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Modeling heat transfer in die milling

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HIGHLIGHTS

- Proposed thermal models are simple and sensitive to the machining conditions.
- Models were validated by other methods applied to solve direct-inverse problems.
- Methods may be used for any part materials, conditions and machining processes.
- 3D model approaches global one when uses mean workpiece temperature.
- Methods can also be extended to analyze cutting fluid performance.

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ABSTRACT

This paper compares two different thermal models by solving computationally direct-inverse problem to estimate the net heat flux and convective coefficient when milling hardened AISI H13 die steel. Global and tri-dimensional transient models were developed and solved by Finite-Volume and Gauss Methods, respectively. Two cutting speeds were considered in dry finishing operation. Experimental temperatures measured by part-embedded thermocouples fed the inverse-problem, which were compared to theoretical temperatures given by direct-problem. Both models are able to estimate the thermal properties for milling processes. Tri-dimensional model approaches global one when using mean temperature of thermocouples. The models agreed with others in the literature.

1. Introduction

Machining is one of the most important manufacturing processes because it accounts for 20%–30% of the value of all goods and services produced [1,2]. Its objective is to remove material from workpiece to confer shape, dimensions and finishing to the product [3]. The removed material is called chip and the complexity of its formation, which encompasses high heat, strain and stresses depends on the zones where it is formed and slides, i.e., primary and secondary shear zones [4].

Machining phenomenon is still not completely understood given the highly non-linear nature and the complex coupling between strain and temperature. Practically, total mechanical energy is converted into heat due to the plastic deformation of chip, friction in the chip-tool and part-tool interfaces [5]. Deformations concentrated in a very small zone produce high temperatures that affect both tool and workpiece [6]. Thus, better cutting conditions for tool and part may be determined if heat flux and temperature field are measured or estimated.

Formerly, studies on temperature or heat in machining were usually experimental or analytical. However, even nowadays experimental approaches bring some drawbacks due to workpiece or tool movement and analytical methods do not always supply simple formulations or solutions. With computational facilities, numerical simulations gained space providing complex and fast solutions [7].

Several thermal studies considering experimental, numerical and analytical methods have been carried out in machining processes [8]. A classic study is from Trigger and Chao [9], which

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developed a bi-dimensional analytical model in steady state to calculate the mean temperature increase as chip leaves the primary shear zone, by adopting the shear plane as heat source. More recently, as aforementioned, computational methods have been largely utilized.

In turning processes, Antonelli and Romano [10] estimated the maximum temperature of the tool by solving inverse-problem, considering the transient and steady cases. Carvalho et al. [11] estimated the temperature at the chip-tool interface by employing a numerical method coupled with a tri-dimensional model based on transient heat conduction. Augustine and Olisaemeka [12] found the heat flux at the chip-tool interface by solving inverse-problem with Finite-Difference Method.

In drilling processes, Brandão, Coelho and Lauro [13] estimated the heat flux and heat transfer coefficient by applying an analytical heat conduction model for hardened AISI H13 steel (55 HRC). Souza et al. [14] investigated the workpiece temperature and heat flux at the chip-tool interface through numerical solution and two transient models: inverse algorithm and Finite-Volume Method.

In grinding processes, using Implicit Method of Finite Differences, Gostimirovic, Kovac and Sekulic [15] modeled the workpiece temperature and heat flux.

In milling processes, applying a numerical model based on Finite-Difference Method, Ulutan, Lazoglu and Dinc [16] estimated the temperature field in chip-tool interface for AISI H13 steels. Pabst, Fleischer and Michna [17] simulated via Finite-Element Method the heat flux for gray cast iron and reached difference of 20% between experimental and numerical results. Luchesi and Coelho [18] applied the inverse method to estimate the heat sources by using Conjugated Gradient Method. Using Deform-2D™ and a proposed analytical model, Cui, Zhao and Pei [19] found heat flux and tool temperature for AISI H13 steel. Lin et al. [7] proposed a thermal modeling to describe the cyclic temperature for 300M steel (52 HRC).

As seen, most of studies related to thermal problems in machining focuses on cutter tool [14]. This is particularly relevant when the objective is to improve the tool performance against thermally activated wear, such as of crater (diffusion) and flank (friction) [20]. However, several workpieces for high performance application, such as alloy steels or difficult-to-cut materials, need to preserve their surface integrity after finishing operations and before using in service [21,22]. Die and mould milling represent this case, in which finishing milling is usually applied in hardened material, but the surface finish, residual stress, subsurface microstructure and surface hardness cannot be negatively affected by machining temperature, aiming to increase the fatigue life of workpieces [23,24]. In these cases, the workpiece and cutting fluid should be the aim of thermal modeling; the first to preserve the surface integrity and the second to improve the efficiency in convectional heat transferring.

This paper develops and compares two different thermal models by solving computationally direct-inverse problem to estimate net heat flux and convective coefficient when milling hardened AISI H13 steel used for moulds and dies production.

2. Thermal modeling of the milling process

Fig. 1 shows the physical modeling of the thermal problem for milling process of a prismatic workpiece.

The variables q_L'', h and T_∞ are the net heat flux, the convective heat transfer coefficient and room temperature, respectively. Net heat flux is the difference between the heat flux generated by cutting tool during the machining process and the heat flux

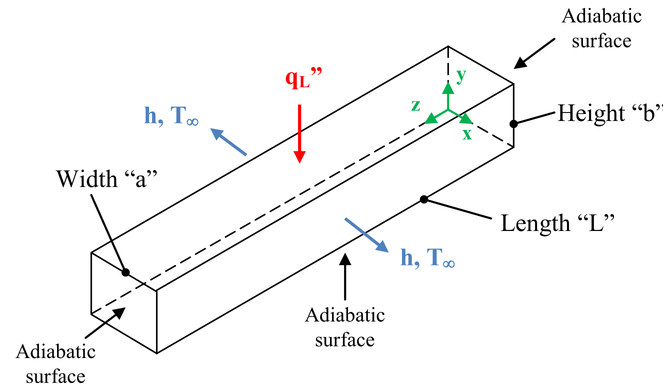

Fig. 1. Thermal model adopted for milling process.

removed by surrounding fluid. The variables a, b and L are width, high and length of workpiece, respectively.

Two thermal models were developed to solve this thermal problem. The first one assumes that temperature inside workpiece depends on time only and it is constant whatever the directions at the same instant. Thus, this transient model was named as GL (Global model) because it utilizes the mean temperature curve of all thermocouples. The second one considers that temperature depends on time and on coordinates of workpiece (XYZ). This transient and tri-dimensional model was studied under two manners, named as 3D-P and 3D-T. Estimations from 3D-P model were done by using the temperature curve of each thermocouple. Thus, five temperature curves provided five estimations of heat flux and convective coefficient, which in turn generated mean values of the estimations. 3D-T model estimated q_L'' and h by means of mean temperature curve, which was assumed as a local result of a single thermocouple. The following simplifying hypotheses were considered to both thermal models.

- Workpiece material is isotropic;
- Heat is added through milled surface at once;
- End and bottom workpiece surfaces are adiabatic;
- Heat flux is constant in the evaluated temperature range;
- Convective heat transfer coefficient is constant and equal to non-isolated workpiece surfaces.

2.1. Global model (GL)

Considering the workpiece as a system (Fig. 1), heat (δQ) which across the system boundaries is provided by milling tool (friction due to chip formation) and work done by the system on its surrounding is zero ($\delta W = 0$). One portion of heat is exchanged with environment or cutting fluid by convection and other one propagates to the workpiece by conduction. Thus, the energy received by workpiece is equal to the variation of its internal energy ($\delta Q = dU$), which appears as temperature variation inside workpiece.

Applying the simplifying hypotheses aforementioned, the energy balance is given by Eq. (1).

$$q_L'' A_S - 2(T_c - T_\infty)(hA_L) = \rho c V \frac{dT_c}{dt} \quad (1)$$

in which T_c is the workpiece temperature (K), T_∞ is the room temperature (K), h is the convective heat transfer coefficient (W/m^2 K), q_L'' is the net heat flux (W/m^2), A_L is the side area $b \times L$ (m^2), A_S is the upper area $a \times L$ (m^2) and t is the time (s), ρ is the specific