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Discrete-element modelling of the grinding contact length combining the wheel-body structure and the surface-topography models

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ABSTRACT

Phenomena governing the grinding process are largely related to the nature and evolution of contact between grinding wheel and ground component. The definition of the contact area plays an essential role in the simulation of grinding temperatures, forces or wear. This paper presents a numerical model that simulates the contact between grinding wheel and workpiece in surface grinding. The model reproduces the granular structure of the grinding wheel by means of the discrete element method. The surface topography is applied on the model surface taking into account the dressing mechanisms and movements of a single-point dresser. The individual contacts between abrasive grits and workpiece are studied regarding the uncut chip thickness, assuming viscoplastic material behaviour. Simulation results are evaluated with experimental measurements of the contact length. The results remark the importance of surface topography and dressing conditions on the contact area, as well as wheel deflection.

1. Introduction

Technological progress must be based on a deeper scientific knowledge of the process. In this context, research work focused on the modelling and simulation of the grinding process is currently very active. The analysis of the contact between the grinding wheel and the workpiece started in the early 1970s, faced by empirical and semi-analytical approaches. The main authorities in grinding remark the need to consider the contact region in the grinding operation [1,2]. Aspects such as material removal and heat generation take place in the contact region. The granular structure of the grinding wheel and the complex surface topography make difficult to model the operation.

The ideal contact model would be the one that reproduces the structure and stiffness of the wheel, combined with an accurate topography description. This work presents a numerical model of the grinding wheel structure by means of the discrete element method (DEM). Surface topography is applied according to the dressing mechanisms and kinematics of the single-point dresser. The model is used to simulate the contact in surface grinding. The penetration is the reference to estimate the cutting force on each grit. The workpiece material behaviour is assumed viscoplastic, and the effect of the centrifugal force is also taken into account. The aim is to define numerically the contact area and wheel deformation with a complete model that provides a general overview of the grinding operation.

2. Literature review

The literature review collects the main contributions on grinding wheel structure models, surface topography models and contact length models.

2.1. Wheel structure models

The performance of a grinding wheel depends significantly on its structure and morphology. So far, models with noticeable simplifications have been proposed, as [3], which describe wheel elasticity with uniformly distributed spherical grains bonded by elastic springs. Their regular configuration does not match the real random distribution of grains and bonds, creating anisotropic bodies.

Numerical tools like the finite element method (FEM) simulate the mechanical behaviour of a heterogeneous body in an extensive domain. Its main drawback is that it would be very difficult to mesh properly the porous structure of the wheel. In addition, the adjustment of the constitutive relationships of the material and contact conditions would be demanding. The use of multi-scale modelling would decrease the size of the model [4]. To the best of the knowledge of the authors, no finite element model of the wheel structure has been published at the time of sending this

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Nomenclature

A_d	area of intersection of the diamond and the grain (mm^2)
a, a_e	set and effective depth of cut (μm)
a_d	dressing depth of cut (μm)
b_d, b_s, b_w	width of the dresser, grinding wheel and workpiece (mm)
c	dumping coefficient
d_b	average grit dimension removed by bond fracture (μm)
d_{DE}, d_g	average discrete element and grain diameter (mm)
d_s	grinding wheel diameter (mm)
E_s, E_μ	grinding wheel and beam Young modulus (GPa)
$F_n'^*$, $F_t'^*$	specific normal and tangential force (N/mm)
$\mathbf{f}_c$, $\mathbf{f}_d$	contact and dumping force on a single-grit (N)
$\mathbf{f}_n$, $\mathbf{f}_t$	normal and tangential force on a single-grit (N)
f_{ce}	centrifugal force on a single-grit (N)
f_d	dressing feed (mm/rev)
G_{dyn}^*, G_o	dynamic and theoretical grain density ($grains/mm^2$)
h_{cu}	uncut chip thickness (μm)
h_f	grit fracture amplitude (μm)
h_s, h_w	grinding wheel and workpiece height on the DEM model (mm)
k_m^*	machine-wheel-workpiece stiffness (N/μm)
l_c^*	contact length (mm)
l_g	geometrical contact length (mm)
L^*	average distance between surface grits (mm)
M	mesh size
M_{iw}	equivalent mass of i element and w workpiece (kg)
N_{DE}	number of discrete elements
N_p^*	number of peaks in the APS signal
N_c	number of discrete elements in contact with the workpiece
N_s	rotation speed of the grinding wheel (rpm)
r	discrete element diameter reduction factor
r_μ	diameter ratio of the beams
r_p	distance between the peak and the discrete element centre (μm)
S	structure number
s	thickness of the mica sheet (μm)
s_n	random number between 0 and 1
t_c^*	contact time (s)
T	temperature (K)
u_d	dressing overlap
v_g	volume of an abrasive grit (mm^3)
V_{DE}	volume of the model domain (mm^3)
V_g	volume fraction of abrasive in the grinding wheel
v_s	cutting speed (m/s)
v_w	work speed (m/s)
$\mathbf{v}_i$, $\mathbf{v}_w$	speed of a discrete element and the workpiece (m/s)
x, y, z	position coordinates (m)
y_p	grit peak depth (μm)
δ_i	penetration of an individual grit on the workpiece (μm)
ε_p, $\dot{\varepsilon}_p$, $\dot{\varepsilon}_o$	plastic strain, plastic strain rate and reference strain rate
μ^*	force ratio
μ_g	grit diameter variation range (mm)
ν_s, ν_μ	Poisson ratio of the grinding wheel and beams
θ	semi-angle of the segment of the grinding wheel DEM model
ρ_d^*	single-point dresser radius (mm)
ρ_s^*	cutting edge sharpness or peak radius (μm)
σ_y	effective yield stress (MPa)

paper.

Li et al. [5,6] propose the first DEM model of the grinding wheel. The model studies the stiffness and resistance of the grinding wheel, the force chain in the bonding material and predicts the surface roughness of the workpiece as a kinematic model. Octahedron discrete elements (DE) substitute SiC abrasive grains. The model is created shaking uniformly distributed elements in position and orientation, like [7,8]. In order to reproduce bonding bridges geometrically and the binder volume fraction, several elastic beams play the role of a single bonding bridge, creating a complex redundant network. In this way, there are several binder spherical DE between the octahedron abrasive DE. Regarding the elements that connects, there are abrasive–binder beams and binder–binder beams. Beam radius is set arbitrarily regarding a fraction of element diameter plus a normal dispersion component. The calibration of beam properties is made by numerical and experimental compression tests, matching the fracture of beams and the noise during tests. In this way, a beam is created if the distance between two intermediate DEs is below a threshold value. However, the resistance under compression is highly dependent on strain rate, which enlarges remarkably the resistance of the conglomerate abrasive–binder at high cutting speeds. The stiffness (or elasticity) is adjusted regarding the load–time slopes in the experimental compression tests. Time is representative of the resistance but not of the stiffness, which is related to the deformation. The model is used to analyse the force chains in the redundant bonding network. The results remark the role of the stresses in tangential direction.

The kinematic model simulates the workpiece roughness, but disregards the effect of dressing. That is the reason for the differences between measurements and numerical surfaces. The octahedron DEs form directly the wheel surface, while the geometry of inner DEs do not play a remarkable role in the structure. The cutting force that acts on each grain is estimated analysing the peaks of experimental force measurements. In this way, the relative position of the surface grit regarding the workpiece (or chip thickness) is neglected, as well as the effect of overlapped peaks. The workpiece is modelled by a rectangular prism composed of DEs. The relationship between workpiece elements is not explained. The authors claim that the model reproduces the material ploughing during grinding, but they do not clarify if the material is removed.

2.2. Surface topography models

Doman et al. [9] review the main topography models presented in the literature. 1D models characterise the surface topography by a single parameter as the grain density, while 2D and 3D models complete the geometrical description of the wheel surface.

The surface topography created by dressing has a direct impact on the performance. Grain and bond fracture are the main dressing mechanisms [2]. The single-point dresser emulates turning movements, levelling out the surface and creating a subtle helix pattern perceptible on the ground surface [7]. Dressing conditions modify the aggressiveness of dressing mechanisms, creating an open softer or a close stiffer wheel surface.

Chen and Rowe [7] create a numerical surface that includes the effect of dressing, using a continuous sinusoidal random function