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On the inverse design of discontinuous abrasive surface to lower friction-induced temperature in grinding: An example of engineered abrasive tools

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ABSTRACT

In order to lower temperature, abrasive tools with passive-grinding, e.g. textured, areas (PGA) have been suggested. However, most of the reported PGA geometries (e.g. slots, holes) have been determined based on the engineering intuition (i.e. trial and error) rather than in-depth phenomenological analysis. To fill this gap, this paper proposes a method to design the PGA geometry according to the desired temperature, i.e. the inverse design method. In the method, the analytical model of grinding temperature for tools with PGA is established and treated as the primary constraint in the inverse problem, while the models of the ground surface roughness and grinding continuity as the subsidiary constraints. The method accuracy is validated by conducting grinding trials with tools with the calculated PGA geometries and comparing their performances (temperature, roughness and force fluctuation) to the required ones. In comparison with conventional tools, our tools designed by the method have been found effective to reduce harmful, or even destructive, thermal effects on the ground surfaces. This work might lay foundation for designing discontinuous abrasive tools, and future work can be probably extended to the tools or the workpiece with more complex shapes (e.g. ball end/cup tools, and free-form workpiece).

1. Introduction

It is well-known that one third of the world energy resources is now spent on overcoming friction in various physical, chemical and biological processes, and nearly all the energy dissipated in friction is converted into heat [1]. In most cases, the excessive friction-generated heat needs to be minimised, or at least kept under control, as it could lead to the degradation of contact surfaces, which can be manifested as changes in both mechanical and microstructural properties.

The need to lower friction-induced temperature also occurs in material removal processes, especially for those that rely on abrasive phenomena such as grinding. Unlike the processes where the material is sheared by the tools with defined sharp cutting edges (e.g. drilling, milling), in grinding the material is removed by the attritive interaction between the abrasive edges of undefined geometries and the workpiece material. This leads to a high value of specific energy (energy to remove a unit volume of workpiece material) associated with elevated temperature at tool-workpiece contact area (even more than 1200 °C in certain cases [2]) when compared with machining with defined cutting edges.

Although the morphology of the abrasive tool surfaces are discontinuous at microscale (grains, binder and porosities discretely and randomly distributed), the limited micro gaps between neighboring grains are found insufficient to provide enough grain-material-disengagement period and coolant reservoir space to cool down the tool-workpiece material contact zone [2]. High temperature and the corresponding workpiece thermal damage (manifested as heat affected zones) caused by intensive cutting parameters therefore, is treated as one of the toughest issues in abrasive processes [3].

As seen in Fig. 1a, one potential solution to reduce thermal damage on the workpiece is to alter the tool-workpiece contact from continuous to discontinuous/intermittent nature by artificially creating special regions without abrasive grains, or Passive-Grinding Area (PGA), on the tool surfaces. In this context, these "engineered" abrasive tools can be categorised into [4]: (i) segmented tools, where the PGA was created by assembling individual abrasive segments onto a tool hub with specific gaps; and (ii) textured tools, where the PGA was achieved by removing abrasive grain area from conventional tool surfaces.

By employing abrasive tools with discontinuous surfaces, significant temperature reduction of 105 °C for aluminum [5], 195 °C for steel [6],

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Nomenclature

a_p	grinding depth (mm)
b	tool-workpiece contact width (mm)
C	grain number per area (/mm)
c	specific heat capability of workpiece (J/kg·K)
c_c	specific heat capability of coolant (J/kg·K)
$d_{max,min}$	maximum and minimum grain diameters (mm)
d_s	abrasive tool diameter (mm)
dt	differential timestep (s)
E_b	thermal energy that is taken away from the material to increase the transported coolant temperature until boiling (J)
E_e	thermal energy that is taken away from the material to continuously evaporate the boiling coolant (J)
E_t	total thermal energy that is taken away by coolant (J)
F_a	axial grinding force (N)
F_{a-left}	axial forces induced by the left PGA part (see Fig. 10a) (N)
$F_{a-right}$	axial forces induced by the right PGA part (see Fig. 10a) (N)
H_{pga}	PGA depth (mm)
h	heat transfer coefficient of workpiece (W/m·K)
$h_{max,min}$	largest and smallest grain protrusions (mm)
k	workpiece thermal conductivity (W/m·K)
$L_{1,2,3,4,5,6,7}$	tool-workpiece contact width (see Fig. 2) (mm)
l	one pass length (see Section 4) (mm)
l_g	tool-workpiece contact length (mm)
M	abrasive size number (#)
m_m	workpiece mass (kg)
n	positive integer
ng	total number of grains that are contacting with the workpiece in the grinding zone
n_{grain}	grain number within the active-grinding region
Q	heat quantity of heat source
q	heat flux density (J/s)
R_z	measured surface roughness (μm)
$Rz_{required}$	required surface roughness (μm)
T	measured grinding temperature (°C)
ΔT	grinding temperature reduction (°C)
T_b	coolant boiling point (°C)
T_{c0}	initial coolant temperature before it enters the grinding zone (°C)
T_e	system equilibrium temperature (°C)
T_m	full temperature field induced by multiple grains (°C)
$T_{required}$	required grinding temperature (°C)
$T_s(x, y, z, t)$	nonsteady-state 3D temperature field (°C)
t	time (μs)
t'	the moment when heat source acts (μs)
t_b	time duration to boil the coolant (μs)
t_c	time duration from the coolant enters to escapes the grinding zone (μs)
t_e	time duration for the system to achieve thermal equilibrium (μs)
v_{grain}	grain velocity (m/s)
v_w	material feed speed (m/s)
$v_{x,y,z}$	translational speed (m/s)
w_a	active-grinding region width (mm)
w_p	passive-grinding region width (mm)
$x, y_{1,2}$	x and y coordinate of grain 1 and 2 (see Fig. 2) (mm)
$y_{1,2max,1,2min}$	maximum and minimum y coordinate of grain 1 and 2 (mm)
y_q	y coordinate of the intersection point Q in reference to the coordinate $x_1O_1y_1$ (see Fig. 4) (mm)
ρ	workpiece density (kg/m^3)
ρ_c	coolant density (kg/m^3)
α	thermal diffusivity of workpiece (E^{-6}·m^2·s^{-1})
β	angle relative to the tool axial direction (°)
μ	mean distribution of grain size (mm)
σ	standard deviation of grain size (mm)
χ	coolant evaporation heat (J/kg)

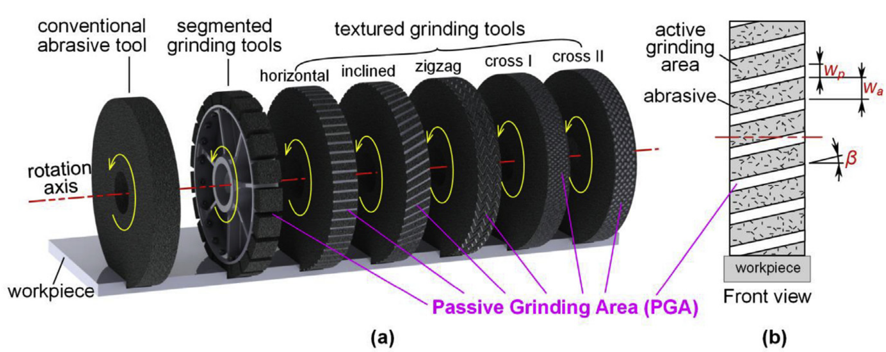

Fig. 1. (a) Illustration of abrasive tools with the Passive Grinding Area (PGA) including both segmented and textured grinding tools, (b) The simplified linear GPA geometries defined by w_p, β, and w_a.

and 200 °C for GH4169 [6] and TC4 alloy [7] was observed in grinding experiments in comparison with conventional tools with continuous peripheral abrasive surface.

Despite the reported research on the use of abrasive tools with discontinuous surface, very few efforts have been noted to theoretically model the temperature reduction for a known PGA geometry under certain conditions. This is the direct problem to solve: given the geometrical characteristics of a specific PGA, determine the reduction in cutting temperature at the tool-material interfaces. Therefore, the tool performances can be neither predicted nor optimised until iterative experimental trials are performed with tools having various PGA geometries.

What is more imperative here is to propose a design method which can determine the PGA geometry according to the desired grinding temperature, i.e. the inverse problem. In fact, similar inverse problems in various kinds of time-dependent processes have been extensively studied, including abrasive waterjet, laser and ion beam machining [8]. However, most previous studies have been focused on the process kinematics (e.g. feed rates, tool paths) to generate the freeform surfaces. To the best knowledge of the authors, no inverse design was presented for designing tool geometry, let alone in the process relying on randomly undefined cutting edges such as grinding.