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Application of a new thick zone model to the cutting mechanics during end-milling

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ABSTRACT

In this paper, a modified Oxley's predictive machining theory was utilized to analyze the mechanics of cutting in end milling using helical end mill tools. The milling tool is modeled along its axis as discrete segments. Each segment of the tool is treated as a single point cutter performing oblique cutting with an instantaneous uncut chip thickness determined by angular position and tool run-out. Subsequently, the cutting force and thrust force are calculated based on the instantaneous chip load. The total forces at a given angular position are obtained by summing up forces contributed by every cutting edge segment engaged into cutting. A modified Oxley's predictive machining theory was utilized as the foundation to obtain the desired milling force components through the work hardening and temperature dependent flow stress. First of all, Oxley's approach was extended by substituting Johnson–Cook constitutive equation by the velocity-modified-temperature dependent power law in order to generalize the applicability of the model for a wider range of work materials. Then, the equidistance thick primary shear zone model has been revised by considering the non-equidistant primary shear zone configuration as a framework to propose a more realistic nonlinear shear strain rate distribution. Finally, several cutting tests have been performed on AISI1045, Al7075 and Ti6Al4V and the predicted cutting forces using the proposed model have been compared with the experimental ones to validate the extended Oxley's model.

1. Introduction

Milling, as a versatile material removal process, is one of the most common machining operations in industry. Due to its widespread application, simulation of milling operation has always been among the main research topics to improve machining accuracy and efficiency. Unlike the single-point cutting tools, the path of each tooth of a milling tool forms an arc of trochoid. As a result, varying but periodic chip load is generated at each tooth-passing interval. Martellotti [1,2] analyzed the of kinematics of the milling process and defined the instantaneous chip load in terms of tool geometry and cutting conditions. Based on Martellotti's analysis, the pioneer work on the prediction of milling forces was initiated by Konnisberger and Sabberval [3]. In their work, the tangential and radial forces were related to the instantaneous chip load by specific cutting coefficients. The milling cutter was considered to consist of a series of orthogonal cutter disk segments. Each segment rotates with respect to the adjacent segment having different chip thickness. The total force acting on the milling tool at a certain angular position can be calculated by adding the forces acting on each of the tool segments. The similar method was used by Kline et al. [4,5] and it was extended to include the effect of cutter run-out. Sutherland and DeVor [6,7] further extended Kline's force model to include the effect of tool deflection. Armarego and Deshpande [8] further studied and discussed the importance of both tool run-out and deflection on the cutting force fluctuations. In their study, three models, namely the ‘ideal’ model for rigid tool with no eccentricity, the rigid tool ‘eccentricity’ model and the more comprehensive ‘deflection’ model, were assessed by experimental data. It was shown that all three models provided good predictions of average cutting forces. The ‘eccentricity’ and ‘deflection’ models yielded satisfactory results for force fluctuation predictions. The ‘deflection’ model outputs the best force predictions especially under the heavy cutting conditions that lead to tool deflections. However, the efficacy of this comprehensive model is traded off by the excessive computer processing time.

Since then, many milling force models have been developed based on the works described above. A common characteristic of most milling force models is the assumption that the cutting

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Nomenclature

Δa	cutting width of the elemental flutes (the axial depth of a disk element)
d_a	radial depth of cut
H	contact length at the chip-tool interface
h	the thickness of the primary shear zone
K	thermal conductivity of the work material
k_{AB}	shear flow stress at the main shear plane AB
k_c	shear flow stress at the chip-tool interface
l_{AB}	the length of the primary shear zone
n_d	total number of flutes on the milling cutter
t_1	uncut chip thickness (chip load)
t_2	chip thickness
t_u	instantaneous uncut chip thickness during milling
w	the width of cut
C_0	the ratio of l_{AB} to h
F_F	friction force at the chip-tool interface
F_C	cutting force
F_{SN}	force component normal to the shear plane
F_S	shear force
F_T	thrust force
F_N	normal force on the tool rake face
P_A	hydrostatic stress at the free surface
P_B	hydrostatic stress at the tool tip
P_C	crossover rate
R_a	radius of the milling cutter
R_T	thermal number
S	specific heat of the work material
T_{AB}	temperature at the plane AB
T_{int}	temperature at the chip-tool interface
T_m	melting temperature
T_w	ambient temperature
U	cutting velocity
V_x	velocity tangential to the primary shear zone boundaries
V_{x1}	the tangential velocity at the lower boundary
V_{x2}	the tangential velocity at the upper boundary
V_y	velocity perpendicular to the primary shear zone boundaries
α	tool rake angle
α_{run}	runout location angle
β	mean friction angle
β_{hx}	helix angle of the milling tools
β_T	the proportion of the heat conducted into the workpiece
δ	ratio of the thickness of the secondary shear zone to the chip thickness
ϕ	shear angle
ϕ_{en}	entry angle
ϕ_{ex}	exit angle
γ	the shear strain field through the primary shear zone
γ_{AB}	the shear strain at the plane AB
γ_{EF}	the shear strain at the upper boundary of the primary shear zone
$\dot{\gamma}$	the shear strain rate field through the primary shear zone
$\dot{\gamma}_{AB}$	the shear strain rate at the plane AB
$\dot{\gamma}_m$	the mean shear strain rate of the primary shear zone
η_c	chip flow angle
λ	the proportion of the lower part to the total width of the primary shear zone
$\Delta\theta$	prescribed rotational increment of the milling cutter in simulation
ρ	the density of the work material
ρ_{run}	run-out magnitude
σ_N	the normal stress at the chip-tool interface
τ_{int}	shear stress at the chip-tool interface

forces can be related to the chip load through specific cutting coefficients which have to be determined empirically. These specific cutting coefficients orientated force models are called mechanistic models. During the development of mechanistic models, the focus is on the accurate calibration of specific cutting coefficients from cutting test data. Since the magnitude of these specific coefficients is directly related to the workpiece and cutting tool materials as well as machining parameters and tool geometry, a large amount of well-designed cutting tests have to be performed to guarantee the satisfactory cutting force predictions for various work-tool combinations and cutting conditions.

Based on the slip line field analysis, Oxley [9] developed an analytical approach that considers the properties of workpiece material. Rather than the specific cutting coefficients, the cutting forces can also be determined by the flow stress of the workpiece material which depends on the strain, strain rate and the temperature during the machining process. The major advantage of Oxley's machining theory is the avoidance of laborious experimental work to determine the required modeling parameters. The success has been achieved in the application of Oxley's predictive machining theory to the simulation of face milling [10,11] and end milling [12,13] processes. However, the work material was restricted to the low carbon steels due to the lack of flow stress data for other materials in Oxley's predictive theory. Some researchers [14,15] have modified Oxley's model by utilizing the Johnson–Cook constitutive material equation [16], to generalize the model and cover a broader variety of workpiece materials. However, these extensions were tested and verified only under orthogonal cutting conditions. Application of extended Oxley's predictive machining theory in oblique machining e.g. milling, has not been found in open literature. Moreover, Oxley's methodology attempted to consider the effects of work hardening and thermal softening. It allowed a continuous flow of material through an opened-up deformation zone. Nevertheless, some parameters like strain, strain rate and temperature were calculated based on the average values which consequently neglect their distributions as key factors in describing the continuous flow. Furthermore, single shear plane model was used to obtain the hodograph which introduced other inconsistencies to the model due to the following reasons: 1) the velocity field allowing for the continuous deformation was not described, and 2) the problem of discontinuity in velocity has not been addressed.

Li et al. [17] used the 'non-equidistant' primary shear zone configuration based on the shear band model [18,19] to estimate the machining parameters such as forces, shear strain, shear strain rate and temperature distributions in the primary shear zone with an assumed thickness of 0.025 mm for all the materials and cutting conditions. They determined the shear angle the using Merchant formula. Li et al. [20] further applied the approach to the simulation of the end milling process. However, the comprehensiveness of their work has been limited by several factors as follows: 1) the effects of machining parameters on the thickness of the primary shear zone cannot be examined; 2) the Merchant formula for calculating the shear angle may not be an appropriate choice for the work hardened material as assumed in their research work [20]. It must be mentioned that Merchant formula