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Research paper

Experimental and analytical combined thermal approach for local tribological understanding in metal cutting

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HIGHLIGHTS

- A thermal analytical model is proposed for orthogonal cutting process.
- IR thermography is used during cutting tests.
- Combined experimental and modeling approaches are applied.
- Heat flux and stress distribution at the tool-chip interface are determined.
- The decomposition into sticking and sliding zones is defined.

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ABSTRACT

Metal cutting is a highly complex thermo-mechanical process. The knowledge of temperature in the chip forming zone is essential to understand it. Conventional experimental methods such as thermocouples only provide global information which is incompatible with the high stress and temperature gradients met in the chip forming zone. Field measurements are essential to understand the localized thermo-mechanical problem. An experimental protocol has been developed using advanced infrared imaging in order to measure temperature distribution in both the tool and the chip during an orthogonal or oblique cutting operation. It also provides several information on the chip formation process such as some geometrical characteristics (tool-chip contact length, chip thickness, primary shear angle) and thermo-mechanical information (heat flux dissipated in deformation zone, local interface heat partition ratio). A study is carried out on the effects of cutting conditions i.e. cutting speed, feed and depth of cut on the temperature distribution along the contact zone for an elementary operation. An analytical thermal model has been developed to process experimental data and access more information i.e. local stress or heat flux distribution.

1. Introduction

Temperature and heat generation in metal cutting have been intensively studied in the past. Measurement techniques as well as modeling have been and are still developed. Temperature has a major influence on machining performance such as tool life as well as workpiece surface integrity and then machined parts resistance. Bacci da Silva and Wallbank [1] and Abukhshim et al. [2] review critically the main previous works focused on the development of experimental, analytical and numerical approaches devoted to the thermal problem of metal cutting.

Analytical models are extensively reviewed by Komanduri and Hou, [3,4]; the main comments related to the analytical works are given in the following. These models are usually based on simplifying assumptions; they generally focus on a two-dimensional and steady state orthogonal cutting operation with simplified tool geometry. The cutting edge is assumed to be perfectly sharp and the rake face is flat. Tool or chip or workpiece are regarded as semi-infinite or infinite media. The material on each side of the primary shear zone is often supposed as two separate bodies in sliding contact; only few works assume it as the same body [3,5]. Both primary shear zone and secondary shear zone are considered as

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planes; tool-chip and tool-workpiece contact zones are currently supposed thermally perfect. Courbon et al. [6] propose an original approach for the tool-chip interface; this one is thermally perfect only for the sticking part of the contact zone whereas a thermal contact resistance is introduced for the sliding part. Generally the plastic deformation in the chip is neglected and the chip is supposed to move as a rigid body. Both tool and chip and workpiece free surfaces are generally regarded as adiabatic *or rarely as convective heat transfer*. Temperature distributions are currently predicted using Jaeger moving heat sources model [7].

The complete thermo-mechanical problem of cutting can be solved using finite element method. This numerical approach includes large deformation formulation; requires relevant friction laws and thermo-viscoplastic material behavior relations available at high strain rate and high temperature, [2]. The obtained models have to solve the tool-chip contact, and to manage the generation of a new surface by considering a separation criterion. As pointed out by Filice et al. [8] and Umbrello et al. [9], a large number of elements are necessary with refinement and remeshing processes to achieve an accurate description of local variables such as deformation and temperature; and due to the calculation time only a limited cutting length may be simulated; thus the steady-state may not be easily reached.

Finally, analytical models are easier to process and improvements are regularly proposed. Moufki et al. propose an analytical thermo-mechanical model of orthogonal and oblique cutting including a temperature dependent friction law at the tool-chip interface [10,11]. The chip is assumed to be formed by shearing in a narrow straight band of constant thickness; the deformation in the secondary shear zone is neglected and the chip was supposed to be a rigid body sliding on the rake face of the tool along the contact length. The chip heating is supposed due to the plastic deformation in the primary shear zone and the friction at tool-chip interface. They use a Coulomb law in which the friction coefficient is a decreasing function of the mean temperature at the tool-chip interface; thus, they have to determine the temperature distribution at this interface by solving the heat equation. However, with the assumption of a single sliding zone at the tool-chip interface, the proposed model overestimates the interface temperatures. Bahi et al. [12] introduce a more complex friction law considering both sticking and sliding contacts and propose a pioneering hybrid analytical-numerical approach. Karpat et al. [13] or Li et al. [14] finally implement the tertiary shear zone i.e. the tool-workpiece contact zone.

This paper proposes an analytical model to determine the temperature distribution in the tool and the work material during an orthogonal cutting process. The assumptions are very similar to those proposed by Komanduri and Hou [3], [4] and [15]. In addition, a parametric model is proposed for the heat source representing the secondary shear zone; it considers both sticking and sliding regions. Temperature distribution is then predicted in the whole cutting zone. Moreover orthogonal cutting experiments are performed; transient temperature distributions are collected using infrared thermography technique. In cutting process, the tool-chip interface is the most critical zone with high stresses and high temperatures values; results are focused on this area. Predicted and measured temperatures at tool-chip interface are thus correlated to provide some significant information about heat flux and heat partition ratio, the normal and shear stresses distributions are extracted then and discussed.

2. Experimental procedure

Orthogonal cutting tests were carried with a Sandvik Coromant turning tool using a TPUN 160308 GC235 coated carbide insert and a CTFPR 2525 M16 tool holder. Rake angle γ and relief angle α are respectively equal to 6° and 5°. The tested cutting conditions are given in Table 1.

Table 1
Cutting conditions.

Cutting speed V_C (m/min)	50	100	150	250
Feed f or undeformed chip thickness t_1 (mm/rev)	0.3			
Width of cut w (mm)	2			

The work material was an AISI 1055 medium carbon steel. It is provided as 50 mm diameter hot rolled rods. Table 2 summarizes its main mechanical characteristics.

Table 2
Work material mechanical characteristics.

Yield stress (MPa)	Tensile strength (MPa)	Hardness HV_{30}
370	700	200

Cutting forces were measured using a dynamometric table Kistler 9257A. Temperature distributions were measured using a FLIR SC7000 camera equipped with a G3 lens. The spatial resolution of the images provided is about 15 μm × 15 μm per pixel. Further information should be found in Artozoul et al. [16]. Analytical calculations are based on assumed thermo physical values for both steel and carbide given in Table 3.

3. Modeling and inverse approach

For an orthogonal cutting process, the tool cutting edge is parallel to the work surface and normal to the cutting direction. The feed f or undeformed chip thickness t_1 is small compared to the width of cut w, and then the chip is formed under approximately plane strain conditions. The tool is perfectly sharp and assumed to be a rigid body; its width is larger than the width of cut w. The chip is formed by shearing in a narrow zone, the so-called Primary Shear Zone (i.e. PSZ). PSZ is reduced to a plane, of length L, according to the Merchant theory [17]; and its inclination in relation to the cutting direction is defined by the shear angle ϕ. Beyond this Primary Shear Zone, the chip is sliding on the tool rake face and is deformed in a Secondary Shear Zone (i.e. SSZ). This zone is assumed to be a plane of length l_c, the tool-chip contact length, and width w, the width of cut. The two main heat sources are these two shear zones, Fig. 1; they are due to plastic deformation and additionally to friction in the SSZ zone. The Tertiary Shear Zone at tool-workpiece contact is ignored.

The developed model is based on moving heat sources solutions recalled in appendix. Temperature distributions are analytically calculated in the tool, the chip and the workpiece superposing rises due to PSZ and SSZ. The tool-chip contact is regarded as thermally perfect. A local heat partition ratio is introduced and values are calculated along the tool-chip contact zone to meet this assumption. All the free surfaces are considered as adiabatic boundaries which is acceptable assumption when dry cutting.

Table 3
Material thermo physical properties.

	AISI 1055		Tool	
	Symbol	Value	Symbol	Value
Density (kg/m³)	ρ_w	7850	ρ_{tool}	11,100
Thermal conductivity (W/m.K)	λ_w	55	λ_{tool}	37.7
Heat capacity (J/kg.K)	c_w	460	c_{tool}	276