Modelling and experimental analysis of high speed air jets used during metal cutting as a cooling technique

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Abstract: A supersonic nozzle has been used to generate a high velocity air jet in order to provide cooling at the tool-chip interface area during metal cutting on a lathe. Previous investigations indicate that there is a reduction in temperature when the high velocity air jet is applied during metal cutting. It is hypothesised that the high velocity air jet is reducing the temperature on the tool-chip interface not only by heat transfer, but also by a mechanical effect. This paper presents the results from finite element modelling of orthogonal machining using high velocity air jets as the primary cooling technique. The finite element analysis is supported with analytical modelling and validated with experimental investigations. Results indicate a significant mechanical contribution due to the air jet impinging on the chip leading to a reduction of 15-20% of cutting temperatures on the tool. This approach shows significant potential for environmentally and economically efficient machining.

Keywords: Modelling, Machining, Temperature Measurement, Air Jets

1. INTRODUCTION

The use of high speed air jet as a coolant in machining is a challenging scenario in environmental friendly machining. Despite the extensive literature, air jet cooling in machining is an area of ongoing research. Until now, the jet cooling technique has been studied only from a thermal point of view. The new aspect investigated in this work is the chip bending ability of the jet. The idea of chip-bending and its beneficial effects in cooling the cutting area is not related to maximizing the heat transfer, but to avoid the temperature increase. The heat generation in the chip-tool interface is due to the contribution of deformation in the shear zone and to the frictional contact between the chip and the rake face of the cutting tool. The importance of the frictional contact is proportional to the friction coefficient and to the pressure of the chip on the rake face. The traditional way of reducing this contribution is using a cutting fluid (flooding) or, more recently, injecting a coolant in the chip-tool interface. The new approach with high speed air jet shows the temperature reduction is strongly dependant on the position of the nozzle. By directing the jet onto the top face of the chip it is possible to reduce the pressure on the rake face, responsible of temperature increase in the chip-tool interface. The pressure on the top face of the chip generates a stress on the bottom face of the chip close to the constraint and in the chip-tool interface. The global stress is due to air jet pressure and cutting pressure on the rake face. When the air jet is directed on the top face of the chip (overhead position) the global stress is less than the cutting stress in dry machining.

A fully thermo-mechanical model has been developed with DEFORM-3D and a mechanical only model with DEFORM-2D, in order to investigate the chip bending. From an analytical point of view the chip can be modelled as a structural cantilevered beam with uniform load. The results from finite element modelling show the displacement of the chip is mainly due to the chip-breaker. The displacement due to the air jet bending moment is minimized by the stiffness close to the constraint point, but the mechanical effect of the air jet has a significant impact on the energy in the tool.

2. THEORETICAL MODEL

Due to the difficulties associated with routinely measuring meaningful machining temperatures, mathematical models for machining temperature has been widely used. The sources of thermal energy in metal cutting include the primary or shear zone, secondary or friction zone and the tertiary or tool-work zone. Generally, the tertiary is ignored when a perfectly sharp tool is assumed. The temperature at the chip-tool interface (secondary zone) is one of the major causes of tool rake face wear. Most of the models are based on estimation of heat partition coefficient in primary zone: Trigger and Chao [1] evaluated temperature in primary zone, Leone [2] used a line heat source to evaluate the heat thickness that is approximated by one-half the uncut chip thickness. Adibi et al. [3] extended Oxley's analysis of machining to use different material models and introduced a new approach to calculate the pressure variation along slip line in the primary shear zone. In their approach, the temperature at the middle of the shear zone is determined by integrating the plastic work done up to the mid-plane of the primary shear zone. All of the analytical temperature models consider a temperature rise due to shearing in the primary deformation zone and a temperature rise due to additional shearing and friction in the secondary deformation zone. All the models considering heat partition coefficient in primary zone are inspired by the fundamental analysis by Loewen and Shaw [4], while the calculations on secondary zone are based on the friction slider developed by Jaeger [5].

2.1 Dry cutting model

Most of the theoretical analysis of cutting temperature use the specific cutting energy in it main components, the shear energy (u_s) and the frictional energy.(u_f). The specific cutting energy has to be expressed as a function of normal pressure (K_n) and shear stress

(K_f). In turning the specific cutting energy is equal to the normal pressure on the shear plane angle (Φ); the frictional component of specific cutting energy is equal to the product of shear stress and shear strain:

$$\begin{aligned} u &= K_n \\ u_f &= \tau\gamma \\ \tau &= (K_n \cos\Phi - K_f \sin\Phi)\sin\Phi \\ \gamma &= \frac{\cos a \ \cos(\Phi - a)}{\sin\Phi} \\ u_s &= u - u_f \end{aligned} \qquad \text{Eq. 1}$$

Following the model proposed by Smithey et al.[6], it is possible to use data from dynamometer to estimate the value of specific cutting energy, in fact the energy is depending on feed (t), cutting speed (v_c) and rake angle (a). The two components of the specific cutting energy can be expressed as a combination of cutting parameters. With the shear plane angle and the expression of K_n and K_f it is possible to find al the components of specific cutting energy (Eq. 1).

Using Shaw's analysis [7] it is possible calculating the primary zone heat partitioning coefficient:

$$R_1 = \frac{1}{1 + 1.328\left[\dfrac{\alpha_1\gamma}{v_c t}\right]^{\frac{1}{2}}} \qquad \text{Eq. 2}$$

where α_1 is the thermal diffusivity of the workpiece. The mean temperature in the shear plane area is

$$T_s = \frac{R_1 u_s}{c_w \rho_w} \qquad \text{Eq. 3}$$

where c_w is the heat capacity of the workpiece and ρ_w is the density. Using the friction slider model [5], heat partitioning coefficient in the secondary zone is

$$R_2 = \frac{C - T_s}{C + B} \qquad \text{Eq. 4}$$

Where

$$C = u_f \frac{V_c A t}{k_t} \qquad B = 0.754 \frac{u_f}{c_w \rho_w}\sqrt{\frac{t^2 v}{l \alpha_w r}}$$

with k_t thermal conductivity of the tool, c_w, ρ_w, α_w respectively heat capacity, density and thermal diffusivity of the workpiece, r is the thickness ratio. The mean interface temperature is

$$T_t = R_2 B \qquad \text{Eq. 5}$$

These calculations provide results for basic cutting, with neither cutting fluid provided nor mechanical effect of air jet considered.

2.2 Modeling the air jet: thermal and mechanical effect

In general, the heat transfer by an impinging jet distribution is presented as the variation of the local Nusselt number with radial position. The basic analysis of forced flow on an isothermal plate is useful to estimate the heat removed from the insert contact face by the air jet. Since the chip-tool interface is not an isothermal plate, this analysis is an idealization. However, by finite elements modelling, it is possible to estimate the error by quantifying the difference between the ideal isothermal plate and the temperature distribution on the rake face. A supersonic nozzle able to play the air flow at a speed if 576 m/s has been used for the experiments: this data has been used also for theoretical calculations. An heat transfer coefficient $h = 2850\ W/m^2\ K$ has been calculated using the isothermal plate equations with a length of plate $l = 1\ mm$, area of plate $A = 0.2\ mm^2$, temperature of plate, $T_w = 500\ °C$, fluid free-stream velocity, $u_{inf} = 576\ m/s$, fluid free-stream temperature $T_{inf} = 4°C$. Since the 2D finite elements model suggest that the isothermal part of the chip is between 75% and 80% of the contact length, a safer value of the heat transfer coefficient (2000 W/m^2 K) has been used for theoretical calculations and boundary conditions in finite elements modelling. The result is consistent with the experimental studies carried out by O'Donovan [8].

The mechanical effect is responsible of the additional cooling effect due to air jet. The specific cutting energy is responsible of temperature increase in the chip-tool interface. This energy per unit of volume in its frictional component is also proportional to the pressure on the rake face. By reducing the frictional component it is possible to reduce the amount of heat generated by friction. The finite element analysis shows that a suitable option for positioning the air jet cooling is overhead because on this position the air jet is applying a constant pressure on the top face of the chip. The new shear stress on the rake face is the sum of the stress due to specific cutting energy and the stress due to the mechanical effect of air jet. The point of maximum stress induced by air jet occurs close to the shear plane, where the chip is connecting to the workpiece, where the bending moment of air jet is maximized. The chip geometry is defined by feed t, depth of cut b and length of the chip-tool interface. The feed and the depth of cut are cutting parameters, the length of the contact results from the 2D simulations. The geometry is out of the hypothesis of Mindlin's plate, therefore calculations based on cantilevered beam have been carried out. The following figure is showing these calculations with a pressure p of 4 bar

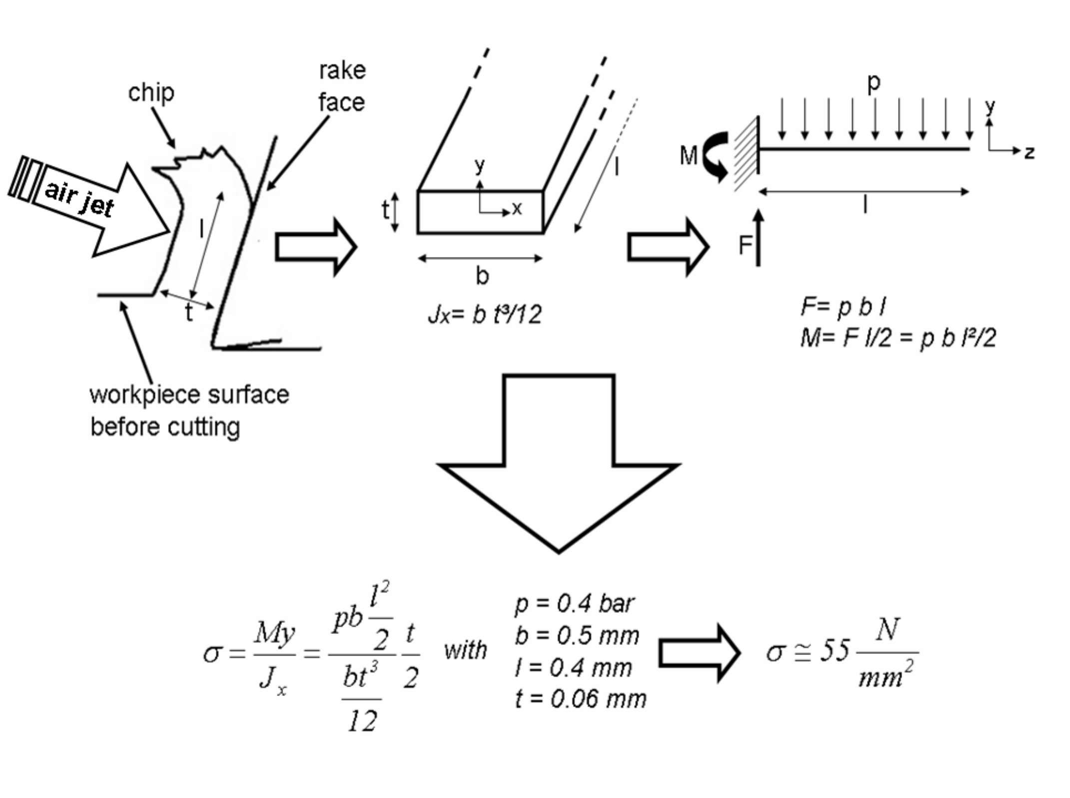

Figure 1 – Mechanical effect of the air jet on the chip

The calculation shows that it is possible to reduce the stress on the rake face from 7% to 11%, depending on air pressure.

2.3 Theoretical analysis results

Combining the theoretical analysis by Loewen and Shaw about basic cutting, friction slider theory by Jaeger [5] with heat transfer by impinging jet and reduction of frictional energy per unit of volume by mechanical effects of air jet it is possible to estimate the overall reduction of temperature by using the impinging jet in overhead position. The following cutting condition have been used: cutting speed of 4.5 m/s, depth of cut from 0.5 to1 mm, feed from 0.06 to 0.12 mm/rev, rake angle of 0°. The pressure of the air jet on the rake face has been considered from 4 to 7 bar. The materials considered were AISI 1020 steel (workpiece) and tungsten carbide (cutting tool). The results by this analytical calculation are according to Shaw [7]. The following table (Table I) show the results from theoretical analysis, where Φ is the shear plane angle, T_s is the shear plane mean temperature, T_{tl} is the mean temperature of the chip-tool interface without any cooling, T_{tlH} is the mean temperature of the chip-tool interface with heat transfer only,

T_{t2} is the mean temperature of the chip-tool interface with mechanical effect only, T_{t2H} is the mean temperature of the chip-tool interface with heat transfer and mechanical effect, l is the contact length, σ is the stress on the rake face due to cutting force.

	Φ (deg)	T_s (°C)	T_{t1} (°C)	T_{t1H} (°C)	T_{t2} (°C)	T_{t2H} (°C)	l (mm)	σ (N/mm²)
t =0.06 mm b= 0.5 mm p= 4 bar	30.41	499	654	637	598	583	0.4089	859
t = 0.06 mm b= 0.5 mm p= 7 bar	30.41	499	654	637	556	542	0.4089	859
t = 0.12 mm b= 0.5 mm p= 4 bar	32.93	472	735	681	674	624	0.7410	846
t = 0.12 mm b= 0.5 mm p= 7 bar	30.41	472	735	681	627	581	0.7410	846
t = 0.06 mm b= 1 mm p= 4 bar	30.41	499	654	620	598	567	0.4089	859
t = 0.06 mm b= 1 mm p= 7 bar	30.41	499	654	620	557	528	0.4089	859
t = 0.12 mm b= 1 mm p= 4 bar	32.93	472	735	627	673	574	0.7410	847
t = 0.12 mm b= 1 mm p= 7 bar	32.93	472	735	627	627	535	0.7410	846

Table I – Results from theoretical analysis

The general trend of these results shows the good cooling ability of the air jet, and a major contribution of the mechanical effect. In particular the mechanical effect is associated to the shape of the chip: the mechanical effect is maximised when the area of the chip exposed to the pressure is maximised. (t = 0.12 mm/rev, b = 1 mm).

3. FINITE ELEMENT MODELING

3D and finite element simulations has been carried out using the commercial software DEFORM 3D v5.1. Two different position of the high speed air jet were modelled: interface and overhead, as shown in Figure 2a and 2b

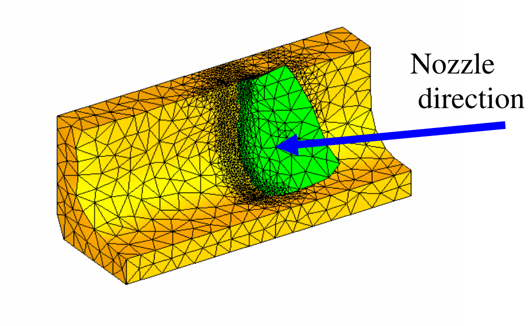

Figure 2a: Interface boundary condition

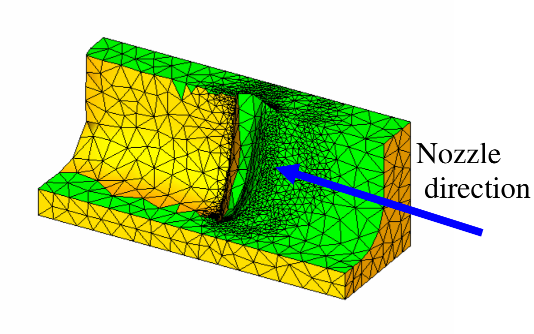

Figure 2b: Overhead boundary condition

Elements marked in green are affected by forced convection and the thermal boundary condition present an heat transfer coefficient of 2000 W/m²K and a pressure of 4 or 7 bar, while the elements marked in yellow presents an heat transfer coefficient of 20 W/m²K (natural convection) and no pressure. Simulation results are shown in the following table for 7 different boundary conditions: dry cutting, heat transfer only with jet in interface and overhead position, heat transfer and mechanical effect in interface and overhead position with 4 and 7 bar of pressure. It can be seen from Table 2 that air jet cooling, allows a considerable reduction of interface temperature, in particular with the overhead jet position. An overall reduction in the predicted chip temperature is evident, demonstrating the effectiveness of jet cooling. The temperature at the interface is shown to be lower when the air jet is directed from the overhead position. This effect may be explained by the strong influence of positional cooling as proposed by Sales et al [9]. The authors proposed that incorrect positional cooling can reduce the temperature in the cutting zone, removing the positive effect of the heat used in softening the material, resulting in higher stresses and higher local temperatures. It can be seen the lowest temperature of chip tool interface is expected when considering the mechanical effect of air jet with a pressure of 7 bar. This suggests the cooling effect is not achieved only by heat transfer, but by mechanical effect. Simulation results also show a temperature growth with incrementing the pressure in interface position. This suggest, according to the theoretical analysis, that directing the jet in interface position there is an increment of stress on the rake face, and relatively small cooling is achieved only by thermal effect.

feed=0.06mm/rev *depth=0.5mm* *speed=270m/min*	**max. workpiece temperature (°C)**	**Interface temp. (°C)**	**Chip temperature (°C)**
Dry	737	760	416
heat transfer only (interface)	727	748	408
heat transfer only (overhead)	721	627	389
heat transfer and pressure (4 bar, interface)	667	669	417
heat transfer and pressure (7 bar, interface)	672	674	419
heat transfer and pressure (4 bar, overhead)	682	601	395
heat transfer and pressure (7 bar, overhead)	681	598	396

Table II: Tool and workpiece temperatures for various cooling conditions

4. CONCLUSIONS AND FURTHER RESEARCH

Mechanical effect of air jet is a new aspect in the world of environmental friendly cooling techniques in metal cutting. Intuition may suggest a positive effect with using the jet in interface position. This displacement of the nozzle is traditionally used for MQL applications. The theoretical analysis show that a reduction of the length of the chip-tool interface leads to a reduction of the temperature, therefore if the mechanical effect of the jet is enough for chip bending, interface positioning could lead to a reduction of the length, but the high stiffness of the chip, close to the shear zone, avoid any significant displacement. On the other hand, by using the jet in overhead position, the stress on the rake face is reduced and the frictional heating as well. Experimental validation using a k-type thermocouple, embedded in the insert, is under development, as shown in Figure 3.

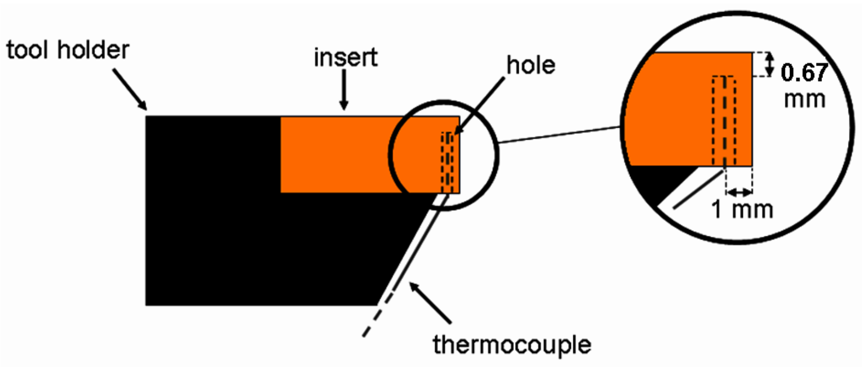

Figure 3 – layout of embedded thermocouple

Finite elements modelling will be used for correlating the temperature of the chip-tool interface to the temperature read by the thermocouple at the end the hole in the tool, as shown in Figure 4.

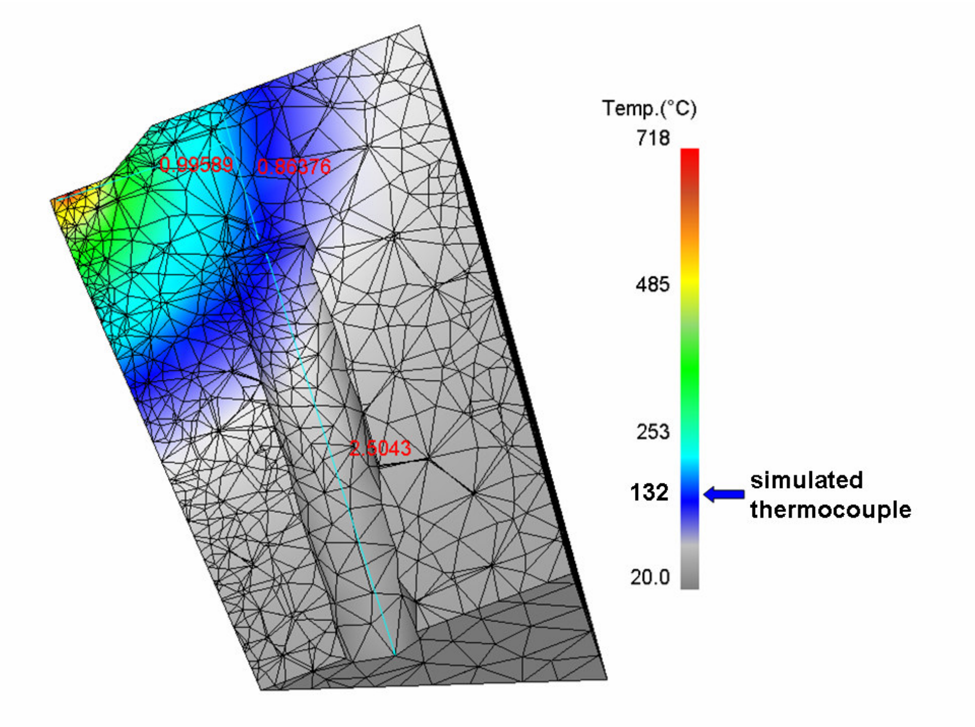

Figure 4 – Use of finite elements for temperature correlation

In conclusion significant benefits in terms of cooling can be achieved using the air jet using its mechanical effect on the chip. This paper presents the early works in this direction. Air jet cooling represent a valid alternative to MQL techniques and an improvement compared to dry machining. A cost analysis for comparing the cost of compressing the air and using an oil based lubricant is under development, but the relatively low pressure and the temperature reduction of 15-20% indicates this technique can be efficient also from an economic point of view.

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