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Analysis of grinding mechanics and improved predictive force model based on material-removal and plastic-stacking mechanisms

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A R T I C L E I N F O

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A B S T R A C T

Numerous researchers have developed theoretical and experimental approaches to force prediction in surface grinding under dry conditions. Nevertheless, the combined effect of material removal and plastic stacking on grinding force model has not been investigated. In addition, predominant lubricating conditions, such as flood, minimum quantity lubrication, and nanofluid minimum quantity lubrication, have not been considered in existing force models. This work presents an improved theoretical force model that considers material-removal and plastic-stacking mechanisms. Grain states, including cutting and ploughing, are determined by cutting efficiency (β). The influence of lubricating conditions is also considered in the proposed force model. Simulation is performed to obtain the cutting depth (a_g) of each "dynamic active grain." Parameter β is introduced to represent the plastic-stacking rate and determine the force algorithms of each grain. The aggregate force is derived through the synthesis of each single-grain force. Finally, pilot experiments are conducted to test the theoretical model. Findings show that the model's predictions are consistent with the experimental results, with average errors of 4.19% and 4.31% for the normal and tangential force components, respectively.

1. Introduction

During grinding, grinding force is a crucial factor influencing grinding performance, form durability of grinding wheel, workpiece surface quality, and deformation of process system [1–3]. Grinding force is caused by elastic flow, plastic flow, debris formation, and friction resulting from contact between grinding wheel and workpiece [4,5]. Building a theoretical grinding force predictive model to predict experimental results bears high theoretical significance and application value. Research on the grinding force model is a fundamental part of grinding theory [6].

Minimum quantity lubrication (MQL) grinding is a green process. After mixing and atomization, a small quantity of lubricants and gas is jetted at a certain pressure to the grinding zone for cooling lubrication [7,8]. On the contrary, Hadad et al. [9,10] reported that MQL grinding does not address the technical limitation of grinding cooling performance; this inability considerably limits the application of MQL grinding. Nanofluid minimum quantity lubrication (NMQL) grinding effectively resolves heat transfer in the grinding zone while enhancing the lubricating property in the zone [11]. Nanoparticles can significantly improve the lubrication and heat transfer of a nanofluid. A force predictive model should be established for NMQL grinding, which has not been reported in the literature.

Numerous researchers have developed theoretical and experimental approaches to determine the force for surface grinding under dry condition. Werner [12] derived a grinding force equation with two structural coefficients, which could be adjusted to interpret chip formation-related force and sliding-related force. Malkin et al. [13,14] argued that grinding force consists of cutting deformation force and sliding force. Li et al. [15] extended Werner's model by separating the effects of cutting and sliding, and derived equations to express the cutting and sliding forces. Similarly, Younis et al. [16] proposed a grinding force model composed of sliding

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Nomenclature

MQL	minimum quantity lubrication
NMQL	nanofluid minimum quantity lubrication
β	cutting efficiency
a_g	cutting depth
a_{gc}	critical cutting depth
α	plastic stacking angle
α_1	critical plastic stacking angle
d_s	integral unit
δ_s	yield stress
δ_b	fracture stress
δ_0	stress in the debris-formation region
δ_1	stress in elastic-plastic flow region
δ_{01}	plastic flow stress in debris formation region
δ_{02}	material removal stress in debris formation region
A_m	area of debris formation
d_{mean}	mean granular size of grains
d_{max}	maximum granular size of grains
d_{min}	minimum granular size of grains
d	granular size of grains
θ	grain vertex angle
N_d	number of dynamic active grains
N_c	number of cutting grains
N_p	number of ploughing grains
L_r	distance of initial grains
σ	standard deviation
z	protrusion height of grain
z_g	axial position of grain
F_n	normal grinding force
F_t	tangential grinding force
F_{tc}	tangential cutting force
F_{nc}	normal cutting force
F_{tp}	tangential ploughing force
F_{np}	normal ploughing force
F_{tcf}	tangential frictional force on rake face of cutting grain
F_{ncf}	normal frictional force on rake face of cutting grain
F_{tpf}	tangential frictional force on rake face of ploughing grain
F_{npf}	normal frictional force on rake face of ploughing grain
$F_{tc(01)}$	tangential plastic-flow force in the debris-formation region
$F_{nc(01)}$	normal plastic-flow force in the debris-formation region
$F_{tc(02)}$	tangential material-removal force in the debris-formation region
S_1	volume of plastic stacking
S_2	debris deformation region
S_3	total volume of grain cutting
a_p	grinding depth
V_w	feed speed
V_s	peripheral speed of grinding wheel
a_{gmean}	average undeformed chip thickness
a_{gmax}	maximum undeformed chip thickness
SEM	scanning electron microscope
m	granularity number of grinding wheel
V_g	corundum concentration
N	Total number of sampled grains of grinding zone
N_x	number of grains along circumferential direction
N_y	number of grains along axial direction
S	organization number of grinding wheel
d_e	equivalent wheel diameter
λ	space between continuous cutting grains
D	diameter of the grinding wheel
L_g	Length of grinding contact arc
b	grinding width of grinding wheel
S_w	tip area of the worn grain
P_0	constant determined by experiment
K_1	constant determined by experiment
$G(\mathrm{d})$	matrix of grain size
$G(z)$	matrix of protrusion height of grains
$G(z_g)$	matrix of axial position of generated grains
$G(a_d)$	matrix of protrusion height of static active grains
$G(a_g)$	matrix of cutting depth of dynamic active grains
R	radius of curvature of cutting path
f_t	tangential frictional force on wear plane of grains
f_n	normal frictional force on wear plane of grains
z_{gk0}	initial coordinate value of grains in Z direction
z_{gkn}	final coordinate value of grains in Z direction
δz_{gkn}	random number meeting uniform distribution
$\bar{p}$	average contact pressure between the grains and the workpiece
μ	friction coefficient between workpiece material and grains
$F_{tc(1)}$	tangential force in elastic-plastic flow region
$F_{nc(1)}$	normal force in elastic-plastic flow region
$F_{nc(02)}$	normal material-removal force in the debris-formation region

force, cutting force, and ploughing force. Tang et al. [17] proposed another model that focuses on the calculation of chip formation forces. They stated that the chip formation forces can be classified into static and dynamic components according to the level of the region shear strain and grinding zone temperature; the experiments validated the feasibility and accuracy of the proposed model. Durgumahanti et al. [18] developed a grinding force model by incorporating the effects of variable frictional coefficient and ploughing force. To obtain grain stages and numbers, researchers proposed a different method [19]. Hecker et al. [20] and Lang et al. [21] assumed that the cutting thickness of grains reflects Rayleigh's probability density distribution. However, this model assumed that all of the grains that contact the workpiece were cutting grains. Zhang et al. [22] developed a granular size probability model based on normal distribution; solved for the probabilities of cutting, ploughing, and sliding grains at a fixed period; and distinguished grains into three grinding processes. These models provide scientific and technological insight into the grinding process. However, these models need to be further improved with the development of science and technology.

Aside from the classical force model, the grinding process has been applied further. Cheng et al. [23] studied grinding forces in the micro slot-grinding of single crystal sapphire. They developed a predictive model for the grinding force in three different orientations of single crystal sapphire: C-orientation, A-orientation, and R-orientation. Zhou and Zheng [24] developed a model for predicting grinding forces in ultrasonic vibration-assisted grinding of SiCp/Al composites. They derived analytical expressions for the chip formation force based on Rayleigh's probability density function, frictional force, and particle fracture force based on Griffith theory. Jiang et al. [25] studied the predictive modeling of grinding force considering wheel deformation for toric fewer-axis grinding of large complex optical mirrors. Hertz contact theory was applied to an irregular contact area. Zhang et al. [26] constructed a model for the reliable prediction of grinding force in ultrasonic vibration-assisted micro-end grinding. In studies on the removal mechanism and the micro-topography of the grinding surface, the micro-end grinding zone is divided into three grinding regions: main grinding region, plowing grinding region, and sliding grinding region. The single-grain force model is then developed under different material-removal modes, and the grinding force model of the entire grinding wheel is developed considering the effect of size.

However, previous studies derived the average cutting depths for