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Identification of heat partition in grinding related to process parameters, using the inverse heat flux conduction model

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HIGHLIGHTS

- A methodology for obtaining the heat partition to workpiece in grinding is proposed.
- The methodology used inverse calculation based on Levenberg–Marquardt algorithm.
- An alternative experimental approach is used to reduce uncertainties.
- A time-dependant heat partition related to grinding chip thickness has been found.
- Results validated by means of indirect measurement: workpiece hardness evolution.

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ABSTRACT

Grinding is an abrasive machining process characterized by producing high quality components for high added-value industries. Thermal damage is an undesired phenomenon that may ruin nearly finished products. The study of thermal damage requires understanding the mechanisms of heat partition between wheel and workpiece. In this work and original methodology and experimental set-up for the study the influence of grinding variables on the heat partition to the workpiece, R_w, is presented. The new methodology avoids errors related to the steep thermal gradients typical of grinding operations. In addition, uncertainty related to the actual area of contact is suppressed thanks to a rigid and controlled experimental configuration. An inverse model based on Levenberg–Marquardt algorithm and a finite element model has been used for heat partition to the workpiece identification. Results have lead to a time-dependant R_w definition which had not been previously proposed in literature, and they have allowed as well relating variations in R_w values to physical removing mechanisms of grinding. Results have been validated by means of an indirect parameter: workpiece hardness variation during the tests, which strengthens the validity of the results.

1. Introduction

Grinding is an abrasive machining process characterized by producing high quality components for high added-value industries (aerospace, energy, tooling…) in terms of tight dimensional tolerances and smooth surface roughness. By contrast, grinding is also characterized by requiring a high amount of energy input per unit volume of material removed. This energy is turned into heat in the contact zone and can cause excessive heating of the workpiece leading to thermal damage on its surface [1]. Thus, the occurrence of thermal damage becomes one of the limiting constraints of productivity in grinding technology.

Increasing material removal rate is limited by the apparition of workpiece burn. The classic solution for burning problems is the use of cooling fluids but their effect is limited. Hence researches try to improve cooling effect by refrigerating the coolant [2] or improving their convective effect [3]. However, these advances are not enough for avoiding burning in some cases. Therefore, understanding the mechanisms that govern workpiece temperature increase and relating them to industrial process parameters become a key factor for grinding process control and optimization.

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Nomenclature

a_e	depth of cut, mm
A_c	contact area, m^2
A_1	attempt frequency, s^{-1}
b	workpiece thickness, mm
h	convective heat transfer coefficient, W/m^2 K
h_{eq}	equivalent chip thickness, mm
h_1	reaction constant (Arrhenius law), W/m^2 kg
H	final material hardness, HV
H_1	hardness of the fully-tempered material, HV
H_3	hardness fully quenched material, HV
l_c	contact length, mm
P	grinding power, W
Q'_w	specific material removal rate, mm^3/mm s
q_{ch}	heat flux to the chips, W/mm^3
q_{fl}	heat flux to the fluid, W/mm^3
q_t	total heat flux generated, W/mm^3
q_s	heat flux to the grinding wheel, W/mm^3
q_w	heat flux to the workpiece, W/mm^3
R	molar gas constant, m^2 kg/s^2 K mol
R_{ch}	heat partition to the chips, –
R_s	heat partition to the grinding wheel, –
R_{fl}	heat partition to the grinding fluid, –
R_w	heat partition ratio to the workpiece, –
T_M	absolute workpiece temperature, K
T_{amb}	absolute ambient temperature, K
U_1	activation energy for tempering, J/mol
v_f	infeed speed, mm/min
v_s	grinding wheel speed, m/s
V'_w	specific volume of part material removed, mm^3/mm
ε	emissivity, –
κ	thermal conductivity
ψ	probability of tempering, –
σ	Stefan–Boltzmann constant, W/m^2 K^4

It is assumed that the power consumed by the grinding wheel spindle is transformed into heat in the contact zone. This heat is evacuated through four ways: workpiece, wheel, ground chips and cooling fluid. The partition of this heat that goes into the workpiece, R_w, is the cause of workpiece temperature increase and thermal damage [4]. Therefore its determination is very important for process optimization. However, it is a parameter difficult to assess since it depends on a large number of parameters: tribological, mechanical and geometrical. In fact, on shallow grinding with Al_2O_3 wheels scientific literature give values between 0.25 and 0.85.

Usually, authors have identified R_w by matching temperature data experimentally obtained with calculated temperature from theoretical models. One of the main limitations of this methodology, and one of the causes of the wide dispersion of R_w above, is the steep thermal gradients found in the contact zone (up to 10,000 K/s [5]), that limit the reliability of the measured temperatures.

For obtaining the theoretical temperature modelization of the process is necessary. Initially, the grinding wheel heating was modeled as a rectangular moving heat source along a semi-infinite body [5]. Analytical models focused their efforts in simulating heat generation. This way [7] found that a triangular distribution of the heat source gave as a result temperature distributions closer to the reality. The model developed in Ref. [8] agreed with this conclusion and added that while for shallow grinding heat generation can be modeled by a band heat source that slides in a plain, in deep grinding an inclined source is necessary. In Ref. [9] an exact solution for an analytical model accounting for heat generation at shear planes, coupled with the heat transfer at wear flats is developed. This model is used to assess the influence of the heat generation (shear planes or wear flats) in the process. Analytical models were progressively replaced by numerical models with the rapid increase of calculation power. As it is gathered in Refs. [10], numerical models are used following similar approaches: workpiece discretization, effect of grinding wheel as a moving heat source and consideration of the convective effect of cooling fluid; but differ in four main aspects: geometry of heat source (rectangular vs triangular), contact length estimation, material properties (constant or not with temperatures), and 2D or 3D models. This way, Brosse [11] used finite element methods and thermography to characterize the distribution of R_w in the contact zone finding the triangular or the parabolic shape of the heat fluxes provided more accurate results.

Following the approach above described, Kohli found values in the range 0.6–0.75 for shallow grinding with Alumina wheels [5]. He used the Jaegers [6] solution with a triangular heat flux shape. Hadad studied grinding with Minimum Quantity of Lubrication-MQL [12]. Based on analytical models found in Refs. [9], his experiments concluded that R_w varies between 0.73 and 0.77 for grinding with MQL, 0.82 for dry grinding and the use of cooling fluid reduced R_w to 0.36.

Inverse methods are numerous and widely used to study various heat transfer phenomena [13]. Recently, the function specification method was used by Meresse to get heat flux repartition on a disc in braking conditions [14]. Ludowski used the Levenberg–Marquardt method [15] to get the thermal boundary conditions in heat exchangers [16]. The conjugated gradient method with adjoint problem has been used by Luchesi to identify a moving heat source in machining conditions [17].

Inverse methodology has already been used in machining to identify thermal parameters of the process. In milling of hardened steels, the steepest descent method was used in Ref. [18] to inversely estimate the amount of energy directed to the workpiece and the convection coefficient, h_f. The Levenberg–Marquardt method [15] has also been used for characterizing the thermal problem in drilling [19]. In this case, authors measured workpiece temperature in drilling tests and compared it to that obtained from a one dimensional moving heat source analytical model and used the minimization of the quadratic error to obtain their results.

In grinding this methodology is widely used to determine R_w by matching experimental temperature with an output numerical data, the nodal temperature at the sensor location, and minimizing the error. Three inverses analyses are used in Ref. [20] to obtain R_w, the geometry of the heat source, and the convection coefficient h_f from temperature data. Experiments are described in Ref. [21] and authors have found R_w values in the range 0.70 and 0.74 for grinding with Al_2O_3 wheels using hardened steel and plain carbon steel. More recently, Hong has presented the assessment of R_w using a finite element method as direct model but results have not been validated by experimental data [22]. In Ref. [25] Anderson et al. performed this work for shallow and deep grinding. For the assessment of workpiece temperature distribution they used the finite elements method, and took into account the material removed by deleting elements in the model for the case of deep grinding. They estimated heat partition ratios to the workpiece by