Case Studies in Thermal Engineering 6 (2015) 128–135

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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

A simple mathematical procedure to estimate heat flux in machining using measured surface temperature with infrared laser

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ARTICLE INFO

Article history:
Received 19 August 2015
Accepted 3 September 2015
Available online 7 September 2015

Keywords:
Machining
Temperature measurement
Infrared laser
Polynomial interpolation
Heat flux

ABSTRACT

Several techniques have been developed over time for the measurement of heat and the temperatures generated in various manufacturing processes and tribological applications. Each technique has its own advantages and disadvantages. The appropriate technique for temperature measurement depends on the application under consideration as well as the available tools for measurement. This paper presents a procedure for a simple and accurate determination of the time-varying heat flux at the workpiece–tool interface of three different metals under known cutting conditions. A portable infrared thermometer is used for surface temperature measurements. A spline smoothing interpolation of the surface temperature history enables to determine the local heat flux produced during stock removal. The measured temperature is represented by a third-order spline approximation. Nonetheless, the accuracy of polynomial interpolation depends on how close are the interpolated points; an increase in degree cannot be used to increase the accuracy. Although the data analysis is relatively complicated, the computing time is very small.

1. Introduction

It is possible to estimate the heat generated in various manufacturing processes and tribological situations either by calorimetric methods or by measuring the forces generated. However, the measurement of temperature generally is not such a simple and straightforward matter. The heat partition between two bodies which are in contact and moving with respect to the other is also a difficult problem. Especially, because the properties of materials used in machining vary with temperature, the mechanical process and the thermal dynamic process are tightly coupled together.

Due to these experimental difficulties many analytical and numerical methods solution have been employed to predict thermal fields in machining. Hou and Komanduri [10] presented a modelling of thermomechanical shear instability in the machining of some difficult-to-machine materials leading to shear localization. Shear instability was observed experimentally in high-speed machining of hardened alloy steels (AISI 4340 steel), titanium alloys (Ti–6A1–4V), and nickel-base superalloys (Inconel 718) yielding cyclic chips. Based on an analysis of cyclic chip formation in machining, possible sources of heat (including preheating effects) contributing toward the temperature rise in the shear band are identified.

Grzesik [9] utilized a standard K-type thermocouple embedded in the workpiece to convert measured efms to the interfacial temperature. For high speed machining of medium carbon steel and an austenitic stainless steel, some optimal

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http://dx.doi.org/10.1016/j.csite.2015.09.001

Nomenclature

A_i	polynomial coefficient of i index	t	time, s
c	specific heat capacity, J/(kg K)	t_i	i index time, s
$f(t_i)$	measured surface temperature history	T	temperature, °C
m	polynomial order	T_a	ambient temperature, °C
N	number of measured temperatures	Vc	cutting speed, m/min
$\dot{q}(t)$	transient heat flux, W/m^2	$y(t)$	polynomial function
		ρ	density, kg/m^3
		λ	thermal conductivity, W/(m K)

coating structures were selected corresponding to the minimum interface temperature. Moreover, it was reported that by an appropriate selection of tool coating and workpiece materials, the effect of a thermal barrier in the top layer of the coating can occur.

To assess the feasibility of the laser assisted machining (LAM) process and to obtain an improved understanding of governing physical phenomena, experiments [17] have been performed to determine the thermal response of a rotating silicon nitride workpiece undergoing heating by a translating CO_2 laser and material removal by a cutting tool.

Many researchers have worked on temperature measurement and prediction. A review of some experimental measurement can be found in Komanduri and Hou [12,13]. Another study on thermal modelling of the metal cutting process (Komanduri and Hou [12,13] deals with the temperature rise distribution in metal cutting due to the combined effect of shear plane heat source in the primary shear zone and frictional heat source at the tool–chip interface. The model was applied to two cases of metal cutting, namely, conventional machining of steel with a carbide tool at high Peclet numbers (≈ 5–20) and ultra precision machining of aluminium using a single-crystal diamond at low Peclet numbers (≈ 0.5).

Davies et al. [7] presented infrared microscopic measurements of the temperature fields at the tool–chip interface in steady-state, orthogonal, machining of AISI 1045 steel for a range of chip thicknesses. The measurements are verified using an energy balance method and simple finite difference calculations.

Beginning from the Jaeger solutions for the temperature growth due to some variable heat sources, Tache et al. [18] determined the variation of the thermal field on the rake and flank faces of the cutting tool, as well as the cumulated effect of the heat sources from the two faces, on the tool temperature. The quantitative and qualitative analysis for temperature variation on the tool surface demonstrate the existence of a maximum, close to the centre of the heat source.

Huang and Liang [11] analytically quantifies the tool wear effect by taking into account the contributions of the primary heat source and considering the distribution of chip temperature rise. The proposed model is verified based on the published experimental data in the orthogonal cutting of Armco iron. Furthermore, a comparison case is presented on the temperature variation with respect to cutting speed, feed rate and flank wear length.

Numerous attempts have been made to measure the temperature in the machining operations. Accurate and repeatable heat and temperature prediction remains challenging due to the complexity of the contact phenomena in the cutting process as explained in [1]. One of the most extensively used experimental techniques to measure the temperature in machining is the use of thermocouples. Abukhshim et al. [2] presents the measurement of temperature by a thermal imaging camera when high speed cutting of high strength alloy.

Yvonnet et al. [20] have determined the heat flux flowing into the tool through the rake face and the heat transfer coefficient between the tool and the environment during a typical orthogonal cutting process. The followed approach is based on an inverse method.

Carvalho et al. [5] proposes the estimation of the temperature and the heat flux at the chip–tool interface using the inverse heat conduction problem technique. The thermal model is obtained by a numerical solution of the transient three-dimensional heat diffusion equation that considers both the tool and the tool holder assembly.

To better understand the mechanisms and thermal effects damaging the cutting tools, Mzad and Saad [14] highlighted the relations between machining stresses, temperature and tool–chip friction law in order to predict the chip shape, the cutting forces and the temperatures.

Ceretti et al. [6] have determined the global heat coefficient as function of the local pressure and temperature at the tool–workpiece interface. The global heat coefficient is determined by an iterative procedure, until the error between the theoretical and the experimental temperature is negligible.

Dinc et al. [8] have performed a validation of finite difference temperature model considering the temperature measured by a high precision infrared camera. The results of thermal measurements are compared with the outputs of the finite difference temperature model, considering the maximum and the mean temperatures in the tool–chip interface zone and the temperature distributions on the tool take face. The experimental results show good agreement with the simulations.

Brandao et al. [3] presents an experimental and theoretical study on heat flow when end milling hardened steels at high-speed. The temperatures on the workpiece have been measured. The heat transferred to the workpiece and the average convection coefficient for the cooling system have been evaluated in order to minimize the error between theoretical and experimental results.

Mzad [15] used a polynomial approximation of measured surface temperature to determine the heat flux rate during