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Heat flux in metal cutting: Experiment, model, and comparative analysis

V. Kryzhanivskyy[a,b,*], V. Bushlya[a], O. Gutnichenko[a], R. M'Saoubi[c], J.-E. Ståhl[a]

[a] Division of Production and Materials Engineering, Lund University, Ole Römers väg 1, Box-118, 22100 Lund, Sweden
[b] Department of Software Engineering, Zhytomyr State Technological University, Chudnivska 103, Zhytomyr, 10005, Ukraine
[c] R&D Materials and Technology Development, Seco Tools AB, SE-73782, Fagersta, Sweden

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ABSTRACT

In this paper, a proof of time-dependent behavior of heat flux into a cutting tool is built. Its implementation calls for a new method for estimating heat flux, which was developed using an inverse problem technique. A special experimental setup was designed and manufactured to implement the method. A series of dry machining experiments were conducted with high speed steel and cemented carbide tooling. A two-stage procedure was developed to overcome the ill-posedness of the inverse heat conduction problem by transforming it into a well-posed parameter estimation problem. The first stage retrieves the value of the heat flux and specific tool heating energy E_t. The second stage parametrizes and compares predefined heat flux behaviors. It was found that the time dependency of heat flux is best described by a decreasing power function.

1. Introduction

Practically all the power consumed in a cutting process is transformed into heat that is distributed between the chip, the tool body, and the workpiece [1]. For practical reasons, heat and consequently the temperature in the cutting tool are important because they determine tool wear and tool performance. The heat reaching the workpiece also influences the quality of the machined surface [2].

The temperature distribution inside the tool body is described by the classical heat equation with boundary conditions corresponding to the heat flux from the cutting zone and heat exchange with the environment [3]. However, direct measurement of these parameters in metal cutting is very difficult due to the minute contact zone for heat transfer. Temperature measurement, on the other hand, is easier, and these measurements are often used to retrieve the heat flux. This retrieval routine is known as the inverse heat conduction problem [4]. The most important feature of an inverse problem is its ill-posedness [5], primarily the fact that the solution does not exhibit continuous dependence on the initial data. As a result, small errors in the temperature measurements (initial data for the inverse heat conduction problem) can lead to unacceptable inaccuracies in the heat flux retrieval (inverse problem solution). In particular, highly oscillatory functions, which are impossible given the physics of the process, are often returned as a solution [6].

The basic approach to overcoming ill-posedness is to use so-called *a priori* information about the potential behavior of the solution [7]. Because it is known from metal cutting practice that the heat flux does not oscillate, the solution methods are designed to exclude such cases from consideration. This procedure is called regularization and renders the problem conditionally well-posed [8].

There are three main approaches to regularizing inverse heat transfer problems: Tikhonov's regularization scheme [9], Beck's sequential function method [5] and Alifanov's iterative regularization method [4]. The main differences between them are the mechanisms used to suppress undesirable oscillations in the sought solution.

Battaglia et al. [10] proposed an approach to estimating the heat flux and the temperature at the tool tip using a single thermocouple to measure temperature at an interior point of the tool insert. A sequential function specification method and a sequential regularization method [5] were used to identify the heat flux. To avoid a non-linear heat conduction problem related to the temperature-dependent properties of materials, a model expressed in a recursive transfer function form was proposed. Lately, this approach has been extended to drilling and milling [11,12]. In all cases, retrieved heat flux values were used for estimation of cutting tool temperature.

Two principal improvements were made by Norouzifard and Hamedi [13,14]: temperature distribution in the tool was computed by performing transient thermal analysis in 3D, and multiple thermocouples inserted at various tool locations provided the inverse solver with input data. The inverse procedure was also based on Beck's

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[*] Corresponding author. Division of Production and Materials Engineering, Lund University, Ole Römers väg 1, Box-118, 22100 Lund, Sweden. Tel.: +380965364841.

E-mail address: vyacheslav.kryzhanivskyy@iprod.lth.se (V. Kryzhanivskyy).

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Nomenclature

ρ	Density, (kg/m^3)
c_p	Specific heat, J/(kg K)
k	Thermal conductivity, W/(m K)
t	Time, s.
u	Temperature, °C
q, $q(t)$	Heat flux, W/mm^2
h	Coefficient of heat exchange with the environment, W/(mm^2 K)
h_{tc}	Total thermal contact conductance, W/(mm^2 K)
n	Outward normal to boundary
$a(t)$	Contact length on the rake, mm
$A = \max\limits_{0 \le t \le T} a(t)$	Maximum value of the contact length, mm
TC1, …, TC8	Acronyms of thermocouples
b	Width of contact on the rake, mm
m	Number of thermocouples
$u_i^{meas}(t)$, $u_i^{calc}(t)$	Respective measured and calculated temperature at the position of i-th thermocouple installation, °C
T	Modeling time, s
t_{rot}	Time of tool engagement on the first workpiece revolution, s
P, P_{tool}	Total amount of power consumed by the cutting process and power consumed by the tool, respectively, W
E_t	Specific tool heating energy, J/mm^2
B	heat partition coefficient, %

sequential function specification method [5]. This procedure uses superposition principles and Duhamel's superposition, and therefore deals only with linear heat conduction problems.

To take into account both the nonlinearity of the heat conduction problem and the complex geometry of a cutting tool, Brito et al. [15] proposed the use of specification function techniques [5] implemented as a MATLAB program in conjunction with a COMSOL Multiphysics environment. The heat flux to the tool was based on the experimental temperature readings. This flux information was then used for reconstruction of the temperature field in a cutting tool.

C.-H. Huang et al. [16] proposed another approach to solving the inverse problem using a steepest descent method to estimate the heat flux to the tool in a drilling operation. Thermocouple readings were used to obtain the heat flux along the drill bit edge at two cutting speeds. The proposed inverse problem technique is a combination of three separate problem solutions: the direct heat conduction problem, the sensitivity problem, and the adjoint problem. In their study, the developed technique works only with temperature-independent properties of materials or linear cases.

Putz et al. [17] developed a method to determine the generated thermal energy and heat fluxes partitioned among workpiece, tool, and chip using infrared thermal imaging. Though a new method based on retrieval of heat flux from generated heat energy was proposed, it was tested only for 2D geometrical models and linear heat transfer cases.

Study of the behavior of computational heat fluxes has found that: (i) heat flux grows relatively slowly after tool engagement (approx. 10 s), (ii) practically stabilizes with small residual oscillations at a certain level or demonstrates a slow growth, and (iii) decreases over a short period of time (approximately 5 s) after tool disengagement [10,13–15]. Other researchers [17–19] reported constant or near-constant heat flux behavior over the machining time. However, this flux behavior differs from the behavior observed during metal cutting, where the temperature in the primary, secondary and tertiary zones reaches its maximum value almost instantly [1]. At the end of machining, the flux should fall to zero abruptly. This weak point of the methods was mentioned by Norouzifard and Hamedi [13]: "These methods deform the shape of the estimated heat flux versus time diagram especially at the regions that the heat flux changes sharply (the start and the end of machining)". Practically all above-mentioned studies utilized heat flux information for reconstruction of temperature field in a cutting tool. In this context, potential inaccuracy of retrieved flux may lead to an incorrectness in calculated cutting tool temperature.

Earlier study by the authors [20] investigated the possibility of matching the experimental and computational data by applying a decreasing heat flux behavior. However, it was not demonstrated if such behavioral trend describes experimental data more adequately than the above-mentioned constant and increasing trends.

Therefore, in this study we present a proof of heat flux behavior over time. To achieve this, we develop conditionally well-posed inverse problem approach that retrieves both the value of heat flux into the tool, and establishes its time resolution. To implement this approach, a sensitivity analysis was carried out, two-stage procedure was developed, a special experimental setup was designed and manufactured, specially selected machining tests were performed, and a computational model was built in a COMSOL Multiphysics environment.

2. Methods

2.1. Experimental setup

As mentioned above, the inverse heat conduction problem is very sensitive to accuracy of measurement and modeling uncertainties [6]. Therefore, the following aspects were taken into account in the design stage concerning the test setup, modeling, and experimental conditions.

1. Machining operation. Orthogonal cutting experiments were performed without coolant as these conditions provide a simple and defined geometry of the tool-chip contact surface.
2. Experimental test array. The materials used in the tool and workpiece pair and the cutting conditions (Table 1) were chosen to avoid flank wear and cratering, which would be additional unknown heat sources.
3. Tool design. The cutting tools were manufactured as solid rectangular bars with a square cross section of side 25 mm and 180 mm length. The tools were ground to provide simple geometry of the cutting edge with a rake angle $\gamma = 0°$, clearance angle $\alpha = 7°$, and edge radius $r_\beta = 20\,\mu$m. Using a solid tool made it possible to avoid the uncertainties inherent in tool assemblies related to the undefined thermal contact parameters at, for instance, the insert-clamp plate, insert-anvil, and anvil-toolholder. The manufactured solid tools corresponded to ISO PCLNL2525M25 geometrical dimensions. Initial modeling and experimental findings showed that smaller tool dimensions are subject to significant size-effects with respect to

Table 1
Experimental test array.

Experiment acronym	Cutting conditions		Materials		Disk diameter, mm
	Cutting speed, m/min	Feed, mm/rev	Workpiece	Tool	
HSS1	300	0.1	Aluminum 5754	High speed steel	470
HSS2	300	0.15	Aluminum 5754	High speed steel	470
CC1	100	0.05	Steel EN S235JR	Cemented Carbide	450
CC2	100	0.1	Steel EN S235JR	Cemented Carbide	424