International Journal of Heat and Mass Transfer 126 (2018) 935–945

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Temperature field sensing of a thin-wall component during machining: Numerical and experimental investigations

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ARTICLE INFO

Article history:
Received 16 January 2018
Received in revised form 25 April 2018
Accepted 2 June 2018

Keywords:
Heat conduction
Thin-wall plate
Temperature field reconstruction
Modal expansion
Machining

ABSTRACT

Thermal dynamics of hard-to-machined components during manufacturing contributes to micro defects and residual stresses in final products and overheating on machine tools, where temperature plays a critical role in the study of the tool-workpiece interface. However, typical temperature sensing approaches are limited in manufacturing due to their dependence on controlled environments without blockages and cutting fluids/chips, complicated algorithms with long computation time, and knowledge of heat source intensity that is hard to estimate. This paper proposes a temperature field reconstruction (TFR) method as a real-time and online approach to investigate the thermal dynamics of a thin-wall disk-like workpiece (WP) during a turning process. Formulating in a modal expansion with physical laws, the method decouples the temperature field into products of spatially-distributed temperature mode shapes and time-varying modal coefficients that are determined from a finite number of nodal measurements. The TFR method is demonstrated and verified with simulated measurements in finite element analysis, and an illustrative application to TFR during machining is presented to justify its ability for real-time computing and online sensing in manufacturing.

1. Introduction

Thin-wall components, made from hard-to-machined materials and featured with high strength-to-weight ratio, have been in great demands from aviation industries. However, their thermal dynamics during manufacturing contributes to micro defects [1] and residual stresses [2] in final products as well as overheating on cutting tools [3], which deteriorates the final product qualities and shortens the tool-service life. While the temperature plays a critical role in the study of the tool-workpiece interface, it is challenging to monitor the time-varying and spatially-distributed temperature fields under machining conditions [4]. Motivated by the interests to investigate the thermal effects on workpiece (WP) deformations and residual stresses, this paper proposes a temperature field reconstruction (TFR) method as a real-time and online approach to capture the thermal dynamics of a thin-wall disk-like WP during a turning process.

Existing measuring technologies are limited to harsh requirements and hard to implement for process state monitoring in practice. While thermocouples are one of the most widely used methods for measuring temperatures in machining [5,6], they could not be installed on WP surfaces because of the material removal in cutting. Also, it is not practical to embed thermocouples in a WP in a destructive way, although it can be done for one-time trial testing in laboratory studies [7]. As thermocouples provide nodal measurements of temperature, sensor arrays are embedded in machine tools to estimate temperature distributions close to the cutting region [8]. Besides, non-contact approaches such as infrared sensing have been developed for measuring temperature fields. Infrared thermal imaging was used to measure the tool and WP temperatures even at high temperature regions as there is no direct contact with the heat source [9,10]. Though complicated the manufacturing environments are with cutting fluids and chips, thermal images do provide a direct way to capture the temperature distribution across the WP. Considering the small cutting region is usually blocked or obscure in an image, it is desired to develop a method to predict the temperature at the inaccessible region based on information of other measurable locations. Field reconstruction methods have been developed analytically or

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.006
0017-9310/

numerically when the physical problems can be mathematically modeled in advance [11–13].

Formulating the thermal dynamics as a boundary value problem (BVP), numerical methods can be employed to reconstruct the distributed temperature fields, among which finite element analysis (FEA) has been widely used [14–18]. With prescribed heating inputs and boundary conditions, the BVP can be solved numerically for the resulting temperature distribution within a targeted space [13,19–22]. This forward approach is well-defined in theory and offers a powerful tool for analysis; however, in manufacturing practices, heat sources are usually unknown and immeasurable because they are affected by cutting processes. Similarly, the assumptions of ideal boundary conditions, such as the Dirichlet's condition [21–26], could lead to modeling errors and thus affect the sensing accuracy in practical applications. To estimate the unknown heat source, inverse approaches have been developed for applications of metal casting [27], welding [28], forming [29] and machining [30–32], and different methods have been proposed such as the least square inverse scheme [33,34], golden section technique [35,36], conjugate gradient method [37,38], local meshless method [39,40], sequential function specification method [41,42]. Most inverse approaches involving iterations are usually too time consuming for real-time applications. In another way, heat generated in metal cutting can be estimated using measured cutting forces and other cutting parameters, such as depth of cut, feed-rate and cutting speed [43]. Recently, the flexible division algorithm is developed with the time-efficiency of 100 ms for real-time prediction of the temperature in cutting with the heat flux estimated from an energy equation and cutting force measurements [13].

As dynamics of physical fields conforms to certain governing partial differential equations whose solutions are derived with the separation of variables, general solutions can be obtained as a summation of eigenfunctions or mode shapes. In this way, displacement and strain fields are reconstructed across a thin-wall WP under machining based on prior knowledge of vibration mode shapes and finite number of nodal measurements [12]. This paper proposes a TFR method as a real-time and online approach to investigate the thermal dynamics of a thin-wall disk-like WP during a turning process. This method does not require expensive instruments, complicated algorithms or even knowledge of heating source intensity in prior, so it provides a simple yet effective approach for process state monitoring in manufacturing. The remainder of this paper offers the following:

- By formulating the WP thermal dynamics as a boundary value problem, the proposed TFR method is developed with modal expansion techniques, where the spatially distributed information and time-varying factors are decoupled, so that the temperature field can be determined from a finite number of nodal measurements.
- Demonstrating the proposed TFR method via modal analysis, dimensionless variable groups are introduced to study effects of material properties on field reconstruction, based on which a guideline is provided to determine the modes employed in reconstruction.
- The TFR method is numerically verified with simulated measurements using FEA, and an illustrative application to TFR during machining is presented to justify its ability for real-time computing and online sensing in manufacturing.

2. Problem formulation

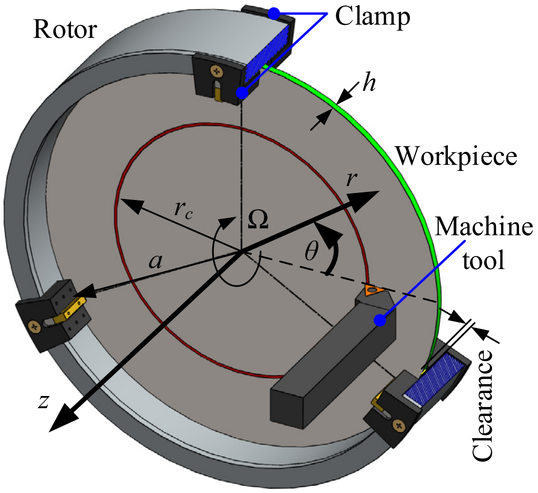

Fig. 1. A circular plate with an axisymmetric heat source.

As shown in Fig. 1, the thermal dynamics of a rotating WP under lathe-machining is modeled as a thin circular plate (of radius a and thickness h) subjected to the heat source at the tip of the cutting tool. A polar coordinate is established at the plate center where the r and θ axes span the plate mid-surface and the z-axis is collinear with the WP rotation axis. Because the heat conduction rate is much slower than the rotation speed Ω, the thermal dynamics is dominated by the rotational effect and is assumed to be axisymmetric. The heat source at the cutting position ($r = r_c$, $z = z_c$) is described by the energy generation (W/m^3) of $g(t, r, z) = g_1(t)\,\delta(r - r_c)\delta(z - z_c)$ characterizing any heat generated during cutting or dissipated into environments. The top ($z = h/2$) and bottom ($z = -h/2$) plate surfaces are subjected to convection while the radial boundary ($r = a$) is thermally insulated given the large aspect ratio (a/h). The initial temperature is set to the room temperature. It is desired to obtain the dynamic temperature distribution across the WP, especially the temperature at the cutting region which is inaccessible in practice.

The temperature distribution $T(t, r, z)$ across the plate is governed by the following partial differential equation

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{k_t} g(t, r, z) = \frac{1}{\alpha}\frac{\partial T}{\partial t}, \quad 0 \leqslant r \leqslant a, \; -\frac{h}{2} \leqslant z \leqslant \frac{h}{2} \tag{1}$$

where k_t is the thermal conductivity, and the thermal diffusivity (m^2/s) is defined as $\alpha = k_t/(\rho C_p)$ with ρ and C_p denoting the density and specific heat, respectively.

Initially, the temperature distribution on the WP is uniformly equal to the initial temperature T_0

$$T|_{t=0} = T_0 \tag{1$'$a}$$

and the boundary condition on the plate surface is provided by

$$T|_{r=0} < \infty, \; \partial T/\partial r|_{r=a} = 0 \tag{1$'$b, c}$$

$$(k_t \partial T/\partial z + k_c T)|_{z=h/2} = k_c T_\infty, (k_t \partial T/\partial z - k_c T)|_{z=-h/2} = -k_c T_\infty \tag{1$'$d, e}$$

where T_∞ is the ambient temperature; the convection heat-transfer coefficient is calculated via $k_c = 0.335 k_a \sqrt{\Omega/\nu}$ [44]; and k_a, ν and Ω are the heat conductivity, air kinematic viscosity and angular velocity, respectively. It is noted that k_a and ν are temperature-dependent; and for a disk temperature ranging between 20 °C and 220 °C, k_c is approximated as 20 W/m^2 K with Ω = 800 rpm to emulate the axisymmetric case under high-speed turning. In practice, the initial and ambient temperatures, T_0 and T_∞, are usually the same.