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MODELLING THERMAL EFFECTS IN MACHINING BY FINITE ELEMENT METHODS

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ABSTRACT

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. Extensive minimum quantity lubricant (MQL) research has been carried out, but minimum quantity cooling (MQC), such as the use of high pressure air jets, has been seldom used, and therefore largely unexplored. By using a supersonic nozzle, it has been possible to obtain benefits in machining comparable with conventional liquid coolants. In this research project a supersonic nozzle has been used to generate a high velocity air jet 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 friction on the tool-chip interface. Chip shape, insert and workpiece temperature have been predicted by 3D finite element modelling using the commercial software DEFORM. The models also demonstrate the ability of the air jet to bend the chip, leading to better access to the tool-chip interface. Changes in chip shape and temperatures when using high velocity air jets are significant and show potential for environmentally efficient machining.

KEYWORDS: Machining, Cooling, Finite Element Modelling

1. INTRODUCTION

The temperature of a cutting tool may reach a high value, up to 700°C, in particular when a heavy cut is taken at high speed; coolant is necessary to prevent thermal damage and tool wear. 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 CIRP conference about High Performance Cutting in 2004, a number of presentations were based on minimum quantity lubrication (MQL) and dry cutting [1, 2], indicating both the active research and industrial interest in environmentally efficient machining. This research work focuses on the modelling of thermal effects in machining using finite element modelling. Previous experimental work demonstrated that when using a supersonic nozzle, it was possible to obtain benefits in machining comparable with conventional liquid coolants [3]. In the current work, cutting forces, chip shape, insert and workpiece temperatures have been predicted by 3D finite element modelling using the commercial software DEFORM. Successful modelling of metal cutting is essential to develop optimal cutting processes. In performing any finite element study of metal cutting, one is faced with a large number of input parameters. These include the material model, which must include large deformations, high strain rates and high temperature effects, the tool-chip friction model, which may be temperature, sliding speed and pressure dependent and the separation criterion.

Since temperature plays a key role in tool wear, cutting forces and chip segmentation, there is a great deal of research on predicting temperatures in metal cutting [4-6].

2. FINITE ELEMENTS COMMERCIAL PACKAGES IN METAL CUTTING

The choice of finite element software for machining analysis is an important factor in determining the quality and scope of analysis that can be performed. Some of the most popular finite element software packages for metal cutting simulation are DEFORM, ADVANTEDGE and ABAQUS. Gardner et al [7] made a qualitative comparison of a number of finite element software packages that can be used for the modelling of machining processes. Some of the issues are highlighted and discussed below.

ABAQUS

- Manual design of workpiece and tool, mesh refinement and boundary condition have to be set manually
- No material library, but materials can be defined in detail
- Partial support in adaptive remeshing
- Good control of the solver

This is a general purpose finite element package, not specifically designed for metal cutting. The learning curve is steep and the complexity of the package means that there is often a significant time investment before a useful model is realised.

ADVANTEDGE

- Very efficient interface to rapidly configure a model, tool library are provided
- Extensive material library
- Uses adaptive remeshing, but controls can not be modified
- Not suitable for customising control functions

This is a package designed specifically for machining, but offers poor control of the solver and poor flexibility in applying unconventional boundary conditions. This software facilitates rapid setup of the model and the libraries are extensive. These features make ADVANTEDGE a powerful tool for industry, but the limited flexibility make it less suitable for research purposes.

DEFORM 3D

- Built in “wizard” for machining
- Good material library and comprehensive material editor
- Uses adaptive remeshing, good control of meshing parameters
- The user can chose the solver and minimal control is permitted

This software allows a simulation model to be setup in a reasonable amount of time, and the boundary conditions are flexible enough to model the effect of various cutting conditions.

3. PROBLEM FORMULATION

In finite element modelling, there are two types of analysis to describe a continuous medium: Eulerian and Lagrangian. In a Lagrangian analysis, the computational grid deforms with the material. In Eulerian analysis the grid is fixed in space. The Lagrangian calculation embeds a computational mesh in the material domain and solves for the position of the mesh at discrete points in time. Most of the metal cutting modelling software use a Lagrangian formulation. In this study, a commercial finite element software DEFORM 3D, which has an incremental Lagrangian formulation with an implicit integration method designed for large deformation simulations, is used to simulate the cutting process. The solver used was the sparse matrix with a direct integration method, because the conjugate-gradient offers an improved computational speed but less stability in convergence. The following cutting conditions where used:

- cutting speed: 270m/min
- feed: 0.06mm/rev
- depth of cut: 0.5mm
- insert configuration: rake angle = 0°, nose radius = 0.2mm, chipbreaker

An AISI 1020 steel workpiece (1.5mm of length) was modelled. The short material length was chosen to save computational time without compromising the model integrity as heat generation in machining is confined in small areas around the cutting zone [6]. As no significant deformation takes place in the tungsten carbide (WC) insert, friction and conduction are the causes of temperature rise. In order to get the correct value of steady state temperature in the insert, a lower heat capacity value has been used. When approaching the steady state the importance of heat capacity decreases to zero. The insert can be considered rigid and the only properties needed for modelling are:

- tool thermal conductivity (k_t): 84 W/m/K
- heat capacity (c_t): 1.2 (this was used in the model, the actual value is 180.7) J/kg/K
- density (ρ_t): 15800 kg/m³

The workpiece was modelled as a plastic material, and the workpiece properties are shown below. The thermal conductivity, heat capacity and thermal expansion are linearly changing with temperature (in the range of temperature (20–800 °C):

- workpiece thermal conductivity (k_w): from 51.9 (at 20 °C) to 33 (at 700 °C) W/m/K
- heat capacity (c_w): from 486 (at 20 °C) to 874.4 (at 700 °C) J/kg/K
- density (ρ_w): 8030 kg/m³
- thermal expansion: from 1.19e-5 (at 20 °C) to 1.49e-5 (at 700 °C)
- Poisson's ratio: 0.3
- Young's modulus (E): from 210,000 (at 20 °C) to130,000 (at 900 °C) MPa

DEFORM 3D uses the Oxley's equation to express the flow stress relation $\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T)$ linking the flow stress to the strain, strain rate and temperature, where $\bar{\sigma}$ is the flow stress, $\bar{\varepsilon}$ is the strain, $\dot{\bar{\varepsilon}}$ is the strain rate and T is temperature.

3.1 Geometry and mesh

Insert geometry was transferred directly from the Pro-E CAD system using STL neutral format files. For computational efficiency a small section of the workpiece (1.5mm x 0.5mm x 0.6mm) was modelled. The workpiece shape is constructed by the DEFORM machining module, and includes geometry created by a previous cutter pass, including appropriate depth of cut and nose radius details. An unstructured tetrahedral finite element mesh was generated using DEFORM's automatic mesh generation system. Remeshing parameters, including minimum element size, and parameters for adaptive mesh definition are set within the system. For these simulations, a minimum element size of 0.01125mm was specified. The adaptive remeshing system uses the minimum element size in the interface area and substantially larger elements in the surrounding area. The total number of elements was approximately 130,000. An unstructured tetrahedral mesh was also used on the cutting insert for thermal calculations.

3.2 Boundary conditions

Two different position of the high speed air jet were modelled: interface and overhead. Thermal boundary conditions were applied, in relation to air jet positioning. Figure 1 shows the two different position of the nozzle. Three different thermal boundary conditions consistent with natural air convection and forced convection were used on the top surfaces of the workpiece and rake face of the cutting insert. The lower face of the insert and the bottom of the workpiece were set to 20°C (the temperature of the surrounding environment). Two heat transfer coefficient (h) were used, as representative of the maximum that may be achieved with air according to the research work undertaken by O'Donovan [8]: h_{nc} = 20 W/m²/K with natural convection, h_{fc} = 2000 W/m²/K with forced convection. Three different simulation models were developed with the appropriate boundary conditions applied.

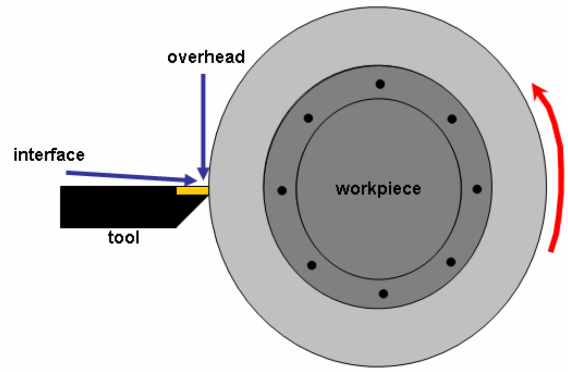

Figure 1: Nozzle position during turning

- Natural convection: h_{nc} = 20 W/m²/K
- Forced convection, interface elements: h_{fc_int} = 2000 W/m²/K
- Forced convection, overhead elements: h_{fc_ohd} = 2000 W/m²/K

Colour	Yellow	Green
h	20 W/m²/K	2000 W/m²/K

Table 1: Convective boundary conditions represented as colour, illustrated in Figure 2

Figures 2a and 2b show the elements of the mesh affected by interface and overhead boundary conditions: elements marked in green are affected by forced convection. The arrows show the nozzle directions. In the interface boundary condition the jet is impinging with a shallow angle on the rake face of the insert and the small region between the bottom face of the chip and the rake face is mainly affected by the heat transfer. In the overhead boundary condition the air jet is directed on the top side of the chip. The chip has a screening effect on the rake face.

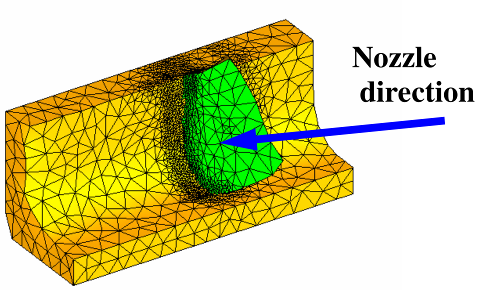

Figure 2a: Interface boundary condition

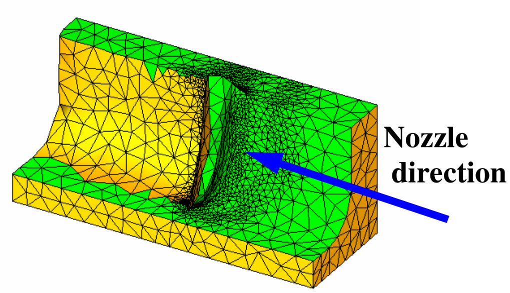

Figure 2b: Overhead boundary condition

4. RESULTS

Figure 3 shows the maximum workpiece temperature in dry cutting (737°C) and the arrow indicates the centre of the upper chip face, where the chip temperature has been measured (416°C in dry cutting). The workpiece temperature reaches a steady state value after few simulation steps, as deformation (and not heat transfer) is responsible for the temperature increase. After 1.1mm of continuous cutting, the tool temperature reaches the steady state value, and the temperature gradient inside the insert is fully developed after 1.5mm of cutting.

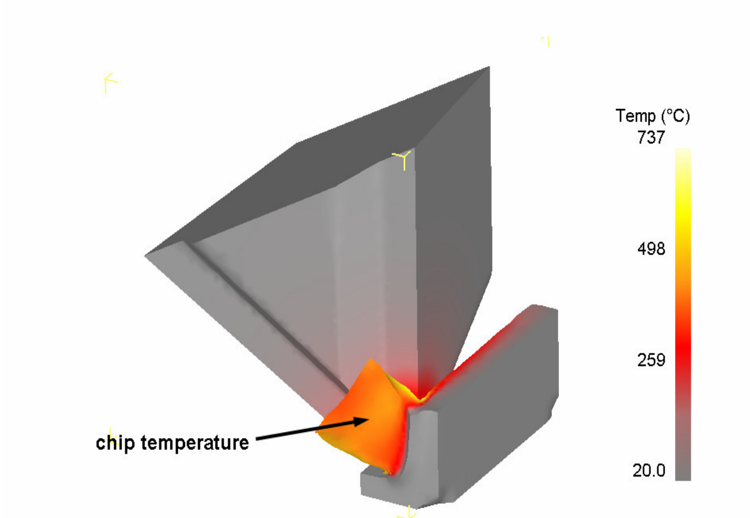

Figure 3: Finite element model showing chip temperature with maximum temperature area identified

The finite element model in Figure 4 shows the gradient of the temperature at the point of maximum temperature. The gradient is significant indicating a temperature reduction from 710°C to 50°C in approximately 1mm.

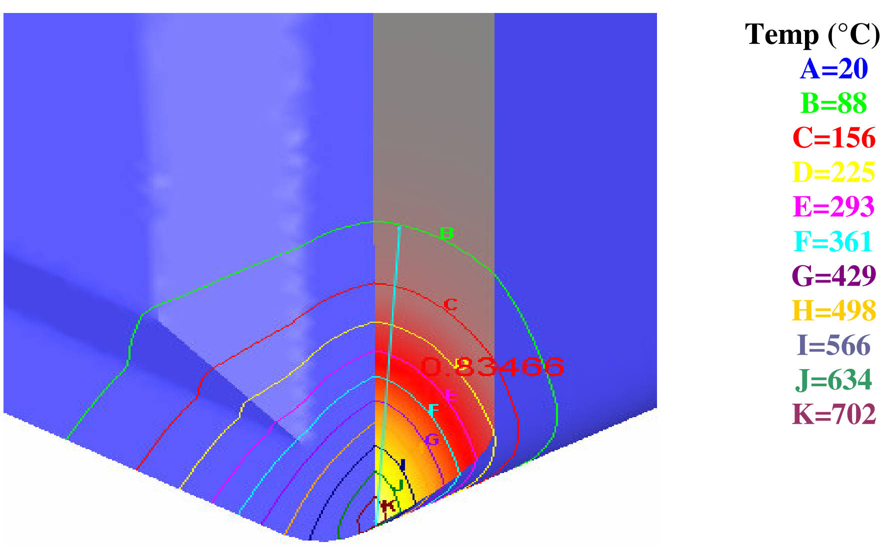

Figure 4: Finite element model showing temperature gradient within the insert

Simulation results are shown in the following table for three different cutting/cooling conditions; dry cutting, overhead air jet application and interface air jet application.

feed=0.06mm/rev depth=0.5mm speed=270m/min	**Max workpiece temp. (°C)**	**Interface temperature (°C)**	**Chip temperature (°C)**	**Cutting force (N)**
Dry cutting	737	710	416	93
Air jet cooling, overhead	721	627	389	92
Air jet cooling, interface	727	648	408	95

Table 2: Tool workpiece temperatures for various cooling conditions

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. This aspect is to be further investigated in future work.

5. CONCLUSIONS

Finite element analysis offers the potential for significant cost savings, providing process insight in cooling and lubricating methods in metal cutting that are no straightforward to realise with experimental or analytical work. Modelling 3D cutting using finite element techniques is an area of ongoing research activity. In particular heat transfer and the modelling of cooling techniques requires careful consideration in any modelling activity. This paper presents approaches for modelling the cooling influence of high velocity air jets with the commercial package DEFORM 3D. Simulation results are consistent with the analytical results from other researchers [6]. Cutting temperatures estimated with DEFORM 3D are consistent with simulation undertaken with ADVANTEDGE [4]. While simulation offers insights into the process which are not easily measured in experiments, careful engineering scrutiny of approaches and results remains necessary.

5.1 Further research

Further research will include the refinement of the finite element model, the estimation of the heat transfer coefficients and improvements in the approach to the air jet modelling. Simulations with different workpiece materials and various cutting conditions are planned. Experimental validation of the finite element analysis work is ongoing.

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