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Green Cutting using Supersonic Air Jets as Coolant and Lubricant during Turning

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Abstract. Advanced materials such as aero-engine alloys and hardened steels provide serious challenges for cutting tool materials due to the high temperatures and stresses generated during machining, consequently accelerating tool wear and increasing manufacturing cost. A change in environmental awareness and increasing cost pressures on industrial enterprises have led to a critical consideration of conventional cooling lubricants used in most machining processes. Extensive Minimum Quantity Lubricant (MQL) research has been carried out, but Minimum Quantity Cooling (MQC), such high pressure air jets, has until now, been seldom used, and therefore largely unexplored.

The focus of the research presented in this paper is to investigate the use of supersonic air jets as alternatives to mineral oil coolant, and examine the benefit on the cutting process from a thermodynamic and mechanical point of view. The potential benefits of this research are very important for many industrial machining processes as well. Initial results indicate the use of supersonic air jets leads to a reduced temperature in the cutting zone, reduced cutting forces and a modified chip shape.

Keywords: high performance cutting, aerospace alloys, MQCL, supersonic air jet

Introduction. As the temperature of a cutting tool may reach a high value, in particular when a heavy cut is taken at high speed, coolant is necessary to prevent thermal damage and tool wear. In machining fundamental studies on heat transfer are quite rare, most workers relying on empirical work. So, in most machining processes cooling is achieved using oil-based fluids. Oil is used for its high specific heat capacity and lubrication qualities. The cutting fluid, although reused several times, must eventually be replaced. During a recent CIRP conference about High Performance Cutting (HPC) in 2004, a number of presentations were based on Minimum Quantity Lubrication (MQL) and dry cutting [1], indicating both the active research and industrial interest in green cutting. The motivations for using air jets are not only environmental and economic considerations, but this approach also has technological benefits. In contrast to minimum quantity lubrication (MQL), minimum quantity cooling (MQC) has until now, been seldom used, and therefore remains a largely unexplored component of the MQCL technique among industrial users. However, the minimum quantity cooling technique can make a major contribution to the solution of thermal problems affecting the tool and/or the part in dry machining operations [2]. These techniques include high pressure air jets, water vapour [3] and chilled air [4]. Current research shows impinging gas jets have a much greater potential for cooling than previously suspected. By using a supersonic nozzle, it has been possible to obtain benefits in machining comparable with conventional liquid coolants. The purpose of this research is to investigate the use of supersonic air jets in turning. Gas jets can be used in many situations where liquid cannot. Furthermore there are environmental and safety benefits, as liquid coolants are traditionally mineral oil based, and they represent a hazard to the environment and are toxic for the operator. The feasibility of using supersonic air jets as a suitable alternative to liquid coolant on a lathe has been investigated. Cutting forces, chip shape and workpiece temperature have been predicted by 3D finite element model using the commercial software Deform-3D™.

Experimental setup. A supersonic nozzle has been designed to direct the air jet on the chip formed by a Tungsten Carbide (WC) tool turning a steel workpiece (AISI 1020) in a lathe. The following cutting condition and references were used:

- Cutting speed: 270 m/min
- Depth of cut: 0.5 mm
- Feed: 0.095 mm/rev
- Insert nose radius: 0.4 mm
- Rake angle: 5°
- Air jet pressure (nozzle inlet): 6 bar
- Insert material: WC
- Workpiece material: AISI 1020 steel

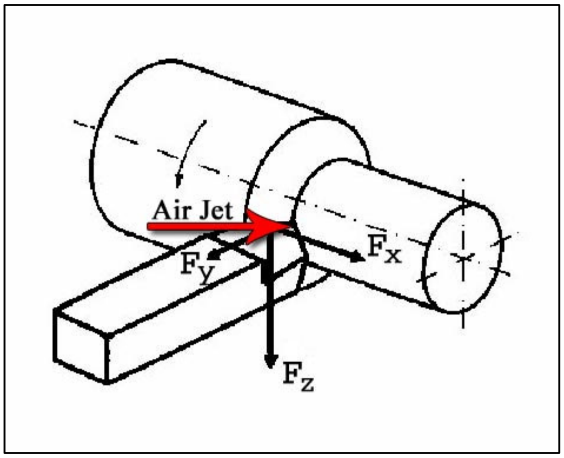

Fig. 1 – Reference System

Fig. 2 is a view of the nozzle placed on the tool. A nozzle holder has been designed to provide a range of positions for directing the air jet at the tool workpiece interface. The cutting forces on the tool have been monitored with a 3-component Kistler toolpost dynamometer. A Hommel surface roughness tester has been used for roughness test. A Finite Element Model has been developed using the commercial software Deform-3D™ and Comsol FEMLAB™.

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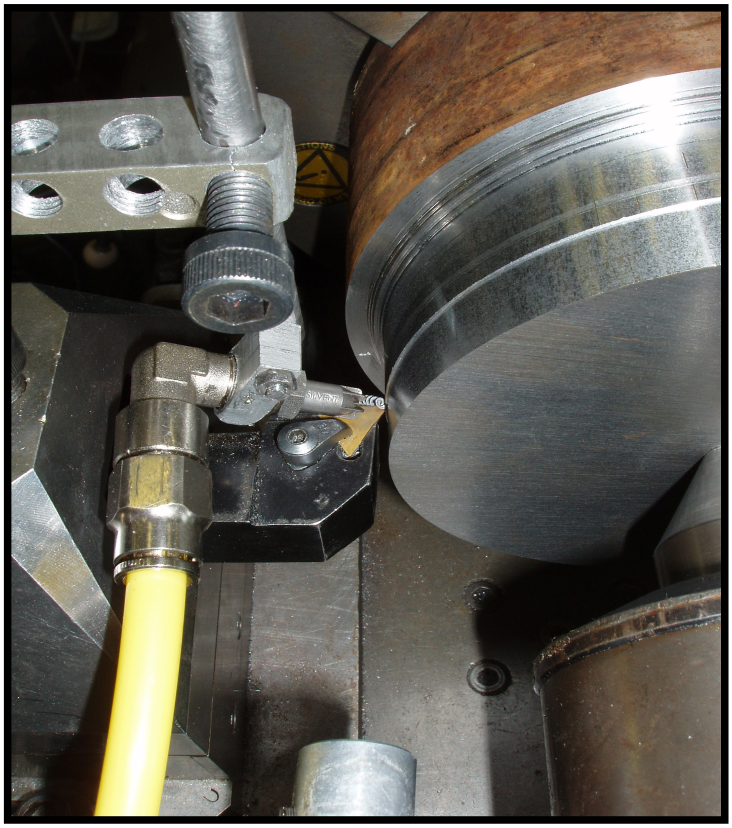

Fig. 2 – Supersonic nozzle placed in the cutting area

FEM prediction. The commercial FE software Deform-3D™ has been used to simulate the machining process. The power of this software is the Arbitrary Lagrangian-Eulerian (ALE) formulation and the ability to perform frequent automatic remeshing. The FE model was used to predict chip shape and workpiece temperature in an incremental analysis (Fig. 3). The figure shows a chip temperature up to 700°C in the shear zone, the model results were found to be in agreement with the work of Sales and Guimara [5]. The results from the FE model have been validated by the experimental investigations (see Fig. 6).

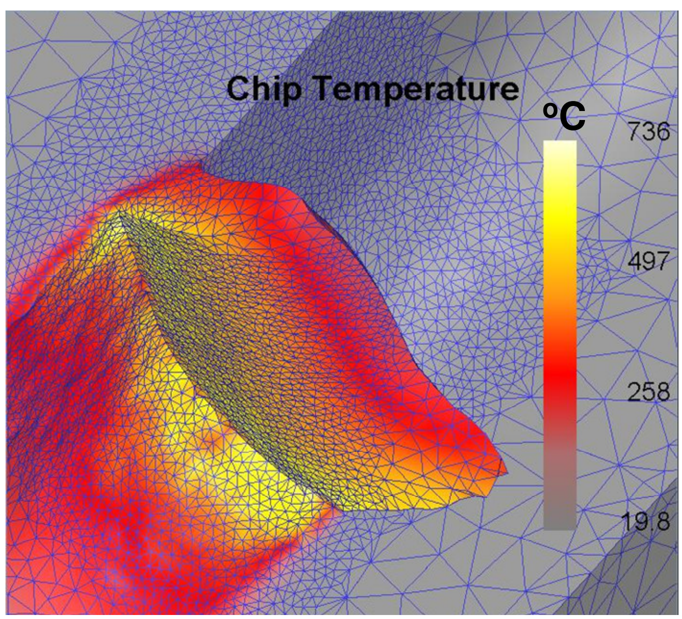

Fig. 3 – Workpiece temperature simulated by Deform

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Since Deform-3D™ does not model heat transfer to the tool very well, the commercial FE software Femlab has been used to investigate the gradient of temperature in the insert, considering in particular the chip-tool interface area (Fig. 4).

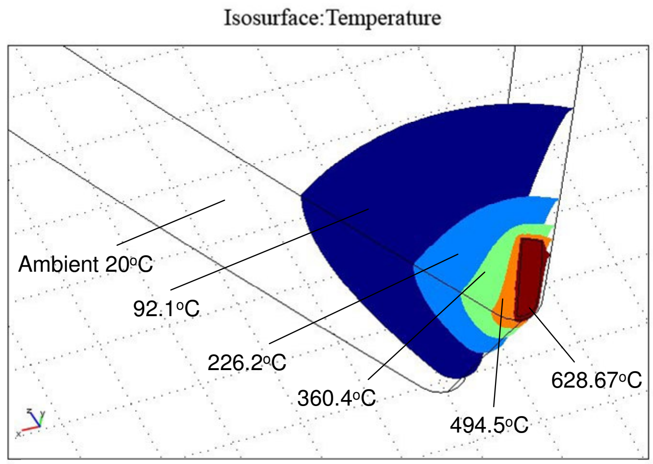

Fig. 4 – Temperature gradient inside WC insert

The model uses the frictional power on the rake face calculated from the Deform-3D™ model as an input, and partitions it between the tool and the chip by assuming that the average temperature of the contact area of both is the same. The results of this simulation show that the temperature falls from a maximum value of 628 °C to 226 °C within a distance of 2.7 mm. This analysis provides support in choosing the most appropriate temperature measurement system for measuring tool temperatures during the experimental investigations.

Preliminary experimental investigations.

The temperature of the cutting tool has been monitored by an infrared camera. Fig. 5 shows the effect of supersonic jet during machining. Two cutting conditions have been considered: with air jet cooling (on the left side), and without air jet cooling (on the right side). Since the resolution of the infrared camera is poor, relative to the chip-tool interface area, this visualization provides only an average value of the temperature, but also shows the ability of the air jet to cool the cutting area.

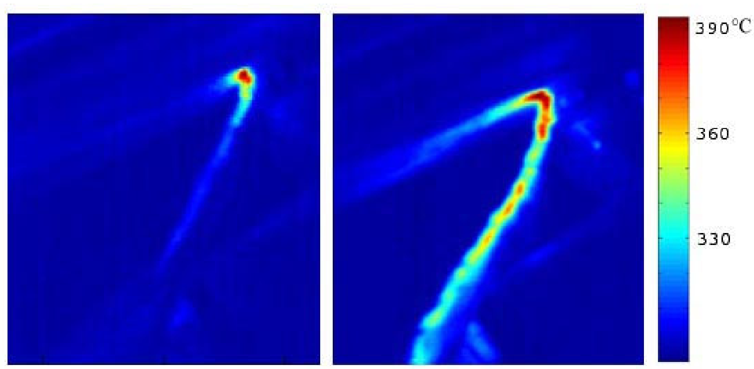

Fig. 5 – Temperature around cutting area with and without air jet

To estimate the benefits of the air jet on finishing, the roughness has been measured with a Hommel surface roughness tester. The results indicate a modest improvement in surface finish with the air jet:

$R_a = 0.76$ μm with air jet

$R_a = 0.84$ μm without air jet

The cutting forces on the tool have been monitored with a 3-component Kistler toolpost dynamometer and are shown in Fig. 6. The results clearly show a step change in cutting force when air jet cooling is used. The cutting force (Z-axis) predicted by the FE model has been compared to the experimental results and the results validate the model developed with Deform-3D.

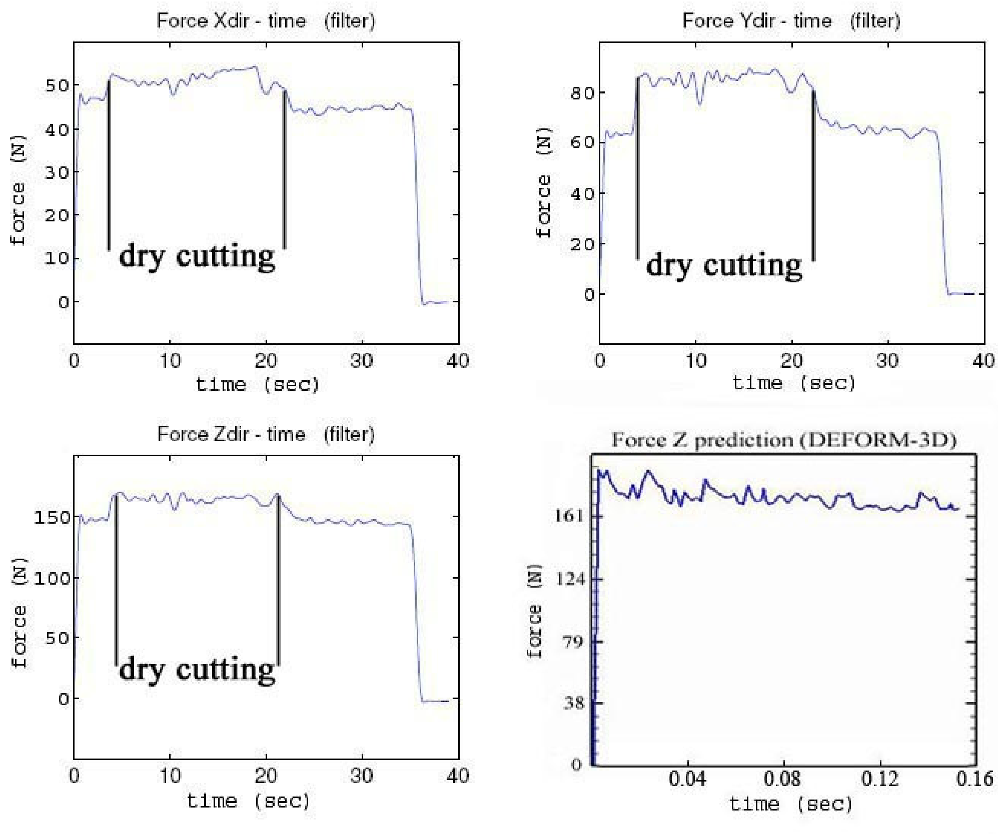

Fig. 6 – Effect of air jet on cutting forces

Present research. Current efforts focus on thermal analysis of the chip-tool interface. Considering the results of FEM carried out with Femlab and Deform, different types of temperature measuring devices are under consideration:

- Spot radiometer, pointing the lens as close as possible to the chip-tool interface
- Standard thermocouple placed inside the insert, drilled using spark-erosive method
- Non-Standard thermocouple using insert and workpiece material

Improvements in the Deform finite element model are also under development: a pressure is applied on chip back face in order to simulate the effect of the air jet and investigating the mechanical effect of the jet on chip shape, since the bending moment should change the shear plane angle, with significant savings in the power required for cutting.

Conclusions and further research. The initial results from the simulations and the experimental investigations undertaken are encouraging. The finite element model predicts measured forces well, and gives a good indication of the temperatures recorded by thermography. Significant benefits in terms of finish and forces have already been developed, but there are several questions still to be answered. Further work is needed to investigate how the ability of air jet to penetrate the chip-tool interface relates to the temperature of the tip of the tool. Quick stop tests are needed to investigate chip shape changes when the supersonic air jet is used; and to optimize the effect of the air jet, a fluid-dynamic FE model will be developed with Femlab. Once these preliminaries are complete, the process will be applied to aero-engine alloys to check the cooling ability of supersonic air jets when machining difficult to cut materials.

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