Finite elements modeling of titanium machining assisted by high speed air jet

M. Monno [1], G.M. Pittalà [2*], A. Bareggi [2]
[1] Politecnico di Milano, Dipartimento di Ingegneria Meccanica, Via La Masa, 1, Milano, Italy
[2] MUSP Laboratory, Strada Statale 10, 29100, Piacenza, Italy.

Abstract
The use of conventional coolants in machining difficult-to-cut materials has been critically considerate after changing environmental awareness and increasing cost pressures. Nowadays conventional and relatively soft materials are dry machined, but after progressively successful minimum quantity lubrication in hard material, such as titanium and nickel-based alloys, there is a trend towards air jet assisted cutting and dry cutting also for these materials, particularly used in aerospace industry. Previous investigations indicates a positive mechanical effect by high speed air jet show a reduction in temperature in cutting conventional materials, such as low carbon steels. By using the commercial software DEFORM-3D the feasibility of air jet assisted cutting has been demonstrated also for titanium. Chip shape, insert and workpiece temperature can be predicted by finite elements software more accurately compared to previous works, by using an optimized remeshing. Predictions by finite elements have been compared to analytical model based on Oxley machining theory. Changes in temperature due to high speed air jet are significant and show potential low cost and environmentally efficient titanium and hard materials machining.

INTRODUCTION

Increasing cost pressures and changing environmental awareness has led manufacturing industry to give critical consideration to the use of conventional coolants and traditional cooling techniques in machining processes. In many high performance cutting applications traditional cooling techniques are ineffective and problematic leading to thermal shock [1]. Furthermore, reducing the operator's exposure to coolants reduces the possibility of operator ill health and leads to better working conditions. Current research shows that impinging gas jets have a much greater potential for cooling during metal cutting operations than previously suspected. By using a high speed air jet, it has been possible to obtain benefits in machining low carbon steel comparable with latest minimum quantity lubrication and cooling techniques. 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 in difficult-to-cut materials. 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. The feasibility of this cooling technique has been demonstrated for AISI 1020 steel. As attempt to use the air based cooling technique on difficult to cut materials, 2D and 3D simulation has been carried out for Ti 6Al-4V alloy turning operations. Temperature prediction with different cutting parameters has been carried out with a reworked analytical model by Oxley et al [ref.]. Finite elements modeling and analytical prediction constitute a scientific base for further experimental investigation on Ti 6Al-4V, with particular emphasis on air jet cooling.

AIR JET ASSISTED MACHINING OF AISI 1020 STEEL

1.1 Finite elements and experimental setup

AISI 1020 is a general purpose mild steel, low-carbon machinery steel, having good over-all mechanical properties easily machinable and weldable, suitable for heat treatment and ideal for carburizing. The AISI 1020 with his wide range of application has been chosen for investigating the use of high speed air jet for cooling turning operations. 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.

PARAMETERS	**VALUES**
Feed	0.06 mm/rev
Depth of cut	0.5 mm
Cutting speed	280 m/min
Rake angle	0°
Nose radius	0.2 mm
Chipbreaking	yes

Table 1: Cutting parameters

The cutting parameters (Table 1) were selected as the best configuration for cutting efficiently the AISI 1020 steel with the provided insert for part finishing and achieving a maximum surface average roughness *Ra = 0.8 µm*. The nozzle has been positioned in order to direct the air jet in 2 different positions: directed in the chip-tool interface and on the top face of the chip (overhead). The impingement angles in testing has been chose to be as close as possible to vertical direction in overhead position and horizontal direction in interface position.

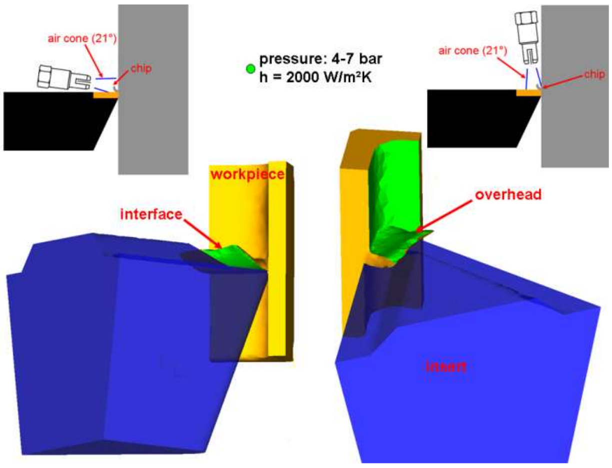

Figure 1: Sketch of nozzle positioning in relation to FE boundary condition

3D finite elements simulation has been carried out for investigating the effect of the air jet. Figure 1 shows a sketch of the nozzle in interface and overhead position and the corresponding boundary condition used in the finite elements model. The green elements represent the surface interested by the air jet. Tests have been carried out at 4 bar of pressure (the maximum available) with a flow rate of 630 slpm, and in finite elements model pressures of 4 and 7 bar have been used, and a heat transfer coefficient of 2000 W/(m²K) as well, according to O'Donovan [3] and Kops [4]. Figure 2 show the mechanical effect of the air jet in 2D finite elements modeling.

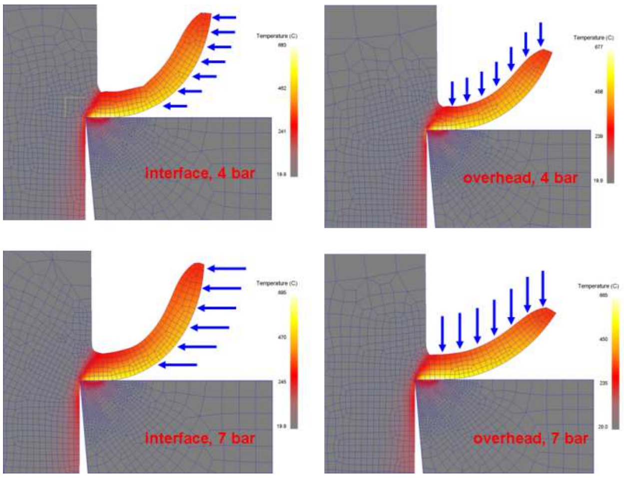

Figure 2: 2D simulation show the mechanical effect of air jet

1.2 Results for AISI 1020: finite elements and experimental investigation

Finite elements modeling and experimental results for temperature have been compared in Figure 3.

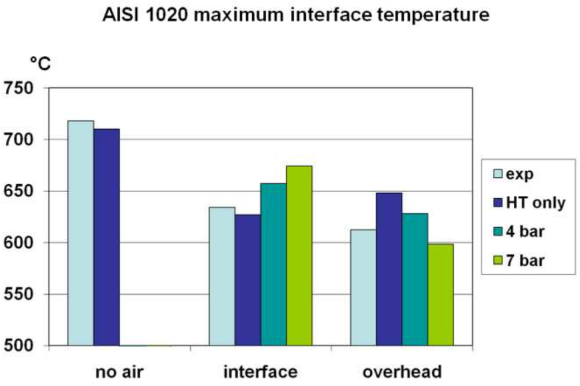

Figure 3: FE analysis and experimental tests results for temperature in turning AISI 1020

Experiments show the reduction of maximum interface temperature by air jet cooling, but the overhead position seems to be more efficient than the interface position, that is not consistent with a more intuitive aiming of the jet in the chip-tool interface. The difference between directing the jet in the interface or on the top face of the chip is due by the mechanical effect. Finite elements results offer the chance to better understand the phenomena. Results for finite elements in Figure 3 show the maximum interface temperature with heat transfer only (HT only) and air jet at 2 different pressures (4 and 7 bar). Considering the heat transfer only, the interface configuration is more efficient, and it’s suitable for MQL application at low pressure [5], but when the jet is directed in the interface a negative mechanical effect is produced. On the other hand, an additional beneficial mechanical effect is presented when the air jet is directed on the top face of the chip (overhead). According to former research [6] the additional stress induced by mechanical effect is responsible for the increment of temperature in interface position and for the reduction in overhead position. As shown by Figure 4, the additional stress is not related to a change in the cutting and feed force, slightly increasing due to the hardening induced in the material by heat transfer, according to Sales et al. [7]. On the other hand, Figure 5 shows a considerable improvement in standard deviation of cutting force when using the air jet, with consequent stability in chip control.

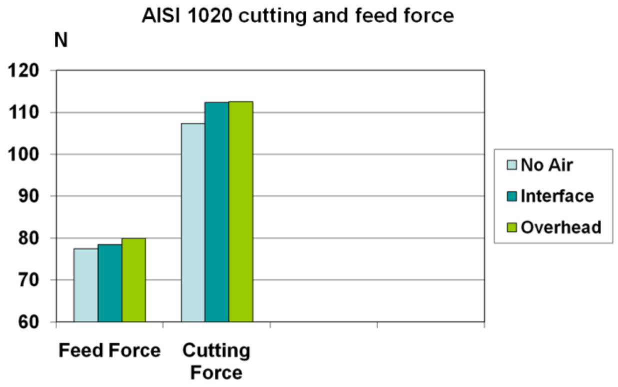

Figure 4: Experimental results for cutting and feed force in turning AISI 1020.

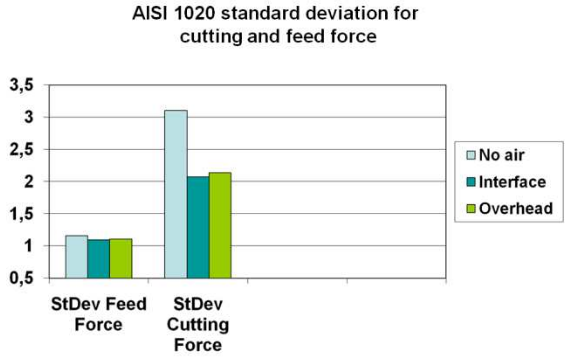

Figure 5: Experimental results for standard deviation of cutting and feed force

The feasibility of air jet cooling in AISI 1020 turning operation and the consideration about the beneficial mechanical effect lead to consider this cooling technique for difficult-to-cut material, therefore preliminary 2D finite elements analysis and Oxley based analytical model for Ti 6Al-4V have been carried out.

AIR-JET ASSISTED MACHINING OF TITANIUM ALLOY

2.1 2D finite elements model setup

The commercial FEA software Deform-2D v. 9.0, a lagrangian implicit was used to simulate the machining of titanium alloy Ti6Al4V. The workpiece was initially meshed with 1500 elements, while the tool, modelled as rigid, was meshed and subdivided into 700 elements.

The friction law used is shear constant, with the constant m = 0.6. To determine the temperature on the tool a steady state analysis is performed.

More detailed information on the FEM model, material model and simulation results are provided in Kobayashi et al. [8] .

The configurations are shown in the Figure 2.

In Table 2 is presented the conditions of the tests.

PARAMETERS	VALUES	
Depth of cut	1 mm	
Cutting Speed (m/min)	139.5 (Low)	279 (High)
Feed rate (mm/rev)	0.06 (Low)	0.1 (High)
Air Pressure	4 bar	7 bar
Rake Angle	0 °	
Clearance Angle	5 °	
Nose radius	Negligible	

Table 2: Test conditions

2.2 Finite elements model results for Ti 6Al-4V: temperatures and cutting forces

The simulation are carried out using two different material models. One is the default material present in DEFORM and the other one is Johnson-Cook based (Lee [8]). The reason is to evaluate the sensibility of the results changing the material parameters.

Then the maximum temperatures on the tool-workpiece interface are considered.

The effect of the pressure is shown in the Figure 6.

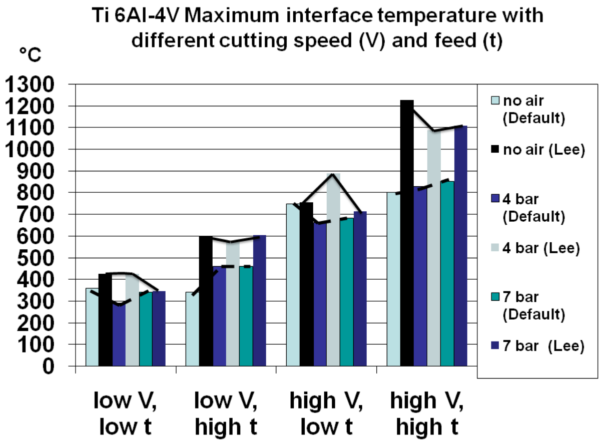

Figure 6: FE analysis results for temperature in turning Ti6Al4V using interface air-jet.

The air jet works with high cutting speed and low feed(with 7 bar) and low cutting speed and low feed (with 7 bar). The reduction of temperature is about 8 %. Using Lee model also the high cutting speed and high feed condition is good.

Then the cutting force and feed force have been considered. As the Figure 7 shows, the cutting forces component is quite constant with the air-jet application. The feed rate changes with the air-jet, but is not very remarkable. In general the Lee model is more strength than the default material.

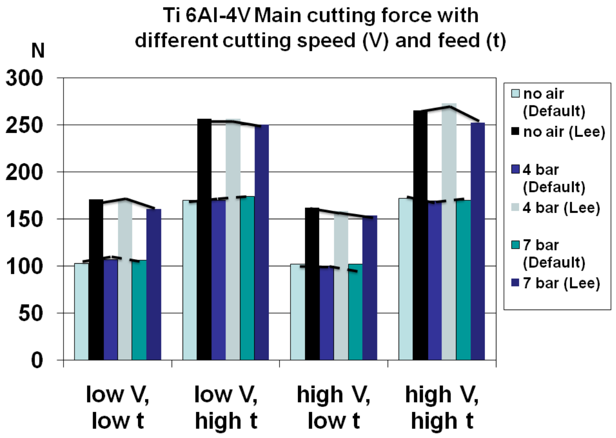

Figure 7: Simulation results for cutting forces in turning Ti6Al4V using interface air-jet.

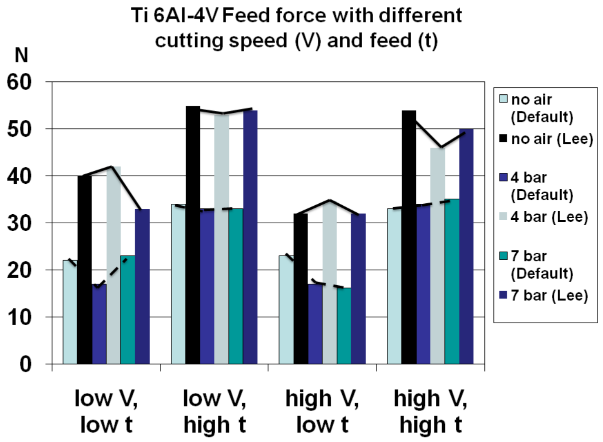

Figure 8: Simulation results for feed forces in turning Ti6Al4V using interface air-jet.

Other simulation are carried out using overhead air jet. The temperature results are shown in Figure 9.

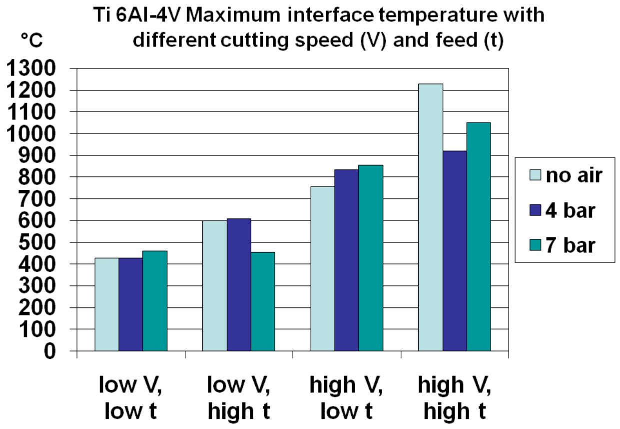

Figure 9: Simulation results for maximum temperatures in turning Ti6Al4V using overhead air-jet.

In this case only the high feed rate condition is good. The reduction is about 30 %. The reason is the incremented exposed area.
The cutting forces remain constant with the application of the air (Figure 10).

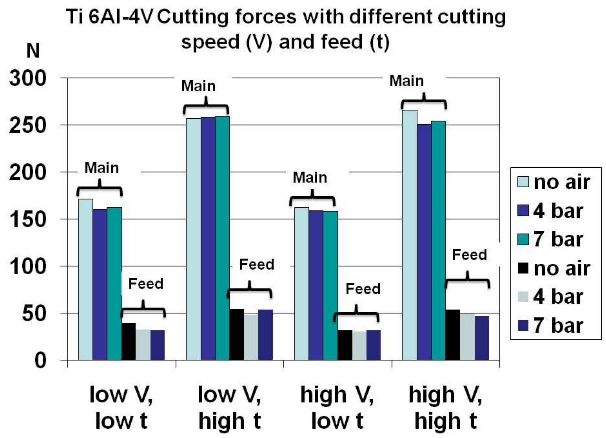

Figure 10: Simulation results for cutting force in turning Ti6Al4V using overhead air-jet.

2.3 3D model results for Ti 6Al-4V

A 3D model for preliminary Ti 6Al-4V machining investigation has been carried out the basis of the model developed for low carbon steel. Pressure configuration has been setup following the scheme in Figure 1. The cutting parameters used in 3D simulation are cutting speed *V*=280 *m/min* and feed rate *t*=0.06 mm/rev, corresponding at high speed and low feed rate in 2D simulation.

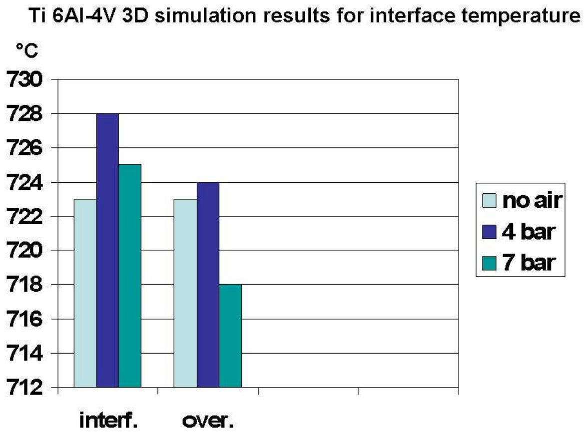

Figure 10: 3D Simulation results for temperature of Ti 6Al-4V

Results from 3D simulation show a reduction consistent with the prediction carried out with the analytical model, and also conceptually consistent with the work carried out for low carbon steel. However, the temperature reduction obtained in machining titanium alloy is much smaller than the effect on low carbon steel.

THEORETICAL MODELLING

3.1 Theoretical model concept

In this work a theoretical model has been used to explain the mechanism of the air-jet application during titanium Ti6Al4V machining following Bareggi [6].
Research carried out on low carbon steel, suggest the hypothesis that pressure on the top face of the chip generates a beneficial state of stress close to the constraint. This stress, algebraically added to the stress due to cutting pressure on the rake face, reduces the global stress on the rake face.
In this analysis the main components of cutting energy are 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 the 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:

$$u = K_n$$
$$u_f = \tau\gamma$$
$$\tau = (K_n cos\varphi - K_f sin\varphi)sin\varphi \qquad (1)$$
$$\gamma = \frac{\cos a \cdot \cos(\varphi - a)}{sin\varphi}$$
$$u_s = u - u_f$$

Where *a* is the rake angle.
K_n and K_f are obtained from previous FEM simulation results. Infact:

$$\begin{cases} F_t = K_n \cdot b \cdot t \cdot cosa + K_f \cdot b \cdot t \cdot sina \\ F_r = K_f \cdot b \cdot t \cdot cosa - K_n \cdot b \cdot t \cdot sina \end{cases} \qquad (2)$$

a=0, then $K_n = F_t / b \cdot t$ and $K_f = F_r / b \cdot t$.
Unlike Bareggi [6] the parallel-sided shear zone theory introduced by Oxley [10] is used to calculate the shear angle. The hypothesis is to consider only the mechanical effect of the air-jet on the top side of the chip.

This energy per unit of volume reduces the amount of heat generated by friction. Infact:

$$u_f = u - u_{s-air}$$
$$u_{s-air} = (\tau_s + \sigma_{air}) \cdot \gamma / 2 \qquad (3)$$

Where τ_s is the shear stress on the shear plane.
In summary the procedure is this:

1. Estimate of mean friction angle (β); in this analysis is considered constant.
2. From Oxley's [10] theory:

$$\begin{cases} F_t = \tau_s[cos\varphi - s \cdot sin\varphi]\dfrac{h}{sen\varphi}\, b \\ F_r = \tau_s[sin\varphi + s \cdot cos\varphi]\dfrac{h}{sen\varphi}\, b \end{cases} \quad (4)$$

Where $s = \dfrac{\left[\left[1+2\left(\frac{\pi}{4}-\varphi\right)\right]+\frac{cos2(\varphi-\gamma)}{tan\beta}-sin2(\varphi-\gamma)\right]}{2}$ (5)

3. Solve the linear equations system (2) and (4) with two unknown variables (τ_s and φ).
4. Use the thermal model (Bareggi [6]) to obtain the interface temperature.

3.2 Analytical model results

The results are presented in term of advantage respect the without air condition. This is

% = $(T_{without\,air} - T_{air})/T_{without\,air} \cdot 100$

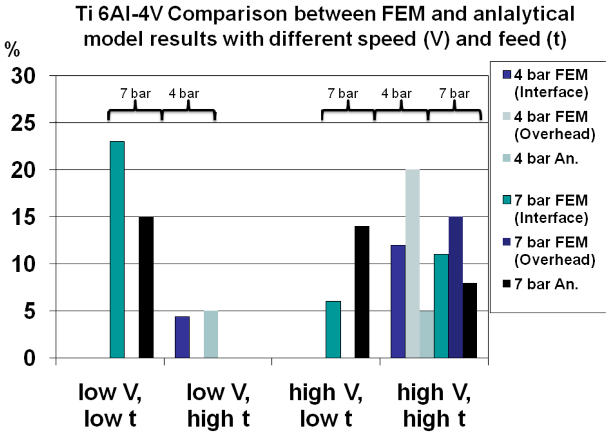

Figure 11: Comparison between analytical and FEM models results in terms of percentage advantage.

The results show that for 4 bar air-jet the analytical model overestimates the advantage, and in 7 bar the underestimates. Anyway the model explains the mechanism of air-jet.

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 and 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 is given by results from the 2D simulations. The hypothesis the analytical model is based on, is consistent with finite elements results. In particular, the solution seems to be sensitive to feed. This can be explained recognising that the mechanical effect is linearly dependant on chip's area (product of feed rate and depth of cut).

CONCLUSIONS AND FURTHER RESEARCH

This work provides fundamental guidelines to design an air-jet system in machining. A better comprehension of the mechanism of air-jet about cutting process is useful for optimal design the cutting tool geometry and choice the best cutting parameters. Experimental analysis has been carried out on steel AISI 1020 suggest the feasibility of high speed air jet cooling for low carbon steel; experimental studies on Ti 6Al-4V are currently under development. The simulation about air-jet assisted of Ti6Al4V machining shows that:

- The mechanical effect of air jet in overhead position offers a good chance of reducing temperature in low carbon steel machining, but the high stiffness of titanium alloy reduce the mechanical effect.
- The material model influences the results. Then it is very important model the right behavior of the material. Material model should be based on reliable experimental tests, since titanium alloys do not deform plastically easily, compared to steels, on account of their hexagonal crystal structure. There are fewer shear planes than in the cubic structures of steels, and this can lead to shear incompatibilities between individual grains.
- An analytical model with air-jet model has been developed. The trends shown by the model are consistent with the analysis carried out by finite elements. In particular, the dependence on feed rate agrees with the hypothesis of a mechanical effect when the jet is directed in overhead position. Predictions carried out with the analytical model can be improved by using an improved estimation of specific cutting energy.
- As demonstrated by experimental test on low carbon steel, 2D finite elements investigations are useful for understanding simple shearing phenomena and for optimal design. However, since cutting is essentially a 3D process, 3D are necessary to reproduce cutting operation. Preliminary 3D simulation has been carried out on titanium alloy turning operation.

Further research address a wide range of investigations. 2D and 3D simulation will be carried out by using different tool geometries and a segmented chip simulation will allow a correct reproduction of cutting process with titanium alloy. In fact, the limited effectiveness of air jet in titanium alloy could be explained with the high curling of the chip. The use of chipbreaker can be eventually used for optimal chip control. The overall effect of air jet should include also heat transfer. As demonstrated for low carbon steel [6], also according to O'Donovan [3] and Kops [4], the role of heat transfer for air jet is equally important as mechanical effect.

REFERENCES

[1] Klocke, F., Essel, I., 2004, Basics of HPC and Mechanical and Thermal Characteristics, Laboratory of Machine Tools and Production Engineering (WZL), RWTH Aachen, Germany, CIRP Conference 2004 (electronic resource).

[2] Hastings, W.F., Mathew, P., Oxley, P.L.B., 1980, A machining theory for predicting chip geometry, cutting forces etc. from work material properties and cutting conditions, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, vol. 371, No. 1747, pp. 569-587.

[3] O'Donovan, T., 2005, Fluid flow and heat transfer of an impinging air jet, Mechanical and Manufactoring Engineering, Trinity College Dublin, PhD thesis.

[4] Kops, L., Arenson, M., 1999, Convective heat transfer coefficients in turning, Proceedings of 15th Brazilian Congress of Mechanical Engineering.

[5] Weinert, K., 2004, Dry Machining and Minimum Quantity Lubrication (MQL), Institut für Spanende Fertigung, Universität Dortmund Dortmunt, Germany, CIRP Conference (electronic resource).

[6] Bareggi, A., Torrance, A., O'Donnell, G., 2008, Modelling and experimental analysis of high speed air jets used during metal cutting as a cooling technique, Proceedings of the 3th International Conference High Performance Cutting, Vol. 1, pp.337-346.

[7] Sales, W.F., Guimara, G., Machado, A.R., Ezugwu, E.O., 2002, Cooling ability of cutting fluids and measurement of the chip-tool interface temperatures - Industrial Lubrication and Tribology, vol. 54, n. 2, pp. 57–68.

[8] Kobayashi, S., Oh, S.K., Altan, T., 1989. Metal Forming and The Finite-Element Method. Oxford University Press, Inc.

[9] Lee, W.-S., Lin, C.-F., 1998, Plastic deformation and fracture behavior of Ti-6Al-4V alloy loaded with high strain rate under various temperatures. Materials Science & Engineering, Vol.A241, pp. 48-59.

[10] Oxley, P.L.B. Mechanics of Machining, An Analytical approach to Assessing Machinability. 1989, Halsted Press, New York.

[11] Leowen, E.G., Shaw, M.C., 1954, On the analysis of cutting tool temperatures, Transactions of ASME, vol.71, pp.217-231.

[12] Jaeger, J.C.; "Moving sources of heat and the temperatures of sliding contacts, 1942, Proceedings of Royal Society N.S.W., vol.76, pp.203-204.

[13] Shaw, M.C., 1984, Metal Cutting Principles, ISBN 0-19-859020-2Oxley