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An analytical force model for modulation-assisted turning

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ABSTRACT

Modulation-assisted machining (MAM) superimposes a controlled low-frequency tool oscillation in the feed direction of conventional machining (CM). The process transforms the otherwise continuous cutting into a series of interrupted cutting events, producing discrete chips instead of continuous chips. This paper makes a geometrical analysis of the MAM process in face turning configuration and classifies it into two cutting phases according to the different direction of the instantaneous feed motion: conventional cutting phase and reverse cutting phase. An analytical force model is proposed to determine the instantaneous forces for both cutting phases, which incorporates material properties, tool geometry, cutting conditions and modulation conditions. Several unknown model parameters are identified via an elitist teaching-learning-based optimization (TLBO) algorithm. A series of face turning experiments are carried out with and without modulation, validating the identified parameters and the proposed force model. Finally, the effects of modulation frequency, modulation amplitude and nominal feed rate on the three-dimensional forces are studied and discussed both qualitatively and quantitatively. The analytical force model in this paper can provide a framework for characterizing the effect of process parameters on applications for MAM.

1. Introduction

Titanium alloys have been increasingly used in aviation and aerospace industries during the recent years [1] due to their superb strength to weight ratio, high temperature performance and corrosion resistance [2] etc. However, titanium alloys are always regarded as difficult-to-machine materials because of their low thermal conductivity, high chemical reactivity and low modulus of elasticity [3], causing high thermal and mechanical stresses on the cutting tools and subsequent fast tool wears [4]. In addition, titanium alloys have good ductility so that long and continuous chips tend to be produced during machining, which are dangerous and difficult to handle [5]. MAM [6–11], superimposing a controlled low-frequency (usually less than 1000 Hz) sinusoidal tool oscillation in the feed direction, has been found effective in controlling chip size and reducing tool wear. The MAM process can transform the otherwise continuous cutting into a series of interrupted cutting events, producing short and discrete chips. Mann et al. [8] found that by adjusting the modulation conditions and cutting conditions, different types of chips can be produced, such as equiaxed, platelet and fiber-shaped particles having narrow size distributions. Guo et al. [6] applied MAM in machining of compacted graphite iron at high machining speeds. They found that the tool life was at least one order of magnitude greater than that in CM at equivalent material removal rates, which was considered as the result of less intimate tool-chip contact, lower cutting temperatures and enhanced fluid action etc.

Although the advantages of MAM due to its discrete regime have been well documented in the previous literatures, the mechanisms of MAM are not well understood. As is well known, cutting forces play a fundamental and important role in machining because they are closely related to tool wear, shear deformation, cutting energy and machining quality [12] etc. Therefore, it is of great necessity to establish a reliable force model to gain a better understanding of MAM. Norman et al. [13,14] proposed an empirical force model for MAM in an orthogonal cutting configuration. They found that the underlying plastic deformation mechanisms were unchanged with modulation over the investigated conditions. Although the empirical models cannot reveal the physical mechanism in the machining process, their work indicated that it was feasible to extend the predictive machining theory from CM to MAM.

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Nomenclature

α_f, α_p	Side rake angle, back rake angle
F_x, F_y, F_z	Total cutting force, feed force, thrust force
γ_f	Side flank angle
w_{BD}	Equivalent width of cut of cutting edge BD
ψ_r	Side cutting angle
δ	Angle between BD and the negative X axis
r_n, r_e	Nose radius, edge radius
A_{ABCD}	Area of the shaded region ABCD
K_r	Approach angle
K_{fc}^b, K_{tc}^b, K_{rc}^b	Cutting coefficients of cutting edge BD
f_0	Nominal feed rate
K_{fe}^b,K_{te}^b,K_{re}^b	Edge coefficients of cutting edge BD
DoC	Depth of cut
F_t^b,F_f^b,F_r^b	Forces acting on cutting edge BD
D_0	Diameter of cylindrical workpiece
α_n	Normal rake angle
θ	Angular position of cutting tool
β_n	Normal friction angle
$f_n(\theta)$	Instantaneous feed rate at position θ
ϕ_n	Normal shear angle
$f_n(t)$	Instantaneous feed rate at time t
i	Oblique angle
$\rho_n(\theta)$	Radial position of cutting tool
η_c	Chip flow angle
f_m, A_m	Modulation frequency, modulation amplitude
τ_1	Shear yield strength of workpiece material
f_w	Workpiece rotation frequency
p_0	Normal pressure at tool tip
φ_d	Phase difference
ω	Exponential pressure distribution
t_1, t_2, t_3, t_4	Characteristic time points
μ	Sliding friction coefficient
T_p	Modulation period
C_M	Merchant's empirical machining constant
t_M, t_N	Arbitrary time points during the conventional, reverse cutting phase
μ_0, p	Constants related to friction
h_p	Springback
V_c, V	Chip velocity, cutting velocity
H, E	Hardness, Young's modulus of workpiece
h	Thickness of shear zone
k_p	A constant related to springback
κ	Non-equidistant coefficient
$z_P\left(\rho_P, \theta_P\right)$	Height of an arbitrary pointP $\left(\rho_P, \theta_P\right)$
τ,γ,$\dot{\gamma}$,T	Shear stress, shear strain, shear strain rate, temperature in the shear zone
d_{min}	Minimum distance
$\dot{\gamma}_0$	Reference shear strain rate
ψ	Central angle of the engaged curved cutting edge
T_m, T_r	Melting temperature, room temperature
$\Delta\psi$	Incremental angle
A, B, C, n, m	Constants in J-C constitutive model
φ	An angle related to the (N + 1)th cutting edge
τ_s,γ_s,$\dot{\gamma}_s$,T_s	Shear stress, shear strain, shear strain rate, temperature on the shear plane
w_r^k	Equivalent width of cut of the *kth* cutting edge
ρ, c	Density, heat capacity of workpiece material
β_k	Angular position of the *kth* cutting edge
χ	Taylor-Quinney coefficient
ξ_r^k	Angle between the main cutting edge and the *kth* cutting edge
q	A power characterizing the nonuniform distribution of the tangential velocity
f_r^k	Equivalent feed rate of the *kth* cutting edge
m_{AC},τ_{AC}	Friction factor, frictional stress on the bottom of build-up region *AC*
A_r^k	Area of undeformed chip section of the *k*th cutting edge
ρ_0,η_0,ξ_0,π_0	Angles related to the slip-line model for edge force
K_{tc}^k,K_{fc}^k,K_{rc}^k	Cutting coefficients of the *k*th cutting edge
R	Fan radius related to the slip-line model for edge force
K_{te}^k,K_{fe}^k,K_{re}^k	Edge coefficients of the *k*th cutting edge
f_{ave}	Average feed rate
F_t^k,F_f^k,F_r^k	Forces acting on the *k*th cutting edge
DC	Duty cycle

Among a large number of force models proposed for CM, analytical models have attracted great attentions because they are the most physics-based. Merchant [15], Armarego [16] and Oxley [17] et al. made a lot of contributions in this field, and based on their pioneering research work, Li et al. [18] proposed a non-equidistant shear zone model to predict the cutting forces in orthogonal cutting. This model, taking into account the workpiece material properties, tool geometry and cutting conditions, can be extended to oblique cutting and other cutting configurations. Bai et al. [19] used the non-equidistant shear plane model to predict the forces in orthogonal elliptical vibration cutting, Fu et al. [20,21] applied it to predict the forces in helical end milling and ball end milling, and Weng et al. [22] applied it for prediction of forces in turning operation with a ceramic round insert. Precise predictive results were obtained compared with the experimental results, indicating that the analytical models were valid for various cutting conditions and workpiece-tool material pairs. The authors [23] had also applied the non-equidistant shear zone model for force prediction in orthogonal cutting with modulation, taking into account the effect of the time-varying undeformed chip thickness on the two-dimensional forces. In this paper, the two-dimensional force model will be extended to a three-dimensional one for modulation-assisted turning.

The paper is organized as follows: In Section 2, geometrical analysis of the face turning process with modulation is carried out, giving the critical condition for chip breakage and showing that the instantaneous feed rate is time-varying. According to the different direction of the instantaneous feed motion, the MAM process is classified into conventional cutting phase and reverse cutting phase. In Section 3, an analytical force model is proposed to determine the instantaneous cutting force. For the conventional cutting phase, the engaged cutting edge is discretized into several parts [24], each of which is considered under a classical oblique cutting condition. For the reverse cutting phase, the engaged cutting edge is considered as a straight cutting edge, which is under an oblique cutting condition as well. The cutting coefficients are expressed analytically based on the non-equidistant shear zone model, while the edge coefficients are obtained from the slip-line model proposed by Waldort [25]. In Section 4, five unknown parameters in regard to the analytical force model are identified through an elitist teaching-learning-based (TLBO) algorithm [26,27] with the help of a set of numerical forces obtained by AdvantEdge software. The TLBO algorithm has been used widely and obtained quite good results for many constrained and unconstrained benchmark functions and engineering problems [28]. The convergence [29] and some successful applications of the TLBO algorithm can be found in [27,30,31]. The TLBO algorithm needs only common control param-