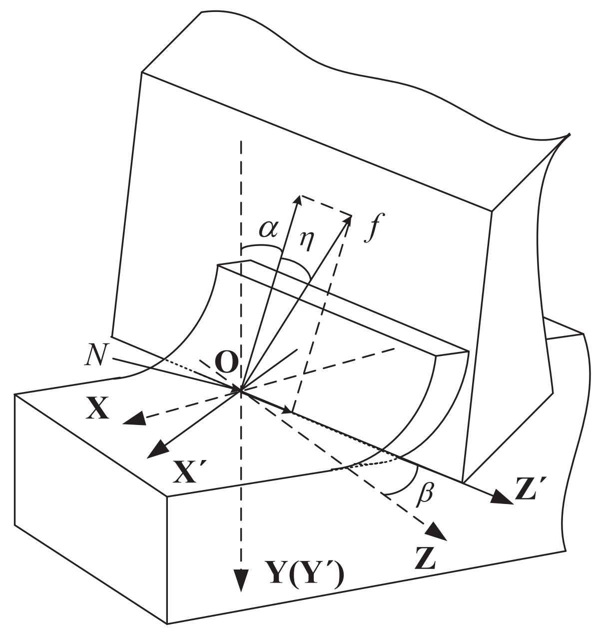

Fig. 2. Oblique cutting model.

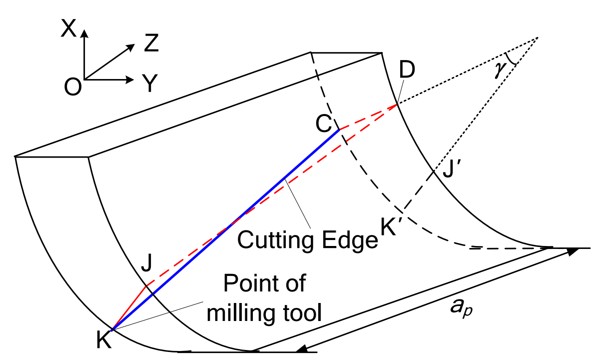

Fig. 3. Physical model of cutting edge and shear curved plane.

$$f = R \cdot \sin\beta_\alpha \tag{4}$$

$$N = R \cdot \cos\beta_\alpha \tag{5}$$

Where a_w is the width of cut; h is the uncut chip thickness; τ_s is the shear stress; ϕ is the shear angle; β_α is the friction angle; α is the rake angle.