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Detailed modeling of cutting forces in grinding process considering variable stages of grain-workpiece micro interactions

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ABSTRACT

Grinding forces are a key parameter in the grinding process, most previous studies on grinding forces, however, (i) were regardless of grain-workpiece micro interaction statuses and (ii) could only predict average/maximal grinding forces based on average/maximal cutting depths or chip thicknesses. In this study, a novel detailed modeling methodology of grinding forces has been analytically established, experimentally validated and utilised to study a specific issue that previous methods can not address. Based on the proposed method, grinding forces with detailed information (e.g. three components including rubbing, plowing and cutting forces) could be accurately predicted. Except for grinding forces, the proposed methodology also enable the availability of other grinding process details at the grain scale (e.g. the ratios of grains that are experiencing rubbing, plowing and cutting stages to the total engaging grain number). Validation experiment results have proved that, the proposed method could, to a large extent, describe the realistic grinding forces. Based on the proposed method, the effects of grinding conditions (including depths of cut, wheel speeds, workpiece feed speeds and grinding wheel abrasive sizes) on each component of grinding forces (rubbing, plowing, and cutting forces) have been analyzed. Some new findings, which could enhance the existing understandings of grinding forces and guide industrial manufacture, have been gained. The proposed method therefore is anticipated to be not only meaningful to provide a new way to model grinding forces in detail, but also promising to study other grinding issues (e.g. grinding heat, machined surface topography, grinding chatter), especially under the trend of miniaturization and microfabrication where grinding details at the grain scale are highly needed to optimise the micro grinding tool efficiency and micro-grinding accuracy.

1. Introduction

Grinding process could be considered as a kind of most widely-used finishing operation in the manufacturing because of low cost, high machining efficiency and good finish quality [1]. Grinding forces are a key element in grinding, influencing material removal rates, machined surface qualities, grinding temperature and vibrations, and further wheel wear and service life [2]. Grinding forces are also an important parameter that could be utilised to optimise machining parameters and grinding machine and fixture structures so that the potential of the grinding process could be fully explored [3]. To this end, many efforts have been made to try to understand grinding forces.

Because grinding wheel topography is of stochastic nature due to the random grain distribution on the wheel surface, most early studies on grinding forces focused on the establishment of empirical models, in which grinding forces could be obtained by using mathematical regression functions between the input data (e.g. the grain density and machining parameters) and the output grinding forces.

The pioneer empirical model presented by Werner and Koenig [4] expressed the normal grinding force per unit wheel width (i.e. specific grinding force) as $F'_n = k_1(C)^{k_2}(v_s/v_w)^{2k_3-1}(a_p)^{k_4}(d_s)^{1-k_5}$. In this model, grains were randomly distributed on the wheel surface and chips with varied cross-section area were also considered based on grinding kinematics. Böttler [5] suggested that Werner's model did not considered the effect of the increasing wheel wear during the grinding process, therefore the author introduced an additional factor (specific material removal V'_m) to Werner's model to compensate this effect. Tönshoff et al. [6] comprehensively reviewed most empirical models proposed before the 90s and provided the basic form of specific normal grinding forces as $F'_n = k_6k_7(v_s/v_w)^{k_8}(a_p)^{k_9}(d_s)^{k_{10}}$, which has been widely used in the later industrial manufacturing. Recent study on the empirical model was performed by Mishra and Salonitis [7], who modified Werner's model [4] by keeping the basic form whilst adding the two-way sensitivity analysis in the regression calculation.

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Nomenclature

$A_{1,2}^{(i)}$	area used in force modeling for grain i (see Fig. 7) (m^2).
A	spike amplification (see Fig. 13) (N/m).
a_p	depth of cut (m).
b	grinding wheel width (m).
b_g	grain width of cut (m).
$C_{1,2}$	experimental coefficient.
C	grain density (m^{-2}).
$d^{(i)}$	distance between grinding wheel center to the cutting point of grain i (m).
$d_g^{(i)}$	diameter of grain i (m).
d_{gmean}	average grain diameter (m).
$d_{gmax,gmin}$	maximal and minimal grain diameters (m).
d_s	wheel diameter (m).
D_g	measured grain diameter (m).
E	elastic modulus of the workpiece ($kg\ m^{-2}$).
$F'_{n,t}$	specific normal/tangential grinding forces (N/m).
$F_{n,t}$	normal/tangential grinding forces (N).
$F_{nc,ns,tc,ts}$	normal/tangential grinding force induced by chip formation and grain-workpiece friction (N).
F_g	resultant grinding force for a single grain (N).
$F_{nr,tr}^{(i)}$	normal/tangential rubbing force of grain i (N).
$F_{np,tp}^{(i)}$	normal/tangential plowing force of grain i (N).
$F_{nc,tc}^{(i)}$	normal/tangential cutting force of grain i (N).
f_{min}	minimal sampling rate in force measurements (Hz).
H_s	scratch hardness of the workpiece ($N\ m^{-2}$).
HB	Brinell hardness of the workpiece ($N\ m^{-2}$).
$h^{(i)}$	protrusion height of grain i (m).
$h_m^{(i)}$	maximal chip thickness of grain i (m).
h_{mmax}	maximal chip thickness of all the grains (m).
$h_{plowing,cutting}^{(i)}$	critical plowing and cutting chip thicknesses of grain i (m).
$h_t^{(i)}$	instantaneous chip thickness of grain i (m).
h_c	chip thickness (m).
h_{max}	maximal grain protrusion of all the grains (m).
$k_{1,2,3\ldots,21}$	empirical coefficient.
k_t	specific grinding energy ($J\ m^{-3}$).
L_{cube}	side length of cube (see Fig. 3) (m).
$L_2^{(i)}$	average bearing width of grain i perpendicular to grinding direction (see Fig. 8) (m).
l_c	wheel-workpiece contact length (m).
M	grain number of the wheel (#).
N	structure number of the wheel.
n_g	total grain number in the wheel.
Q	chip cross section area (m^2).
r_c	ratio of chip width and thickness.
S	spike interval (see Fig. 15) (s).
s	average grain interval (see Fig. 11) (m).
t	time (s).
V_{wheel}	grinding wheel volume (m^3).
v_w	workpiece speed (m/s).
v_s	wheel speed (m/s).
$x, y, z_{local}^{(i)}$	coordinate of the cutting point of grain i in the local coordinate system $x_iO_iz_i$ (see Fig. 5) (m).
$x, y, z_{global}^{(i)}$	coordinate of the cutting point of grain i in the global coordinate system xOz (see Fig. 6) (m).
x_g, z_g	coordinate of global coordinate origin (m).
$x, y, z_c^{(i)}$	cube center coordinate (m).
$x, y, z_{ran}^{(i)}$	3d random vector (m).
ϵ	Poisson's ratio.
ζ	random variable (m).
$\theta^{(i)}$	wheel rotation of grain i (degree).
$\mu_{r,p,c}^{(i)}$	friction coefficients for the rubbing, plowing and cutting stages of grain i.
ρ	workpiece density ($kg\ m^{-3}$).
φ	grain volume rate of the wheel (%).

Experiments showed that the proposed model can estimate grinding forces with acceptable accuracy where the maximal relative error of the average normal specific forces among the six sets of validation trials was reported to be 10.68%.

Besides, other mathematical theories were also utilised in the modeling of grinding forces. Fuh and Wang [8] employed the back propagation (BP) neural network to predict grinding forces because the authors believed the multiple regressions employed in the previous studies were not enough to describe the complicated input/output relations in the grinding process. The results indicated that the maximal error rate among the ten runs of validation trials was only 2.03%, proving the good ability of the proposed model in learning and self-organising information based on a small amount of data. Liu et al. [9] believed the regression of experimental force data should not be the simple multiple regression but the multivariate multiple regression and therefore the authors proposed another empirical model, by which grinding forces could be accurately predicted in comparison with the experimental values. Similar multivariate analysis was also conducted by Guo et al. [10] and the model improvement was made by considering the dynamic forces induced by the wheel imbalance and non-stationary wheel-workpiece interactions. Good agreement between predicted and experimental grinding forces was observed in the validation trials.

Although empirical models were considered to be practical and easy-to-use for industrial applications, they intrinsically have some crucial drawbacks due to the empirical nature, including: (i) they required laborious efforts on the grinding operations, measurements, data acquisition and regression calculations, (ii) a substantial amount of experimental data was required to obtain optimum empirical coefficients, and (iii) most empirical coefficients were determined under a certain condition, and therefore the obtained coefficients might probably not be applicable to other cases.

To overcome the above issues, semi-analytical and analytical models were proposed. The pioneer study of these models was given by Malkin et al. [1,11], who observed from the experiments that, both normal and tangential grinding forces were respectively consisted of two components: the forces induced (i) by chip formation and (ii) by grain-workpiece friction, i.e. $F_n = F_{nc} + F_{ns}$ and $F_t = F_{tc} + F_{ts}$. Li et al. [12] assumed the normal cutting force of a single cutting edge in grinding was similar to turning forces and could be expressed by a power function of the chip cross section area Q i.e. $F_n = k_{11}Q^{k12}$. Malkin's model [11] therefore was transformed to be $F'_n = k_{13}(v_s/v_w)a_p + (v_s/v_w)^{k14}(a_p)^{k15}(d_s)^{k16}$. Based on Li's model [12], Yao et al. [13] predicted grinding forces of the Aermet 100 steel and the predicted results showed a reasonable agreement with those experimentally obtained. The different derivation of grinding forces was given by Younis et al. [14], who believed that grinding forces were composed of three components according to the three possible stages of grain-workpiece interactions, i.e. forces generated during the (i) rubbing, (ii) plowing and (iii) cutting stages, and the specific normal force in this model was finally expressed as $F'_n = k_{17}(v_s/v_w)a_p + k_{18}[l_c - k_{19}(v_s/v_w)a_p - k_{20}(v_s/v_w)] + k_{21}(v_s/v_w)$. The optimisation of the Younis's model [14] was recently performed by Durgumahanti et al. [15] by assuming the coefficients of friction and plowing forces were varied according to the machining parameters and workpiece and abrasive grain materials. Although the proposed force expression was similar to Younis's model [14], more accurate predicted forces were obtained. Tang et al. [16] proposed another model which focused on the calculation of chip formation forces. The authors stated the chip formation forces can be divided into static and dynamic

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