Identification of the heat input during dry or MQL machining

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Abstract

Machining with minimum quantity lubrication (MQL) has been the focus of many scientific investigations since the last 20 years. Nevertheless an acceptable method of predicting the thermal influences on the workpiece quality has still not been developed. This paper describes a simulation approach to estimate the distribution of the cutting energy during machining. During machining, the cutting power is measured to calculate the specific cutting power for each machining process – here drilling, tapping and milling of aluminum. In parallel, the warm-up of the part is measured by fast response thermocouples implanted closed of the machined zone. These thermocouples identify the cutting energy entering into the work piece.

Keywords:

Machining, Heat transfer, Finite Element Method (FEM)

1 INTRODUCTION

Machining with minimum quantity lubrication (MQL) [1] has been the focus of many scientific investigations since the last 20 years. The technology has been optimized and is nowadays widely used in machining industry. Nevertheless an acceptable method of predicting the thermal influences on the work piece quality has still not been developed.

The lack of cutting fluid in dry or MQL machining provokes local warm-ups of the part. These temperature rises deform the work piece in an inhomogeneous way during its manufacturing which can cause quality problems, depending of the size of tolerances. With the help of FEM simulations using an estimation of the heat flow for each cutting process, these local warm-ups can be easily identified.

This paper describes a method to identify, with part temperature measurement during machining, intensity of the heat flux going to the part. Originality of this method is in determination of measuring point position with shape criteria on temperature curves. It allows avoiding errors links to measuring point position into part. In a second part, thermo-mechanical distortions of an aluminum (AS9U3) clutch case during manufacturing are simulated.

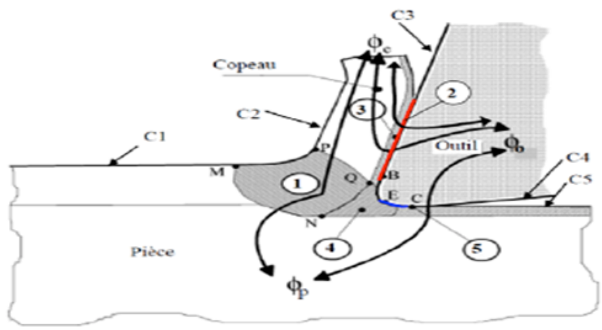

Figure 1: Heat sources during machining [2,3]

Fleischer *et al.* [4] made an extensive literary research to precise repartition of the cutting energy during dry or MQL machining (Table 1). Heat input into work piece varies between 1 to 35 % of the cutting energy depending of process studied.

2 STATE OF THE ART

Generally, authors consider that about 90% to 100% of energy associated with chip formation is converted to heat during machining. Figure 1 illustrates the five heat sources that could be observed during machining.

1. Plastic strain in primary shear zone
2. Friction between tool and chip
3. Plastic strain in secondary shear zone
4. Plastic strain in tertiary shear zone
5. Friction between tool and part

Heat created in these zones is distributed between tool (Q_t), chip (Q_c), work piece (Q_p) and environment (Q_e). In first approximation three main heat sources are distinguished: plastic strain of chips (Q_{cc}), friction on rake face (Q_{fc}) and friction on flank face (Q_{fd}), Figure 2.

Main part of the cutting energy is going to chips, tool and work piece; heat going to environment is unimportant.

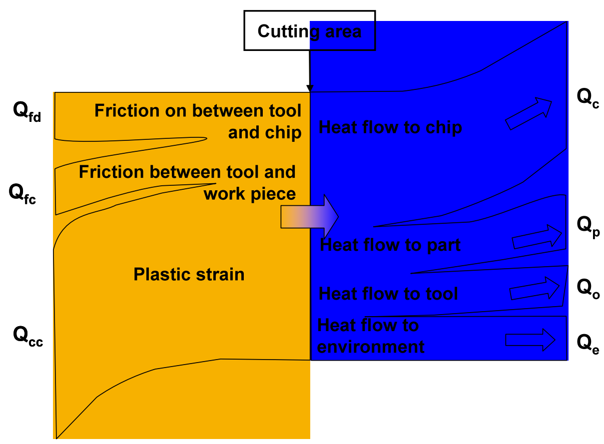

Figure 2: Heat sources and distribution during machining

Authors developed two different approaches to identify heat flow going into part during machining. On first hand, authors' aim is to identify partition of the cutting power going into part [5-10]. On the other hand, authors directly identify heat input as a function of cutting speeds and tool geometry [2-4,11-14]. The literary research shows that heat input into work piece is dependant of many factors: work piece material, machinability, tool geometry and material, cutting conditions, etc. All these method are based on temperature measurement of parts during machining.

	Drilling	Turning	Milling
Tool	5 – 15%	2.1 – 18%	5.3 – 10%
Work piece	10 – 35%	1.1 – 20%	1,3 – 25%
Chip	55 – 75%	1.3 – 25%	65 – 74,6%

Table 1: Distribution of the cutting energy during machining [3]

Davies *et al.* [14] propose a comparison between different measurement methods of temperature in material removal processes (Table 2). According to their study, a method based on thermocouple was chose for its thermal and time resolution properties and its for cost and easy of set up reason.

3 OBJECTIVES

Main objective of this paper is to propose an identification method for heat flow going to part during manufacturing. This method is an inverse method based on FEM simulations with a unit heat flow and measurement of temperature rise (with a thermocouple) into parts during machining. Originality of this method is reconstruction of thermocouple position with temperature curve shape. Heat flow will be identified as a part of the cutting energy.

4 EXPERIMENTAL SETUP

4.1 Power consumption

Cutting energy is estimated using spindle power consumption. A wattmeter is plugged to measure instantaneous spindle electric consumption. Only cutting energy is considered, energy needed for tool displacement is not considered (weak compared to cutting energy).

4.2 Temperature measurement

For temperature measurements, fast response thermocouples (type K) are inserted into parts near the machined zone (distance lower than 2 millimeters). Position of thermocouple is choose near machined zone to increase precision of heat flow identification.

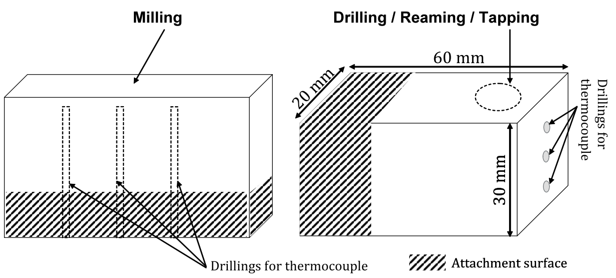

Figure 3: Parts geometry used for heat flow identification

4.3 Parts geometry

Figure 3 shows dimension of machined parts. Two parts where designed: first one for milling tests and second one for drilling and tapping tests. Three drills for thermocouple are done in each part to insert thermocouple. Direction of drilling is orthogonal to heat flow vector to minimize perturbation of thermal fields by drilling geometry.

5 FEM SIMULATIONS

5.1 Principe

Commercial FEM code does not allow imposing mobile heat flow representative of tool movements directly. To avoid this problem, strips are cut off into machined surface using direction of tool displacement. Figure 4 illustrates, for cylindrical (drilling, reaming, tapping) and plane surfaces, method of machined surface cutting.

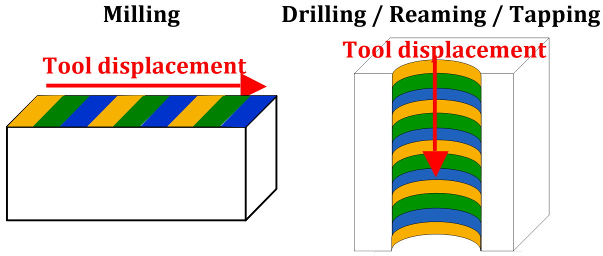

Figure 4: Stripping of machined surface

Heat flow is successively imposed on each strip. For continuity reasons, heat flow is imposed in three times on each strip: first a growing heat flow, then a constant heat flow and last a decreasing heat flow (Figure 5). Different strategies were tested for increasing and decreasing heat flows (discontinuous, linear, polynomial). FEM simulation shows that continuity of heat flow is important but that strategies for increasing and decreasing have no effects on results.

Length of strips is a compromise between having a continuous response of the model and having an acceptable calculation time.

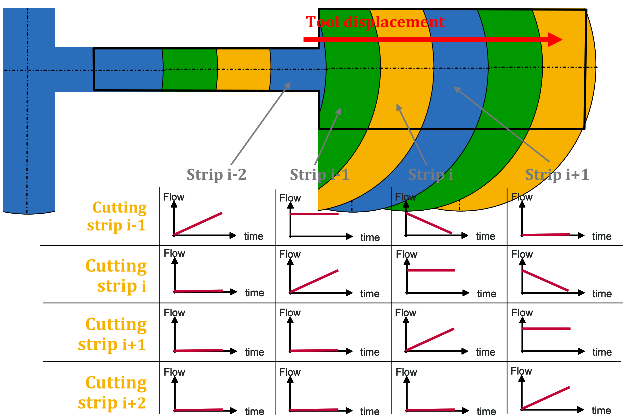

Figure 5: Heat flow put on each strip for FEM simulations

5.2 Hypothesis

Influence of conductivity with fixture and convection with environment

In heat transfer analysis, thermal diffusivity (*D*) is the thermal conductivity divided by density (ρ) and specific heat capacity (c).

$$D = \frac{\lambda}{\rho . c}$$

A thermal characteristic time τ could be defined using thermal diffusivity *D* and a length *L*. This characteristic time is duration needed to transmit a temperature signal over length *L*. Table 3 shows for classical, automotive materials, orders of magnitude for thermal characteristic time.

$$\tau = \frac{L^2}{D}$$

In first seconds of simulation, affected zone by heat flow is thin (a few centimeters). If fixture is far from imposed heat flow, heat conduction to fixture could be neglected.

Heat convection is not taken into account because of short duration of analysis.

Influence of errors on thermal material properties

Model sensibility about error on thermal conductivity and thermal capacity (ρ.c) were studied with FEM simulations. On the first hand, an error on thermal conductivity of +/- 10% links to an error of 10% on response model. On the other hand, error on thermal conductivity is less important: variation of +/-10% of conductivity links to an error of 2%. Thermal conductivity of material studied must be correctly estimated to reduce errors on heat flow identification.

Influence of drilling for thermocouple

Simulation shows a great influence of thermocouple drilling into part on thermal fields. To identify precisely heat flow during machining, simulations have to be done with drilled parts (correct diameters and length).

5.3 Results of FEM simulations

Simulations were conducted using FEM code Abaqus©. A preprocessor was written to automate data converting, computing processes, and data extraction from results of analysis.

Figure 6 presents an example of results for simulation of a unit mobile heat flow on a plane (milling case at feed speed 20 m/min). Length between heated surface and measurement nodes influence temperature and shape of temperature curve. These two data will be used to identify position of thermocouple during machining and heat flow into part due to machining.

6 INVERSE IDENTIFICATION METHOD

For a speed of the moving heat flow and at one point of the part, maximum simulated temperature depends on heat flow put on the machined surface and distance between measuring point and machined surface.

6.1 Thermocouple position

Position of thermocouple is identified using a shape criteria on temperature curve. Precision of the method is directly linked to number of node in the measurement area. This parameter is controlled by user when part is meshed.

In first step, a unit heat flow is used to simulate temperature in part for different positions of thermocouple. These simulations are done using different mesh: each one correspond to one position of thermocouple. Temperature curves for thermocouple are extracted of FEM results.

During second step, temperature curve are normalized with maximum temperature (Figure 7). Shapes of curve are different for each position of thermocouple. When distance between machined surface and thermocouple increase, expand of temperature curve is observed.

A least-square method is used to identify witch two simulated temperature curves are most looking to measured curve. An upper and lower position of thermocouple is estimated: precision is linked to number of simulation done.

For a position of thermocouple, maximum simulated temperature at thermocouple position is proportional to intensity of heat flow. Using positions determined previously, intensity is estimated.

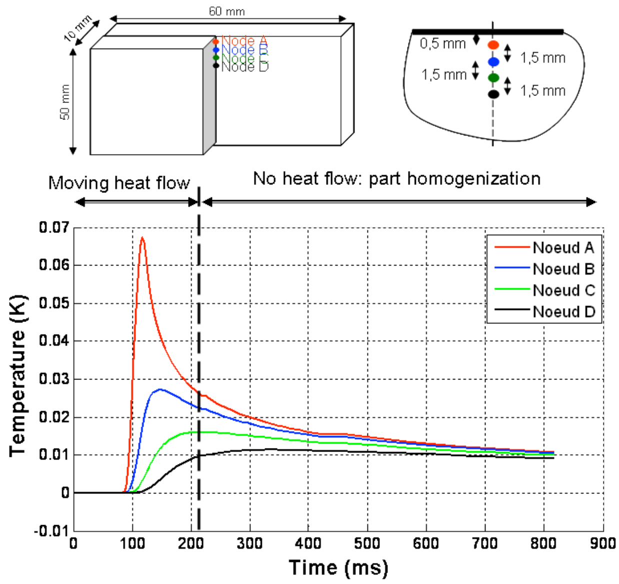

Figure 6: Example of result for a unit heat flow moving on a plane at 20 m/s (milling case)

Figure 8 describes evolution of maximum temperature obtained by simulation for a unit mobile heat flow in function of distance to machined surface. For a good precision of maximum measured temperature, thermocouples have to be in first millimeters under machined surface. Along two first millimeters, maximum temperature is proportional to distance. An error of n% on estimation of thermocouple position pull to an error of n% to heat flow estimation.

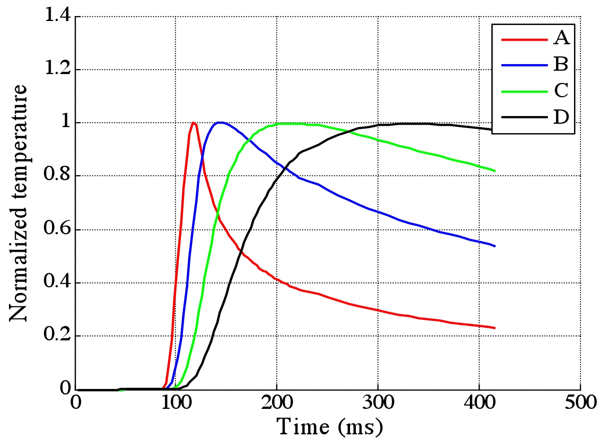

Figure 7: Normalized temperature curves for same node as figure 6

	Thermal conductivity *W / (m.K)*	Density	Specific heat capacity *J / (Kg.K)*	Thermal diffusivity *m² / s*	Thermal characteristic time (s)	
					L = 1 cm	L = 1 mm
Aluminium (AS9U3)	237	2,7	945	$9{,}29.10^{-5}$	1,08	$1{,}08.10^{-2}$
Cast Iron (GL09)	100	7,2	550	$2{,}53.10^{-5}$	3,96	$3{,}96.10^{-2}$
Steel	46	7,8	500	$1{,}18.10^{-5}$	8,48	$8{,}48.10^{-2}$

Table 2: Orders of magnitude of thermal characteristic for classical automotive materials

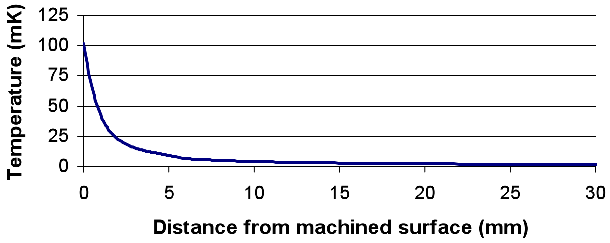

Figure 8: Evolution of maximum temperature obtained by simulation with distance from machining surface (milling case, unit mobile heat flow at 20 m/s)

6.2 Heat flow identification

Heat flow is proportional to maximum temperature observed. Upper and lower position of thermocouple identified with shape criteria is used to determine an estimation of heat flow during machining.

Milling	**Cutting speed** *(m/min)*	**Feed rate** *(mm/th)*	**Cutting width** *(mm)*
	2 000 3 000 4 000	0.1 0.15 0.2	1 2
Drilling	**Tool diameter** *(mm)*	**Cutting speed** *(m/min)*	**Feed Rate** (mm/tr)
	5 6.75 8	200 300 400	0.1 0.2
Tapping	**Tool diameter and pitch**	**Cutting speed** (m/min)	
	M6x1 M8x1.25 M10x1.5	40 60 80	

Table 3: Cutting conditions for milling, drilling and tapping tests

7 CONCLUSION

This paper describes a method to identify heat flow going into part during milling, drilling and tapping. Originality of this method is to avoid errors links to estimation of thermocouple position.

This method will be used to identify heat flow going into part during milling, drilling and tapping of aluminum alloy (AS9U3). Goal of the study is to be able to predict temperature rise and mechanical distortions of an aluminum clutch case.

Table 3 precise cutting conditions that would be tested for milling, drilling and tapping. These cutting conditions are representative of those used in automotive industry for machining of aluminum parts. Tools are also chose to be representative of automotive machining: drills and tap drills are carbide tools. Milling tool has four PCD tool (diameter 63mm).

FEM simulation of thermal distortions during machining will help manufacturer to chose to do (or not) cooling of parts or thermal compensation during machining or will help them to reorganize plan of procedure to minimize distortions during manufacturing.

8 ACKNOWLEDGMENTS

This paper presents work funded by the French agency for environment and energy consumption (ADEME) – Project Alusisec. Aim of this project is to study dry and MQL machining for automotive parts.

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