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A Thermal Modeling to Predict and Control the Cutting Temperature. The Simulation of Face-Milling Process

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Abstract- This paper presents a new procedure to evaluate the cutting temperature milling. In HSM. The study of the thermal behavior is important because the life expectancy of a cutting tool is limited by its temperature: the higher the temperature, the shorter its life. Tests made on many uncoated tools at stand still, after milling, have shown that there is an important drop for the temperature measured values. This is due to the ventilation phenomenon which was created by the rotation of the mill, which, in turn, requires the knowledge of the global overall coefficient of heat transfer at the tool interface as a function of the cutting conditions in order to predict the cutting temperature. The performance of the model is compared to the analytically and numerically (FEM) determined performance of a cutting tool with boundary conditions or to the experimentally determined performance and the results obtained are in good agreement [12].

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I. Introduction

During machining, heat is generated at the cutting point from three sources. Those sources cause the developments of cutting temperature:

- Primary shear zone where the major part of energy is converted into heat.
- Secondary deformation zone at the chip–tool interface where further heat is generated due to rubbing and/or shear. At the worn out flanks due to rubbing between the tool and the finished surfaces. LOWEN and SHAW [1] have shown that the heat generated is shared by the chip, cutting tool and the workpiece.

The apportionment of sharing that heat depends upon the configuration, size and thermal conductivity of the tool-work material and the cutting condition. The maximum amount of heat is carried away by the flowing chip. From 10 to 20% of the total heat goes into the tool and some heat is absorbed in the workpiece [1]. With the increase in cutting velocity, the chip shares heat increasingly. The effect of the cutting temperature, particularly when it is high, is mostly detrimental to both the tool and the workpiece [2]. The major portion of the heat is taken away by the chips. So attempts should be made such that the chip takes away more and more amount of heat leaving small amount of heat to harm the tool and the work. The possible detrimental effects of the high cutting temperature on cutting tool edge are:

- Rapid tool wear, which reduces tool life, Plastic deformation of the cutting edges of the tool material is not enough hot-hard and hot strong.
- Thermal flaking and fracturing of the cutting edges due to thermal shocks.
- And the possible detrimental effects of cutting temperature on the workpiece are:
- Dimensional inaccuracy of the workpiece due to thermal distortion and expansion-contraction during and after machining.
- Surface damage by oxidation, rapid corrosion, burning etc.
- Cutting temperature can be determined by three ways:
- Analytically using mathematical models for thermal field which can be developed. This method is simple, quick, inexpensive but less accurate.
- Experimentally, this method is always used because it is more accurate, precise and reliable.
- Numerically, this technique is widely used tools for thermal machining simulation and benefits the reduction of the cost and increase technical performance. Many researchers have developed models and studied, mainly experimentally, on the effects of the various parameters on cutting temperature like: work material, process parameters, cutting tool material, tool geometry and cutting fluid. A well established overall empirical equation is:

$$T = \frac{0.4U}{\rho C}\left(\frac{vt_o}{K}\right)^{0.333} \quad (1)$$

Where T = temperature-rise at tool-chip interface; U = specific energy; v = cutting speed; t_o = chip thickness before cut; ρc = volumetric specific heat of work material; K = thermal conductivity of the work material.

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Recently, Lazohlu and Altintas4 [3] have applied the FDM, finite difference method, for the first time for the prediction of steady-state tool and chip temperature fields in continuous machining and transient temperature variation in interrupted cutting (milling) of different materials such as steels and aluminum alloys. A combination of grids in Cartesian coordinates for the chip and in cylindrical polar coordinates for the tool like in Refs5.[4]. The analytical approach to temperature modeling is difficult to apply to milling due to the intermittent cutting process and the varied thickness. Jaeger and Carslaw and Jaeger [5] introduced the heat source method for solving a variety of heat transfer problems for orthogonal cutting. The Jaeger moving heat source model has been modified and developed to represent the physical characteristics of peripheral milling, and has described how it can be applied in an industrial context to model workpiece temperatures due to peripheral milling. This intermittent heat is represented as a band of heat because the teeth move rapidly through the material and the time between cutting teeth is constant [6]. This model should be applicable to the milling of other materials such as titanium and carbon composites. The thermal impact to the cutting tool during heating is larger in down milling than in up milling [7].

Versions of a system equivalent circuit are commonly used in the manufacturing industry, due to its simplicity and its ability to provide reliable results,. This paper describes how it can be applied to model a tool when milling. The tool thermal model is based on the equivalent circuit. A simple RC circuit is employed to predict the cutting temperature. In the thermal model, all heat losses tool are represented by a current source injecting heat into the system. The capacitances are combined as one lumped capacitance. The thermal resistance is represented by a nonlinear term and the temperatures are represented as thermal potentials.

II. Cutting Temperature Control

Apart from photo cell technique and infrared photographic technique, cutting temperature can be controlled and reduced as far as possible, in varying extent, by the well following general methods:

Tool work thermocouple technique, moving thermocouple technique which cannot be applicable in operations like milling, grinding etc., embedded thermocouple can serve the purpose. However, the standard thermocouple monitors the cutting temperature at a certain depth d from the cutting zone so the T(d) curve has to be extrapolated up to d=0 to get the actual milling zone temperature.

III. Experimental Set-up

we purpose a new method to predict the cutting temperature by taking measurements of tool edge when the tool leave the work piece, at shutdown, almost 12s, the values Ti has to be very low, which is not possible, so the curve T (t) has to be extrapolated to correct the temperature drop during cooling, and would not be linear due to the rotating tool, which is not the same problem in turning. The problem of extrapolation is related to the adequate tool cooling. This in turn, requires the knowledge of the mechanism by which heat is transferred from tool edge to the surroundings [8], we also include some simple but useful equations of the lamped capacitance under thermal analogy, enabling us to determine with reasonable accuracy, the heat loss, temperature rise, equivalent resistance, etc., of tool cutting.

The thermal conductivity as function of temperature is taken into account as shown in fig.1.b.

A series of experiments were carried on mild steel specimens to measure tool temperature under different tools materials. The cutting tools were uncoated carbides; all operations were executed in dry conditions. The tests were executed at a cutting speed Vc ranging from 100 to 1000 m/min, and a feed rate ranging from 1 to 5 (mm/min). An infrared radiation pyrometer was placed at a distance Im from the rake face, we report some of the experimental results, concerning temperatures measurements of cooling mill as a function of short period of time where the cutting speed was decreasing, see fig.5.b.

Table 1 : Cutting conditions

Vc(m/min)	ae(mm)	ap(mm)	f(rd/s)	U(W/m^3.s)
400	1	5	2547/60	4.5

Table 2 : Tungsten carbide thermal properties

Conductivity (W/mK)	Specific heat (J/kg.K)	Density (kg/m^3)	Heat_Transfert coef (W/m^{2}K)	Emissivity
174	130	19300	$h = 7 + \sqrt{\frac{Vc}{60}}$ [5]	0.3

IV. Mill Thermal Model based on Equivalent Circuit

Due to its simplicity and ability to provide reliable results, we use an equivalent circuit.

In electricity and according to Ohm's law current which flow through it; in thermal, we broaden the meaning to describe the thermal behavior of a system or device when cooling or heating with its surroundings.

$$T = R_{th} q^n \tag{2}$$

T: thermal potential (°C), R_{th}: non linear thermal resistance (m^{2}°C/ W), q: thermal flux (W), n: indice

In contrast to an analytical solution, which allows for temperature determination at any point in the medium, a numerical solution enables determination temperature at only discrete points. The first step in any numerical analysis is to subdivide the mill (semi-infinite cylindrical form), 10 mm diameter, and 65mm length, into a number of small discs assigning to each a reference and involves 2 resistances by convection and conduction respectively, for one dimensional system, may take the form shown by the figure 1. The main is to calculate the equivalent resistance of single pin fin of rectangular profile.

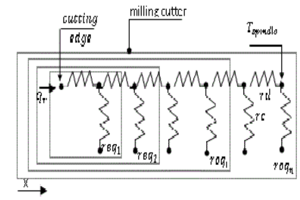


Fig. 1 : The equivalent resistance model

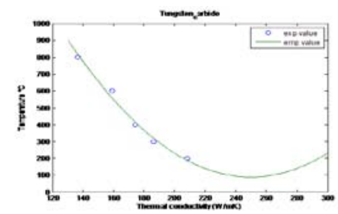


Fig. 2 : The temperature dependence of the thermal conductivity of tungsten carbide [5]

Recalling the definition of the conductive and convective resistance, that is:

$$rd = \frac{ep}{k.sf} \quad \text{and} \quad rc = \frac{1}{h.sl} \tag{3}$$

ep: disc thickness, sf and sl: frontal and lateral surfaces of the disc, respectively.

We can write the first equivalent resistance:

$$req_1 = \frac{rd.rc}{rd+rc} \quad \text{and} \quad req_i = rd + \frac{req_{i-1}.rc}{req_{i-1}+rc} \quad \text{Finally:} \quad req_n = rd + \frac{req_{n-1}.rc}{req_{n-1}+rc} \tag{4}$$

a) *Rate of Convergence Analysis*

As shown in the figure 3.a, the equivalent resistance model chosen converges for all cooling time, and the convergences values increase from the beginning to the end of cooling [1s,12s]. Consequently, we can write the following expression:

$$req_n = req_{n-1} \text{ then } req_n = rd + \frac{req_n.rc}{req_n+rc} \tag{5}$$

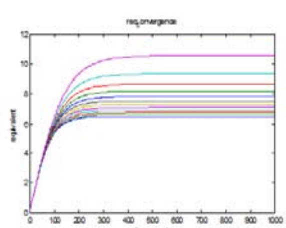
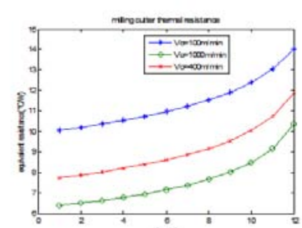


Fig. 3 : *(a)* Convergence of the equivalent resistance different times;



(b) Equivalent resistance of milling cutter values for during cooling

b) *Modified lumped thermal capacitance method*

Our objective is to develop procedures for determining the time dependence of the temperature distribution within the mill during transient process as well as for determining heat transfer between the mill and its surroundings. The nature of the procedure depends on assumptions that may be made for the process. The essence of the modified lumped capacitance method is the assumption that the temperature of the mill is not uniform at any instant during the transient process. This assumption implies that temperature gradient within Intel the first disc is negligible. This behavior is analogous to the voltage decay that occurs when a capacitor (first disc) is discharging through a nonlinear resistor (other discs) per conduction, convection and less degree per radiation. Fig.4.

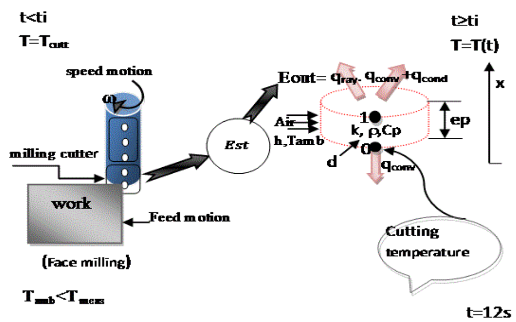


Fig. 4 : Disc node at one dimensional transient conduction with convection and radiation

$$\rho V c\frac{dT}{dt}=\left[\frac{1}{req(t)}+\frac{1}{r(t)}+\frac{1}{r'c(t)}\right][T-T_{amb}]\ and\ T_{final}=T_{measured}$$

$$\frac{\Delta T}{\Delta t}=\frac{1}{\tau(t)}[T-T_{amb}]\ \text{ and } T_i=T_{i-1}+\frac{T_{i-1}-T_{amb}}{\tau(t)} \quad (7)$$

$$\text{With: } \frac{1}{\tau(t)}=\left[\frac{1}{req\ (t)}+\frac{1}{r\ (t)}+\frac{1}{r'c(t)}\right].\left[\frac{1}{\rho VC}\right] \quad (8)$$

Where $\tau(t)$ may be interpreted as the *modified thermal constant time* and $\tau(t)=R(t)_t.C_t$ (9)

$$R(t)=req(t)//r(t)//r'c(t) \quad (10)$$

$$C=\rho Vc \ \text{ and } \ h_r(t)=\varepsilon\sigma s_l(T+T_{sur})(T^2+T^2{}_{sur})$$

Where $h_r(t)$ is the heat transfer coefficient per radiation, ε is the emissivity of the uncoated carbide $\sigma=5.67*10^{-8}W/m^2K^4$: Stefan Boltzmann constant and $r'c=\frac{1}{h'sf}$ is a linear convective resistance.

Any increase in R(t) or in C will cause the mill to respond more slowly to changes in its thermal environment[10]. The non linear resistance is due to the turbulence produced by the revolving mill, thus any increase in cutting speed will cause the reduction in temperature rise(T_I-T_{i-1}). The cutting temperature is calculated by inverse method as seen in the fig.5, $T_1=789\,℃$ for tungsten carbide.

The temperature of the spindle edge may also be measured by a thermometer.

The temperature of the cooling agent: air may be measured at a distance of 1m from the tool cutting.

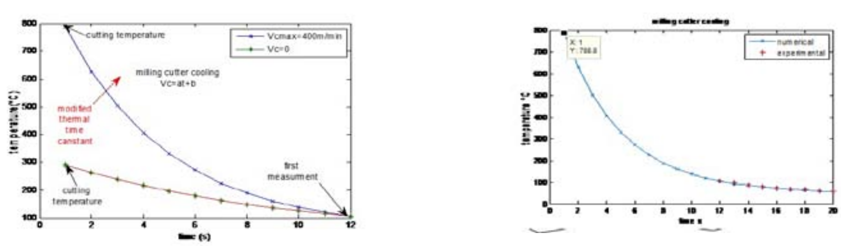


Fig. 5 : Results of cutting temperature calculation using inverse method a) taking into account rotating speed b) temperature comparaison between experimental and calculated values

c) Validity of the purposed thermal model

The study of the cutting power is important because it gives us a clue how it may be reduced.

It is created by machine which may be evaluated by the product of the torque developed by the spindle times its rotational speed, this power is required to cut metal, and 98% was transformed into heat causing the cutting temperature to rise.

The cutting power is given by: $P_{cutt}=U.MRR$ (11)

MMR is the material removal rate. $MRR=ae.ap.f$ (12)

If we suppose that the portion of cutting power go to the tool, we have: $P_{mill}=10\%\,P_{cutt}$ (13)

To estimate the cutting temperature, we have: $T_{cutt}=U_{tot}P_{mill}+T_{amb}$ (14)

Where: $U_{tot}=\frac{1}{req}$, the overall heat transfer coefficient $U_{tot}<h$ [10], We find: $T_{cutt}=799\,℃$

V. Conclusion

In this paper, a simple and quick method is performed in order to calculate and control the cutting temperature in operation like milling:

The warmest up part in the milling cutter is the rake face. The hot spot temperature is rather difficult to measure because it has to be taken when the tool rotate and at a depth from the rake face where start the crater due to the higher temperatures, is in contact with the moving chip. Hence, the measurements were taken when the tool leave the work piece after 12s, at standstill, however, a large drop in temperature is found, which is corrected by the study of heat transfer in transient state, which, in turn, seems require the knowledge of the nonlinear equivalent resistance due to the turbulence created by the rotating mill. The equivalent resistance for a semi infinite cylinder as a function of time, is plotted with accuracy and it increase with the decreasing cutting speed, this because milling cutter blows air over to the surrounding [11]. The cooling curve is also plotted by inverse method both for two cases: when the mill rotates and if it does not and the cutting temperature is illustrated in fig.5.a and is in good agreement with equation 14. We can broaden the meaning of the equivalent resistance concept to predict the temperature for several cutting speeds provide that temperature at standstill must be taken. The precision of the thermal models depends on the exactitude of the parameters: thermal properties, cutting conditions: work and cutting material.

This brings us to very important conclusions: this method may succefully also be applied in drilling operation where radiation exchange cannot be neglected in this case. The performance of this model will reduce the need for expensive experimental measurements.

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