STRESS AND HEAT FLUX DISTRIBUTION IN RAKE FACE ANALYTICAL AND EXPERIMENTAL APPROACHES

J. Artozoul[1], C. Lescalier[1], A. Dacunto[1], A. Bomont-Arzur[2]

1 - Arts et Métiers ParisTech – 4 rue Augustin Fresnel –57070 Metz France
2 - ArcelorMittal Global Research and Development Gandrange R&D – Long Carbon Bars & Wires
BP 3, F- 57360 Amnéville

Abstract: Metallurgical solutions for an improvement in machinability currently use non-metallic inclusions in order to create solid lubricants at the interfaces between tool and workmaterial. It is possible to identify and quantify these layers afterwards. However it is important to know the conditions for which these layers appear: tribological conditions, kinematical conditions (i.e. cutting speed, feed and depth of cut) and thermomechanical conditions (stress and temperature distribution in the interfaces). We focus on the tool / chip interface and more precisely on the thermomechanical conditions. This contribution is concerned with both the analytical modeling and measurement of the temperature distribution in the chip forming zone. We propose a correlation between theoretical and experimental values.
Keywords: tool-chip interface, heat flux, infrared thermography,

1. INTRODUCTION

The thermal heat flux density in both the shear zones depends on the local values of the shear stress and the strain rate. A bibliographic survey highlights the various normal and shear stress distributions which have been proposed in theoretical approaches or measured using some experimental protocol [Astakhov, 2006]. However most of the distributions seem to agree on a few points, i.e. the normal stress increase in the vicinity of the cutting edge, the tool chip zone is generally divided between a sticking and a sliding contact zone. The direct measurement of the normal and shear stress distribution in the tool-chip interface is quite complex. However the shear stress at the tool chip interface and the strain rate measured in the chip at the vicinity of the rake face directly influence the heat flux generated within the secondary shear zone. It seems interesting to investigate the indirect measurement of the shear stress from an accurate temperature distribution measurement and a easily computable model for the temperature distribution.

2. MODELLING

The modelling concerns an orthogonal cutting operation. Some common assumptions are used: the cutting operation is considered as a steady state problem, the tool is perfectly sharp, the rake face is plane, the chip thickness is constant all along the tool chip interface, the chip is considered as a rigid body, the chip and the tool are considered as semi-infinite medium, the outer surfaces of the different bodies are supposed to be perfectly adiabatic, the thermophysical parameters of the tool and the workpiece are not supposed to be temperature dependant. The temperature rise in the cutting zone is assumed to be due to the cumulative effect of both the primary shear zone (PSZ) and the secondary shear zone (SSZ). These shear zones are considered as plane heat sources respectively located on the shear plane, according to Merchant theory, and along the the tool / chip interface. The adiabaticity of the free surfaces is taken into account using a common method the termperature rise due to the cumulative action of the actual heat source and a virtual symmetrical heat source.

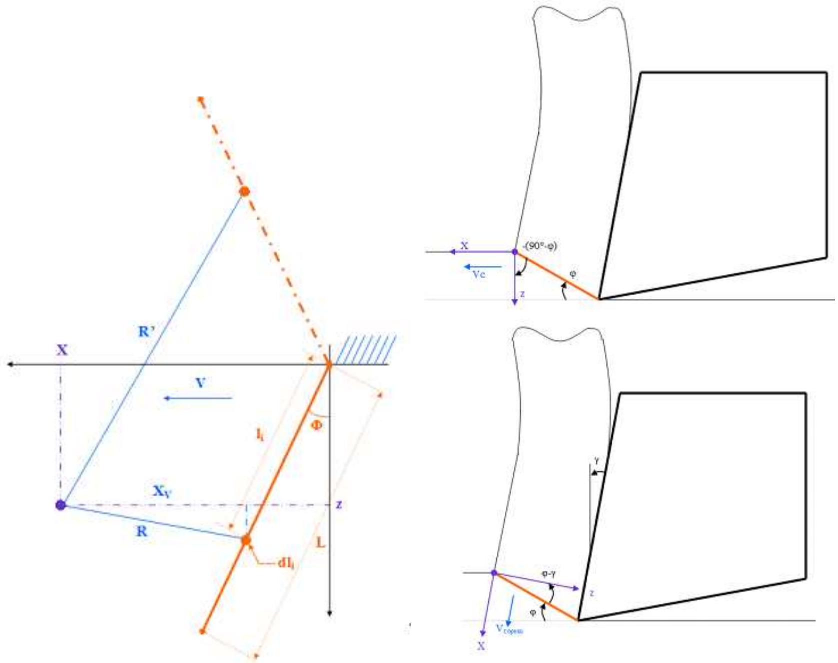

Figure 1 - Simplified analytical modelling of the primary shear zone

The temperature rise due to the primary shear zone on the workpiece side is evaluated using:

$$T(X,z)=\frac{Q_{\mathrm{PSZ}}{}^{\mathrm{workpiece}}}{2.\pi.\lambda_w}.\int_0^{L_{\mathrm{ZCP}}} e^{+\frac{V_c.(X-l_i.\cos(\varphi))}{2.\frac{\lambda_w}{\rho_w.C_{p_w}}}}\{K_0(\frac{V_c.R}{2.\frac{\lambda_w}{\rho_w.C_{p_w}}})+K_0(\frac{V_c.R'}{2.\frac{\lambda_w}{\rho_w.C_{p_w}}})\}\,\mathrm{d}l_i$$

The temperature rise due to the primary shear zone on the chip side is evaluated using:

$$T(X,z)=\frac{Q_{PSZ}{}^{chip}}{2.\pi.\lambda_w}\int_0^{L_{ZCP}} e^{-\frac{V_{chip}.(X-l_i.sin(\varphi-\gamma))}{2.\frac{\lambda_w}{\rho_w.C_{p_w}}}}\{K_0(\frac{V_{chip}.R}{2.\frac{\lambda_w}{\rho_w.C_{p_w}}})+K_0(\frac{V_{chip}.R'}{2.\frac{\lambda_w}{\rho_w.C_{p_w}}})\}\,dl_i$$

where K_0 is a modified Bessel function of the second kind.

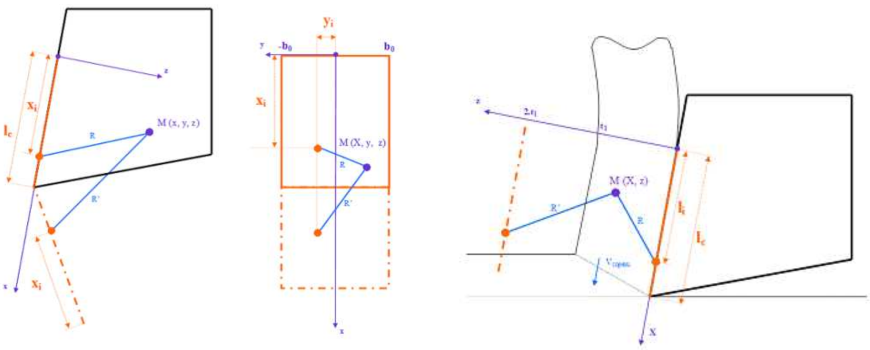

Figure 2 - Simplified analytical modelling of the secondary shear zone

The temperature rise due to the secondary shear zone on the chip side is evaluated using:

$$T(X,z) = \frac{1}{2.\pi.\lambda_w}.\int_0^{l_c} Q_{SSZ}{}^{chip}.e^{-\frac{V_{chip}.(X-l_i)}{2.\frac{\lambda_w}{\rho_w.C_{p_w}}}}\{K_0(\frac{V_{chip}.R}{2.\frac{\lambda_w}{\rho_w.C_{p_w}}}) + K_0(\frac{V_{chip}.R'}{2.\frac{\lambda_w}{\rho_w.C_{p_w}}})\}\,dl_i$$

The temperature rise due to the secondary shear zone on the tool side is evaluated using:

$$T(x,y,z) = \frac{1}{4.\lambda_T.\pi}\int_{-b_0}^{b_0}\int_0^{l_c} Q_{SSZ}{}^{tool}.(\frac{1}{R}+\frac{1}{R'})\,dx_i\,dy_i$$

The global heat fluxes are easily calculated from a basic mechanical chip formation model using forces and velocities decomposition. The main problem consists in the determination of the heat flux density distribution all along the heat source as well as the determination of the heat partition ratios i.e. the heat quantity produced in the shear zones and flowing into the bodies in contact. For instance, a uniform distribution of both heat fluxes leads to mean values for Q_{PSZ}, the heat flux density distributed along the shear plane, and for Q_{SSZ}, the heat flux density distributed along the tool-chip interface. These values should be calculated using:

$$\overline{Q_{PSZ}} = \frac{V_s \times F_s}{2 \times b_0 \times L_{PSZ}} \quad and \quad \overline{Q_{SSZ}} = \frac{V_{chip} \times F_f}{2 \times b_0 \times l_c}$$

Different simulations are performed using experimental values (cutting forces and shear angle and chip thickness and velocities) and different heat partition ratio values for the primary shear zone. These simulations seem to highlight that the influence of the primary shear zone on the temperature distribution at the tool-chip interface could be neglected. The temperature rise at the tool-chip interface due to the primary shear zone is almost equivalent to the temperature measurement accuracy. It seems more to focus on the heat partition ratio for the secondary shear zone: B defines the heat flux entering the tool. The heat fluxes entering the tool and the chip are evaluated using:

$$Q_{SSZ}^{tool} = B \times Q_{SSZ} \quad et \quad Q_{SSZ}^{chip} = (1-B) \times Q_{SSZ}$$

The litterature proposes many shear stress distributions and so as many heat flux density distributions 0. In fact, whatever the distribution mathematical modelling is, the local heat flux density value is conditioned by the two following equations:

$$Q(l_c) = 0 \quad and \quad \int_0^{l_c} Q(l_i)dl_i = \frac{V_{chip} \times F_f}{2 \times b_0}$$

Komanduri proposes an interesting analytical modelling which focuses on the temperature distribution due to both the shear zones [Komanduri et al., 2000], [Komanduri et al., 2001-1], [Komanduri et al., 2001-2]. Concerned with the tool chip interface, the model proposes to equalize temperatures on the both sides of the interface. It implicitly assumes a thermically perfect contact. Moreover this model introduces a local heat partition ratio. For instance, for the secondary shear zone, the heat flux flowing into the tool and then into the chip varies all along the tool contact length. This assumption is evaluated for the most popular heat flux distributions in the tool chip contact zone (see Table 1). This analysis reveals some interesting points such as a similar trend for all the curves presenting the local heat partition as a function of the position within the tool chip contact zone: the heat flowing into the tool seems to increase regard to the distance to the cutting edge, the vicinity of the cutting edge is always physically unacceptable (some authors talk about a heat sink in the vicinity of the cutting edge [Chao et al., 1955], some authors implement a local heat flux near the cutting edge).

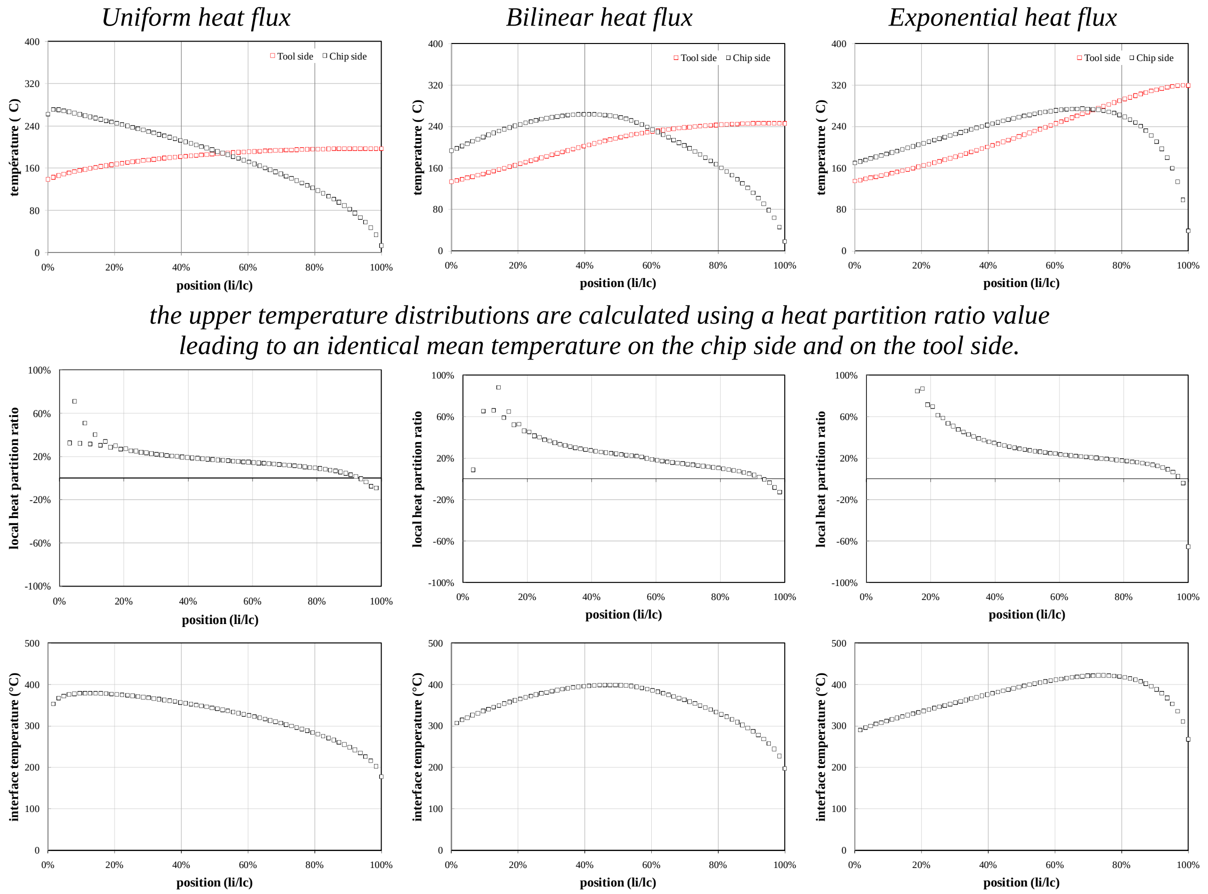

Table 1 - Distribution of temperature and heat partition ratio along the tool chip interface
cutting edge = 100% - end of the tool chip contact = 0%

3. EXPERIMENTS

An experimental device is designed to perform orthogonal cutting tests and to measure simultaneously the cutting forces and the temperature distribution (see Figure 3). The experiments consist in pipe machining operations. The pipe material is currently a carbon steel or a free cutting steel. The tool is a basic TiN coated carbide tool insert provided by Sandvik. The tool rake face is perfectly plane. The chip breaking device consists in an adjustable carbide wedge (a particular attention is drawn to its position). The tool is mounted on a Kistler 9257 table. The insert side face is ground so that the infrared camera optical axis is as normal as possible to the surface observed and the camera observes the substrate tool material. The camera is a FLIR SC7000 equipped with a close-up ×3 lens. The sensor material is made of indium antimonide. The thermal image is composed by 640 × 512 pixels. The pixel resolution is about 15 µm. The spectral response extends from 1.5 to 5 µm (MWIR). The software provided by FLIR enables to operate simultaneously with four integration times and so to cover a wider temperature range. Two different temperature ranges are calibrated: 5 - 300°C and 500 - 1300°C.

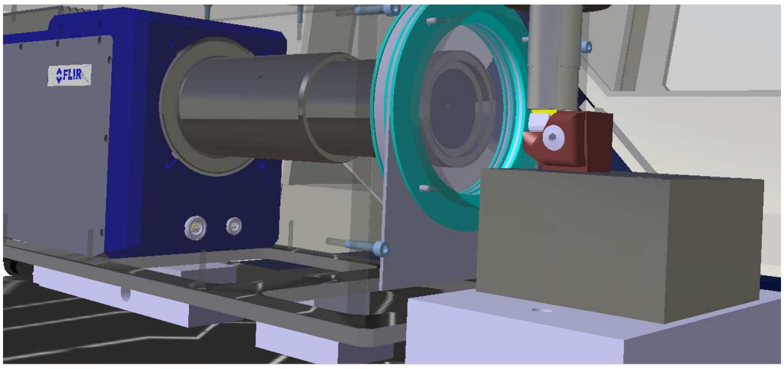

Figure 3 - Experimental device

Experiments focus on the evolution of both the cutting forces and the temperature distribution towards the cutting conditions (i.e. cutting speed, feed and depth of cut). The inserts are observed using an optical microscope after the machining operation in order to check the tool-chip contact length and compare the value to the one measured on infrared thermal image. The thermal image clearly indicates the position of both the shear zones and enables to measure the shear angle as well as the chip thickness (the assumption of constant chip thickness is easily checked). A particular attention is drawn to investigate the influence of the chip breaking device on the cutting forces. The thermal image shows a temperature increase due to the friction between the chip and the chipbreaker. An assumption is implicitly made: the temperature distribution at the tool – chip interface is not affected by the friction on the chipbreaker. A comparison between the measured temperature distribution and the calculated temperature distribution enable to determine the most relevant heat flux distribution as well as the associated parameters. The analysis of the thermal image presented above leads to a tool-chip contact zone with consecutive sticking and then sliding contact. The fraction of sticking contact is about 10% of the overall tool-chip contact length. The workmaterial is a free cutting steel with high sulphur and lead contents. The calculated and measured temperatures show a very good agreement.

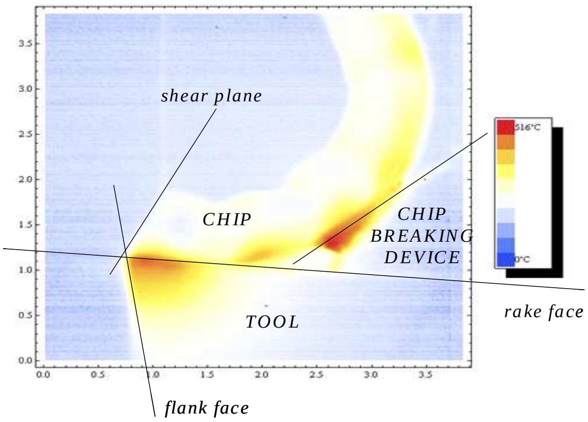

Figure 4 – Thermal image recorded
free cutting steel – Vc = 110 m/min – f = 0,4 mm /rev – ap = 1,5 mm

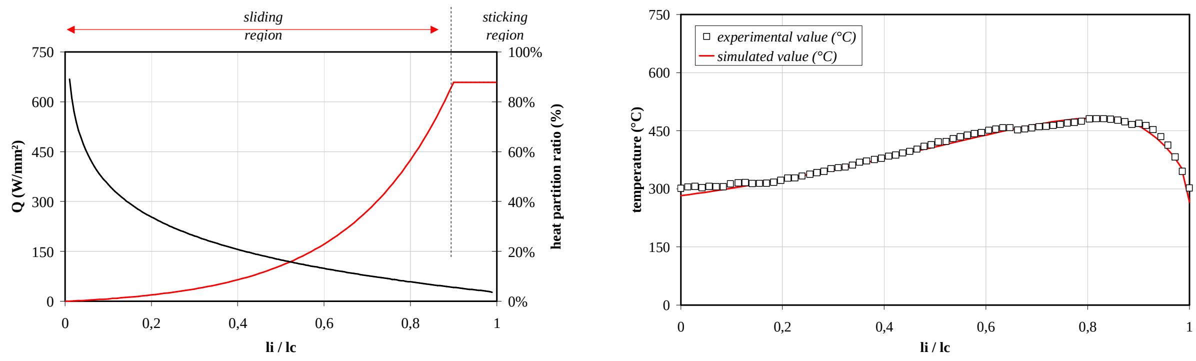

Figure 5 – Temperature distribution and heat flux
free cutting steel – Vc = 110 m/min – f = 0,4 mm /rev – ap = 1,5 mm

4. CONCLUSIONS

We propose an approach combining an analytical thermal modeling and experimental measurements based on infrared thermography. Analytical modeling enables fast computing of the temperature distributions as well as easy parameters evaluation using inverse methods. Thermography enables to get relevant informations about the orthogonal machining operation such as the shear angle and the different temperature distributions i.e. in the tool and the chip. This approach enables to determine the distribution of the most relevant heat flux as well as the heat parition coefficient for the tool-chip contact zone. Further developments concern the implementation in the temperature modeling of realistic material thermophysical constants and the comparison of different steel grades.

5. REFERENCES

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7. INFORMATION ABOUT AUTHORS

E-mail address : christophe.lescalier@ensam.eu

Tel.: +33-3-87 37 54 35 ; fax: +33-3-87 37 54 70