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Surface roughness and thermo-mechanical force modeling for grinding operations with regular and circumferentially grooved wheels

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ABSTRACT

A thermo-mechanical model is developed to predict forces in grinding with circumferentially grooved and regular (non-grooved) wheels. The geometric properties of the grinding wheel grits needed in the modeling are determined individually through optical measurements where the surface topography of the wheel and kinematic trajectories of each grain are obtained to determine the uncut chip thickness per grit and predict the final surface profile of the workpiece. The contact length between the abrasive wheel and the workpiece is identified with the thermocouple measurement method. In this approach, a few calibration tests with a regular wheel are performed to obtain sliding friction coefficient as a function of grinding speed for a particular wheel-workpiece pair. Once the wheel topography and sliding friction coefficient are identified it has been found that it is possible to predict cutting forces and surface roughness by the presented material and kinematic models. Theoretical results are compared with experimental data in terms of surface roughness and force predictions where good agreement is observed.

1. Introduction

In abrasive machining, tool consists of randomly oriented, positioned and shaped grits which act as cutting edges and individually remove material from the workpiece to produce the final workpiece surface. Considering the stochastic nature of the abrasive wheel topography and high number of process variables, the chances of achieving optimum conditions in a repeatable manner by only experience are quite low. Therefore, modeling of the process is crucial in order to design a successful process. Process models for abrasive machining vary greatly. The distribution and shape of the abrasive grits strongly influence the forces and surface finish. Tönshoff and Peters (1992) stated that the kinematics of the process is characterized by a series of statistically irregular and separate engagements. They presented both chip thickness and force models and compared different approaches. Brinksmeier and Aurich (2006) claimed that the grinding process is the sum of the interactions between the abrasive grains and workpiece material. In literature, abrasive wheel topography is generally investigated as a first step for both surface roughness and force analysis; the wheel structure is modeled by using some simplifications such as average distance between and average uniform height of abrasive grains (Brinksmeier and Aurich, 2006). Lal and Shaw (1975) formulated the undeformed chip thickness for surface grinding in terms of the abrasive grit radius and discussed the importance of the transverse curvature of the grit. Some parameters such as those related to wheel topography and material properties were often represented by empirical constants as presented by Malkin and Guo (2007). Empirical surface roughness models have had more success in the industry since they do not require abrasive wheel topography identification and extensive knowledge about the chip formation mechanism and process kinematics, Hecker and Liang (2003). However, the drawbacks of these models are that they result in a lack of accuracy and cause an excessive need for experimentation.

There is also literature concerning semi-analytical surface roughness models (Tönshoff and Peters, 1992). They need experimental calibration of some parameters required in semi-analytic formulations. Once these parameters are determined correctly, it is claimed that roughness can be calculated by these equations. The approach in the literature for semi-analytical models consists of two categories: statistical and kinematic approaches. Gong et al. (2002) stated that the statistical studies focus on distribution function of the grit protrusion heights whereas kinematic studies analyze and investigate the kinematic interaction between the grains and the workpiece. Hecker and Liang (2003) used a probabilistic undeformed chip thickness model and expressed the ground

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Nomenclature

a	axial depth of cut (mm)
b	radial depth of cut (mm)
a_{grit}	axial depth of cut per grit (mm)
b_{grit}	radial depth of cut per grit (mm)
$feed$	workpiece velocity (mm/s)
$feed_r$	workpiece velocity per revolution (mm/rev)
h	instantaneous uncut chip thickness (mm)
V_c	cutting velocity (m/s)
θ	grit position angle (degrees)
M	grit number
S	structure number of the grinding wheel
l_c	length of cutting zone between wheel and workpiece (mm)
$l_{c\text{-}area}$	area of cutting zone between wheel and workpiece (mm^2)
l_{cr}	length of contact at rake face of abrasive grit (mm)
l_p	length of sticking contact at rake face of abrasive grit (mm)
D	diameter of the grinding wheel (mm)
R	radius of the grinding wheel (mm)
b_{wheel}	width of the grinding wheel (mm)
C	Grain number per mm^2
W_{area}	area of grinding wheel surface (mm^2)
T_{grains}	total number of grains on the grinding wheel
A_g	active grain number
α	grain rake angle (degrees)
α_n	normal rake angle (degrees)
r	grain edge radius (µm)
h_{cuz}	grain penetration depth (µm)
d_{gx}	maximum grain diameter (µm)
h_{max}	maximum chip thickness (mm)
h_θ	instant chip thickness (mm)
F_{tc}	force in tangential direction (N)
F_{nc}	force in normal direction (N)
F_{rc}	force in radial direction (N)
F_{tp}	ploughing force in tangential direction (N)
F_{np}	ploughing force in normal direction (N)
F_{rp}	ploughing force in radial direction (N)
$F_{tc\text{-}g}$	force per grain in tangential direction (N)
$F_{nc\text{-}g}$	force per grain in normal direction (N)
$F_{rc\text{-}g}$	force per grain in radial direction (N)
F_f	frictional force (N)
F_s	shear force (N)
MRR	material removal rate (mm^3/s)
$Ø_s$	shear angle (degrees)
$Ø_{ns}$	normal shear angle (degrees)
β	friction angle (degrees)
β_n	normal friction angle (degrees)
i	oblique angle (degrees)
η_c	chip flow angle (degrees)
τ	shear stress (MPa)
Δ	average distance between abrasive grits (µm)
γ	shear strain
γ'	shear strain rate
γ_0'	reference shear strain rate
T	absolute temperature (°C)
T_r	reference temperature (°C)
T_m	melting temperature (°C)
T_w	absolute temperature of the workpiece (°C)
q_w	heat transferred into the workpiece material through contact length
μ_a	apparent friction coefficient
μ	sliding friction coefficient
$V_{chip\text{-}grit}$	volume of the chip removed from work material by a single grain (mm^3)
N	normal force acting on the rake face (N)
P_0	normal stress on the rake face at the grit tip (N)
M_{sf}	moment at the grit tip due to normal shear force acting on the shear plane (Nm)
M_{gr}	moment at the grit tip due to the normal pressure on the rake face (Nm)

surface finish as a function of the wheel structure considering the grooves left on the surface by ideal conic grains. Agarwal and Rao (2010) defined chip thickness as a random variable by using a probability density function and established a simple relationship between the surface roughness and the undeformed chip thickness. In one of the representative works for kinematic analysis; Zhou and Xi (2002) considered the random distribution of the grain protrusion heights and constructed a kinematic method which scans the grains from the highest in a descending order to predict the workpiece profile. Yueming et al. (2013), on the other hand, investigated three different grain shapes (sphere, truncated cone and cone) and developed a kinematic model based simulation program to predict the workpiece surface roughness. They also presented a single-point diamond dressing model having both ductile cutting and brittle fracture components. Apart from these studies, Gong et al. (2002) used a numerical analysis utilizing a virtual grinding wheel by using the Monte Carlo method to simulate the process generating three-dimensional surface predictions. Mohamed et al. (2013) examined circumferentially grooved wheels and showed the groove effect on workpiece surface topography by performing creep-feed grinding experiments. They showed that the grinding efficiency can be improved considerably by lowering the forces with circumferentially grooved wheels.

Once the abrasive wheel topography and grain properties are determined, force prediction becomes possible through chip thickness analysis. Models often need experimental calibration of cutting or ploughing force coefficients in semi-analytical formulations as well (Malkin and Guo, 2007). Durgumahanti et al. (2010) assumed that there was variable friction coefficient focusing mainly on the ploughing force. They established force equations for ploughing and cutting phases which need experimental calibration. Single grit tests were performed in order to understand the ploughing mechanism where the measured values are used to calculate the total process forces. Chang and Wang (2008) focused more on the stochastic nature of the abrasive wheel and tried to establish a force model as a function of the grit distribution on the wheel. Identification of the grit density function is challenging, requiring correct assumptions for grit locations. Hecker et al. (2003) followed a deterministic process by analyzing the wheel topography and then generalized the measured data through the entire wheel surface. Afterwards, they examined the force per grit and identified the experimental constants. Rausch et al. (2012) focused on diamond grits by modeling their geometric and distributive nature. Regular hexahedron or octahedron shaped grits are investigated and the model is capable of calculating engagement status for each grain on the tool and thus the total process forces. Koshy and Iwasaki (2003) developed a methodology to place abrasive grains on a wheel with a specific spatial pattern and examined these wheels' performance.

There is a need for a model that requires less calibration experimentation and no additional measurements for different wheel geometries and process conditions. In literature, secondary shear zone is usually ignored for abrasive machining processes;