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Numerical simulation of grinding with realistic representation of grinding wheel and workpiece movements: a finite volumes study

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Abstract

Thermal models have been long established for the simulation of thermal phenomena occurring during machining processes which involve intense heat exchange, such as grinding. These models, if properly combined with experimental results and observations, can provide significantly accurate results concerning quantities that are difficult to be measured directly and lead to a deeper understanding of the occurring phenomena. The vast majority of such simulations often include simplifications such as replacement of grinding wheel with a moving heat source. In the current study, a finite volumes thermal model with explicit representation of the grinding wheel and workpiece movements is presented and cases involving the use of various machining conditions are conducted with a view to determine temperature distribution and heat affected zones within the workpiece in each case.

Keywords: grinding; finite volumes method; thermal modeling; heat affected zones

1. Introduction

Grinding is an abrasive process capable of producing high surface quality of machined components or removing efficiently large bulks of material. Grinding as a process involves the use of a rotating wheel containing microscopic level grains of abrasive material at its surface, tied on the wheel by means of bonding material.

Among other, a notable characteristic of this process is the significant effect of heat produced by the contact of grinding wheel and workpiece which results in several thermally-induced phenomena on the workpiece, such as grinding burn or alterations of microstructure and creation of hardened zones beneath the surface. Apart from the thermal phenomena, surface quality and residual stresses are frequently studied in respect to process parameters and materials used, as they determine largely the life and integrity of machined components.

Due to the importance of this process, several theoretical works have been conducted starting from the early 20th century in order to explain the underlying mechanism of abrasive cutting and other related phenomena. As the effect of produced heat is significant and dimensions of grinding chip are almost negligible, the majority of theoretical work is concentrated on thermal models in which a moving heat source with magnitude determined from process parameters and experimental findings, travels along the surface of the workpiece. The results of these models, such as temperature fields, determination of heat affected zone (HAZ) and microstructural alterations are particularly useful for the design of the process and the prevention of undesired outcome. These investigations are primarily conducted with the well-established Finite Elements method (FEM) [1, 2].

In the present paper, a different approach is attempted with a less frequently used in machining processes modeling method, namely the Finite Volume Method (FVM). More specifically, a 2D thermal model of grinding is presented,

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with an explicit modeling of the grinding wheel. The heat absorbed by both the wheel and the workpiece is modeled by means of moving heat sources with the heat source on the grinding wheel moving on its circumference. Cases with variable depth of cut are considered. Furthermore, two different approaches concerning grinding wheel material model are presented and results on the development of temperature fields on the grinding wheel and workpiece are discussed.

2. Grinding process modeling

In this section, a brief presentation of various types of grinding process models, encountered in the relevant literature is conducted.

2.1. Thermal models

The earliest simulations of thermal phenomena during grinding were conducted by thermal models, the basic details of which are summarized in the works of Malkin and Guo [3] and Doman et al. [2]. Some indicative works are summarized below. Mamalis et al. [4] presented a 2D model based on the moving heat source model (Jaeger model) in order to determine the temperature field and HAZ during grinding of several types of steel. The same model was applied by Mamalis et al. [5] to cases involving various types of grinding wheels. Morgan and Rowe [6] presented a detailed thermal model as well as indicative values for model parameters. Garcia et al. [7] used a 3D transient inverse heat flux conduction model to determine workpiece heat partition ratio (R_w). Their model incorporated other domains of the grinding process such as the air layer and included also a model of hardness calculation. Their findings indicated that R_w is more preferable to be time-dependent and that this procedure leads to more accurate hardness prediction. Shah et al. [8] performed studies regarding phase transformation and residual stresses during grinding by means of a thermal grinding model.

2.2. Thermal models with cutting fluid modeling

In most of the earliest thermal models the influence of grinding fluid is included through partition ratio calculations or as a heat flux boundary condition at the workpiece surface [4-6]. However, several researchers have conducted studies focusing on details of the cooling process and cutting fluid flow. Liao et al. [9] created a model with two thermal sources at the grain-workpiece interface and the shear plane between the workpiece and the chip. Heat transfer coefficient for each source of the thermal model was determined in detail and the model parameters were taken from actual experimental data. Comparison between the produced results and experimental ones proved that this model had sufficient accuracy for the prediction of temperature fields in the workpiece.

As the determination of heat transfer coefficient in grinding is very important for the simulation, Lin et al. [10] developed a detailed methodology for this goal, based also on experimental results. This model showed that heat coefficient values can be relatively high and vary with the machining conditions. Hadad and Sadeghi [11] used a complex thermal model for grinding under minimum quantity lubrication (MQL) conditions. This model was based on the principle of moving heat source but several modifications were introduced in the calculations of heat partition ratio and mainly, in the calculations of heat transfer coefficients which took into consideration the MQL conditions. Subsequent comparison with experimental results proved that a high level of accuracy was attained using this model mainly for MQL grinding and lower accuracy was attained for general fluid or dry grinding.

Finally, models with grinding fluid flow field calculations were also reported in the relevant literature. Specifically, Mihic et al. [12] created a computational fluid dynamics (CFD) model with volume of fluid method to study heat transfer and fluid flow during grinding. Their model was tested in cases of both dry and wet grinding and they managed to determine fluid velocity field as well as temperature distribution of the workpiece. Thus, the effect of grinding fluid was demonstrated explicitly. Moussa et al. [13] simulated the flow inside the distributor of grinding fluid and determined velocity, pressure contours and flow rate. The model was validated by comparison with particle image velocimetry experiments.

2.3. Grinding wheel and abrasive grains modeling

In the previously mentioned studies, grinding wheel contribution to the process was modeled through heat partition coefficients and some of its characteristics, but no explicit modeling of its surface topography or the grain characteristics was taken into consideration. Various models of grinding wheel are presented briefly in the work of Doman et al. [14] and some indicative studies concerning the characteristics of grinding wheel will be presented afterwards. Zahedi and Azarhoushang [15] employed a FEM model to study the interaction between abrasive grains and the workpiece surface. Using an appropriate methodology which was comprised of a probability density function for the position of abrasive grains and a kinematics model, they managed to extend the produced results with the single grain model to predict workpiece surface topography after grinding with multiple grains.

Another model of grinding wheel topography and its interaction with workpiece surface was developed by Nadolny et al. [16]. After their methodology was described, they exhibited how this model can lead to the design of new types of wheels and to the reduction of cost in the development of new wheels. Zhang et al. [17] created a model of grinding wheel with randomly placed abrasive grains and studied the contact behavior of grains and workpiece as well as the development of grinding forces. Wang et al. [18] constructed a mathematical model of abrasive grains, which were realistically placed on the circumference of a grinding wheel. The interaction of grains and workpiece surface was monitored and after an iterative process took place, the final topography of the workpiece surface was computed. These two models are particularly interesting, as they propose relatively simple ways to create a multi-grain geometry for the