# Measurement of the thermal contact parameters at a workpiece – tool interface in a HSM process

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ABSTRACT: In high speed machining process, the workpiece-tool thermal contact is not well known. We propose an experimental approach founded on an original measurement principle that allows accurate estimation of the thermal contact parameters. These latter are three: the thermal contact resistance, the generated heat flux density and the partition coefficient of this latter. In this paper we present the principle of measurement of these parameters considering the global theoretical model and its difficult and propose a simpler alternative model. This latter consider separately both sub domains to estimate the thermal superficial conditions. That allows determining the three parameters of contact allowing a precise formulation of the boundary condition at the workpiece-tool interface. The purpose of this simplified model is to uncorrelate the estimates of generated heat flux and the partition coefficient.

Key words: Heat conduction, temperature, thermal contact resistance, generated heat flux and partition coefficient.

## 1 INTRODUCTION

Authors propose different formulations of the thermal contact condition at the workpiece – tool interface during a HSM proceeding. A common hypothesis is that all the mechanical energy is converted into heat in the secondary shear zone and the distribution of heat sources is uniform and constant. Experimentally, Kato and Fujii estimate the heat flux which flows into the workpiece[1]; they measure a temperature with a pyrometer and consider that the temperature field obeys to the solution proposed by Jaeger [2]. The partition coefficient is considered as the ration of heat flux in workpiece divided by mechanical energy transmitted to the tool. Numerous authors suppose that, in machining, the thermal contact is perfect. They estimate the partition coefficient by fitting the mean temperature on each side of workpiece – tool interface [3-5]. Chao and Trigger estimate the partition coefficient with a similar method but suppose an exponential distribution of the heat sources [6]. They set a perfect contact over all the contact.

The target of our study is to characterize the thermal contact at the workpiece – tool interface. The needed contact parameters are the thermal contact resistance, the partition coefficient and the generated heat flux density. The bibliography shows that the thermal global problem of sliding interface leads to a difficult estimate generated heat flux of the partition coefficient because these variables are strongly correlated [7]. We propose a simpler model to estimate and more accurately the interface parameters. The experimental estimated parameters supply data for HSM numerical model.

The text is organized in two sections. The first section presents the global problem of heat conduction in the workpiece and the tool. In a second time, the non-linear estimated methods are described in each sub-domain. These methods allow estimation of superficial conditions on both sides of the interface: temperature and heat density. The three interfacial parameters are deduced from the superficial conditions.

## 2 MEASUREMENT PRINCIPLE

The thermal study of the workpiece – tool contact requires the thermal response into the two solids. We study orthogonal machining that allows considering only the heat conduction in two directions.

### *2.1 Global formulation at a sliding interface*

The schema on the figure 1 represents the thermal contact between two mobile solids where the coordinates system is fixed in respect to the tool. In this system, the workpiece has a sliding velocity of $V$ (m/s). The contact is located at the abscissa $x = 0$. It is supposed imperfect and is the seat of an intense heat flux of intensity $\varphi_g$ (W/m²) due to the friction. The heat flux is shared according to a ratio $\beta.\varphi_g$ into the tool and $(1-\beta).\varphi_g$ in the workpiece. The contact length is equal to $2.b$ (m) and other free surfaces are subjected to a natural convection with a constant convection coefficient noted $h_{ext}$ (W/°C.m²).

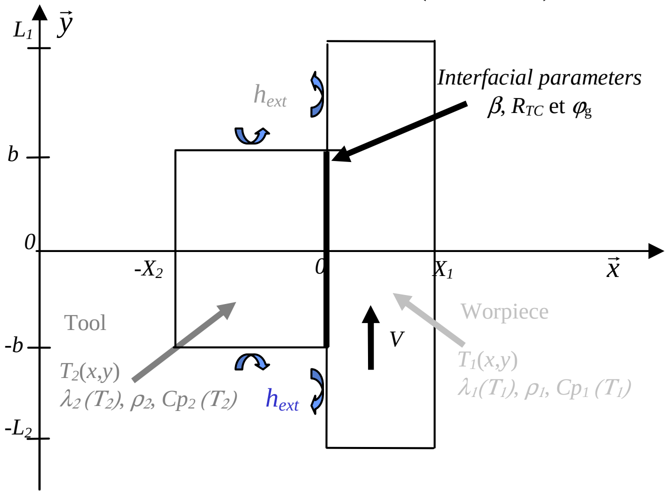


Figure. 1. Global heat transfer model.

The mathematical model is a 2D conduction model that is non-linear and unsteady with a transport term $V$ in the workpiece. It is described by the following set of equations:

$\forall x \in [0, X_1]$, $\forall y \in [-L_2, L_1]$, $\forall t > 0$

$$\frac{\partial}{\partial x}\left[\lambda_1(T_1).\frac{\partial T_1}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_1(T_1).\frac{\partial T_1}{\partial y}\right]=\rho_1.Cp_1(T_1)\left(\frac{\partial T_1}{\partial t}+V.\frac{\partial T_1}{\partial y}\right)$$

$\forall x \in [-l_2, 0]$, $\forall y \in [-b, b]$, $\forall t > 0$

$$\frac{\partial}{\partial x}\left[\lambda_2(T_2).\frac{\partial T_2}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_2(T_2).\frac{\partial T_2}{\partial y}\right]=\rho_1.Cp_1(T_2)\frac{\partial T_2}{\partial t}$$

The governing equations for the imperfect thermal contact are at the interface:

$\forall y \in [-b, b]$, $\forall t > 0$

$$-\lambda_1(T_1).\frac{\partial T_1(0,y,t)}{\partial x}=-\lambda_2(T_2).\frac{\partial T_2(0,y,t)}{\partial x}+\varphi_g$$

$$-\lambda_2(T_2).\frac{\partial T_2(0,y,t)}{\partial x}+\beta.\varphi_g=\frac{T_2(0,y,t)-T_1(0,y,t)}{R_{TC}}$$

In these equation, the calculated variable is the temperature $T_j$ (°C), the variables $\lambda_j$ , $\rho_j$ and $Cp_j$ are respectively the thermal conductivity (W/m.°C), the density (kg/m$^3$) and the thermal capacity (J/kg.°C) of each solid. The index $j = 1, 2$ indicates respectively the workpiece and the tool.

This direct problem is solved numerically and the solution can be well controlled. But the inverse problem allowing the estimate of thermal contact parameters is difficult. The reason is that the needed parameters appear in the same term of the boundary condition that is the non-homogeneity $\beta.\varphi_g$ in the last equation. That involves a strong correlation between the two parameters if they are estimate simultaneously. Consequently, another approach is considered to avoid this problem of parameters correlation. The described model is then replaced by a simpler model that considers separately both sub domains in the tool an the workpiece. Moreover, it presents a shorter calculus time and improve the estimation accuracy of estimate of $\beta$ and $\varphi_g$.

### *2.2 Reduction hypothesis*

This model considers that each sub-domain is independent. These sub-domains are fixed in their own system coordinates, so the transport term vanishes in the workpiece sub-domain. Furthermore in this sub-domain, the heat conduction can be supposed one-dimensional.

The estimation is sequential. In the first step the superficial parameters, namely the superficial temperature and the heat flux density that flows into the sub-domain, are estimated in the workpiece sub-domain. In next step, the superficial parameters are estimated in the tool sub-domain. Lastly, the heat transfer at the interface is supposed only due to the generated heat flux and the three thermal contact parameters are deduced from previous estimations.

### *2.3 Reduction hypothesis validations*

#### 2.3.a One-dimensional heat conduction

In the linear case, the analytical solution of a 2D temperature field due to a constant moving heat source is given by Carslaw and Jaegger [2]. This solution is compared with one in 1D in order to analyse the velocity influence. The two analytical temperature fields are described by the following dimensionless parameters:

$$x^* = \frac{x}{2.b} \qquad y^* = \frac{y}{2.b} \qquad t^* = \frac{t.\kappa}{4.b^2}$$

$$\tau^* = \frac{\tau.\kappa}{4.b^2} \qquad T^* = \frac{T.\lambda}{2.\varphi.b} \qquad Pe = V^* = \frac{2.V.b}{\kappa}$$

The variable $\kappa = \lambda/\rho.Cp$ (m²/s) is the thermal diffusivity of the material. $\varphi$ (W/m²) is the constant heat flux density. The dimensionless velocity is the thermal number of Peclet which compares the heat which flows by forced convection and the heat which diffuses into the material. Both solutions are respectively given by:

$$T_{1D}^* = 2.\sqrt{t^*}.ierfc\left(\frac{x^*}{2.\sqrt{t^*}}\right) - 2.\sqrt{t^* - \tau^*}.ierfc\left(\frac{x^*}{2.\sqrt{t^* - \tau^*}}\right)$$

$$T_{2D}^*\left(x^*, y^*\right) = \frac{1}{\pi}.\int_{-1/2}^{1/2} \exp\left(\frac{Pe}{2}.\left(y^* - y_0^*\right)\right). K_0\left(\frac{Pe}{2}.\left(x^{*2} + \left[y^* - y_0^*\right]^2\right)^{1/2}\right).dy_0^*$$

The contact length variable appears in the 1D model through the contact time: $\tau = 2.b/V$ . The 2D model solution is given in the system coordinates fixed to the heat source.

The figure 2 presents the difference between the two model functions of the Peclet number. For high Peclet number, the difference between the two models becomes insignificant. The heat transfer can be considered as one dimensional into the workpiece when the Peclet number is greater than 130. Practically, the Peclet number in a HSM process at the tool tip is over 150. That validates the one dimensional heat conduction hypothesis in the workpiece.

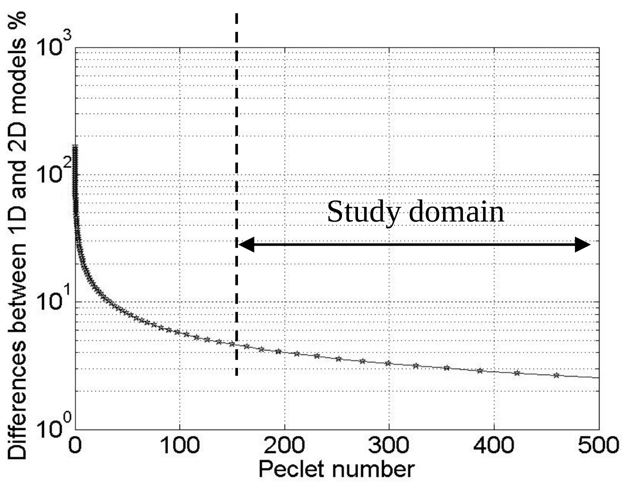


Fig. 2. Difference between 1D and 2D model.

2.3.b Interfacial heat transfer only due to the friction

Recall that the initial temperature gap between the two solids in contact involves a heat flux of density $\varphi_{\Delta T}$ that can be written in the linear case as:

$$\varphi_{\Delta T} = -\frac{2.\lambda_2}{\sqrt{\pi}}.\frac{B_2}{B_1 + B_2}.\left(T_2^{init} - T_1^{init}\right)$$

where $B_j$ (J.s$^{1/2}$/m.°C) is the thermal effusivity defined by $B_j = \sqrt{\lambda_j.\rho_j.Cp_j}$ ($j$ = 1, 2).

In HSM process this heat flux density is about 10 kW/m². The numerical simulation shows such an order of magnitude is really small compared to heat flux density due to the friction that is a thousand times greater. Then, the friction can be considered as the single thermal source for the interfacial heat transfer.

# 3 ESTIMATION METHOD OF THE THERMAL CONTACT PARAMETERS

The interfacial temperature and heat flux are calculated in each sub-domain by numerical way because of the problem non-linearities.

## *3.1 Estimation in the workpiece sub-domain*

The direct problem is solved numerically by finites differences with Crank-Nicholson scheme. The inverse heat conduction technique employed is the Beck sequential method [8]. The measurement principle of superficial parameters in the workpiece sub-domain is schemed in the figure 3 and needs recoding of two thermocouples implanted in two locations judiciously chosen. The second thermocouple gives the boundary condition of the direct problem and the first one gives the additional information needed by the inverse technique.

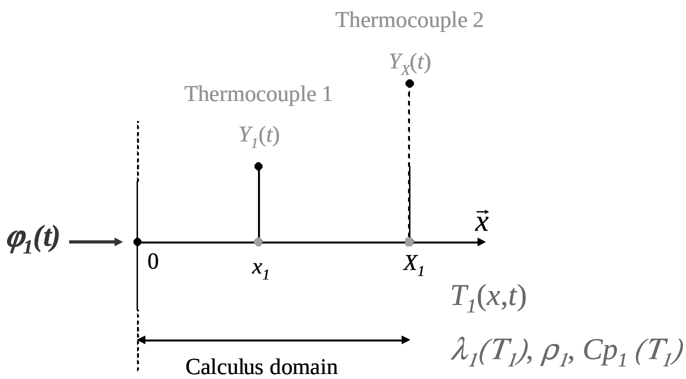


Fig. 3. Measurement principle on workpiece sub-domain.

This method allowed to check the relation between friction and heat flux density when the partition coefficient was supposed to be in the thermal effusivity ratio [9].

### 3.2 *Estimation in the tool sub-domain*

The heat transfer in the tool sub-domain is considered as a 2D field. The solution is obtained numerically by finite element. The Gauss-Newton inverse method is used in order to estimate the heat flux that flows into the tool. Four thermocouples are embedding into the tool and all their records give additional information for the inverse technique. The thermocouples are located at the beginning and the end of the friction zone. In the case of a friction test [10], the thermocouple locations are presented in the figure 4.

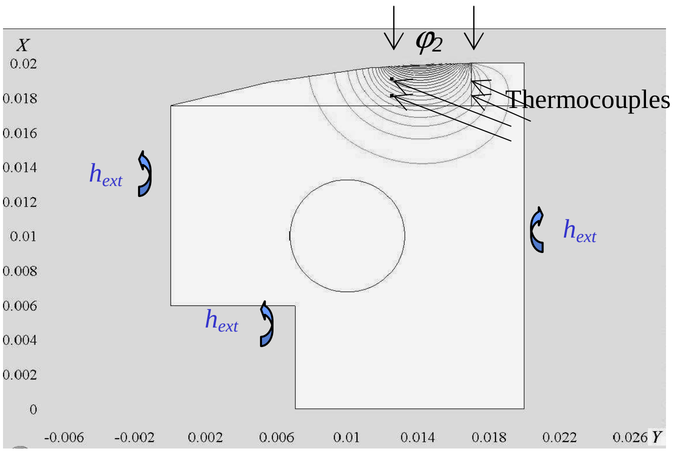


Fig. 4. Measurement principle on tool sub-domain.

### 3.3 *Estimation of the thermal contact parameters*

The hypothesis presented in the section 2.3.b, that there is only one heat source at the interface, allows to estimate the generated heat flux and the partition coefficient merely with the estimation of the heat flux density on each side of the interface.

$$\varphi_g = \varphi_1 + \varphi_2$$

$$\beta = \frac{\varphi_2}{\varphi_1 + \varphi_2}$$

As well, this hypothesis reduces the imperfect thermal contact equation. So the thermal contact resistance can be written as:

$$R_{TC} = \frac{T_2(0,y) - T_1(0)}{2.\beta.\varphi_g}$$

The thermal contact resistance estimation need the estimation the two superficial temperatures and the two heat flux densities.

## 4 CONCLUSIONS

An original approach is proposed to estimate easily the three parameters of the thermal contact: the generated heat flux density, the partition coefficient and the thermal contact resistance. This estimation method consists on some problem reductions which the hypotheses derive from the HSM values of the speed and the generated heat flux. Thereby, the estimate of the generated heat flux and the partition coefficient are uncorrelated with this method. In each subdomain of the tool and the workpiece, the superficial temperature and the heat flux density are singly estimated by inverse method. After, the thermal contact condition is obtained from these four estimations.

## ACKNOWLEDGEMENTS

The authors would like to thanks the Fondation de France / CETIM for the financial support for this study.

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