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A new procedure to increase the orthogonal cutting machining time simulated

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Abstract

Surface integrity is extremely affected by manufacturing processes conditions especially the evolution of cutting tool performance. Many researchers, in steel machining field, focused their works on the elaboration of models predicting tool wear combining both numerical and experimental approaches.

Most of published numerical cutting models simulate the chip formation for a few micro to millisecond time periods. For that, all corresponding experimental tests, needed for the model validation, are usually carried-out in special time conditions which is not reflecting industrial situations. Indeed, the latters are characterized by tool wear whose evolution can affect extremely cutting force levels and the final workpiece integrity.

In this context, the main purpose of the proposed research work is to develop a FEM model, based on the commercial code ABAQUS©, to simulate wear phenomenon of tool insert in the case of orthogonal cutting operation. The present research exposes a lagrangian approach simulating the chip formation in the case of AISI 4140 machining. A strategy that aims to reach high machining time simulated with moderate computational time is presented. It is based on ensuring the thermal continuity of the tool from one calculation to another. A considerable gain of calculation time is achieved comparing to the most common models developed on ABAQUS©.

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1. Introduction

Studying tool wear is crucial for designing more performant tools, decreasing machining costs and improving manufactured products quality. For that, many researchers focused on elaborating models predicting tool wear in orthogonal cutting [1,2].

Most of published studies concerning tool wear prediction are based on experimental tests or empirical equations to estimate tool life as a function of cutting conditions. In this case, tool life is provided as a function of several cutting parameters [3,4,5].

More recently, researchers focused on elaborating numerical models to simulate tool wear in machining operations. These approaches resort generally to the Finite Element Method (FEM).

They are based essentially on implementing subroutines to estimate tool wear caused by a specific tool wear mechanism such as abrasion, diffusion and so on, by supposing that one of them is preponderant [6,7].

However, FEM-based softwares are limited in terms of simulated times. In fact, an orthogonal cutting simulation lasts, in most cases few milliseconds, which is not sufficient to reach steady state conditions. In addition, these short times simulated generate high computational times [8].

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Nevertheless, tool wear study requires the simulation of several minutes of machining which involves the use of sophisticated machines such as supercomputers with high processor performance. So, to reach high simulated times in machining operations without resorting to powerful machines with higher costs, researchers developed several methods on different software. Yen et al [9] used the "Konti-cut" module available on DEFORM 2D© which consists on eliminating chip and machined workpiece after a certain period of time. Although this method allows simulating six minutes of machining, it has the inconvenient that mechanical and thermal histories of the workpiece are lost.

Salvatore et al [10] proposed also a solution to increase the simulated time on ABAQUS©. It is based on partitioning the chip since it can be considered uninteresting for his study that focuses on tool wear estimation. The simulation is made on a workpiece length more important to reach high process simulated time. However, the model adopted has the inconvenient of not respecting the assumption made on the geometrical model. This assumption consists in considering that the surface to be machined is flat, which remains valid only for small lengths.

That's why, a new approach is presented in this paper to increase machining time simulated in orthogonal cutting. First of all, a Finite Element (FE) multi-part model will be presented based on the commercial code ABAQUS© following a lagrangian approach. It simulates chip formation in the case of AISI 4140 machining with a carbide tool.

Then, a strategy that aims to reach high machining time simulated with moderate computational time is presented. It is based on ensuring the thermal continuity of the tool from one calculation to another. Results will be compared with experimental data found in literature.

2. Numerical approach

2.1. Geometrical model

In order to optimize contact management during simulation, a multi-part model, inspired from MABROUKI proposal [11] is presented. It is composed from four parts (fig.1). PART **(1)** is the tool made by a tungsten carbide WC ISO-P20 insert. PART **(2)** is the region of the workpiece that may be removed as chip. The tool-tip passage zone, PART **(3),** is made of a damageable narrow band. It represents the area where the separation of the material occurs. And finally, PART **(4)** is the rest of the workpiece.

The mesh is made of CPE4RT elements to achieve temperature-displacement coupled simulations [12].

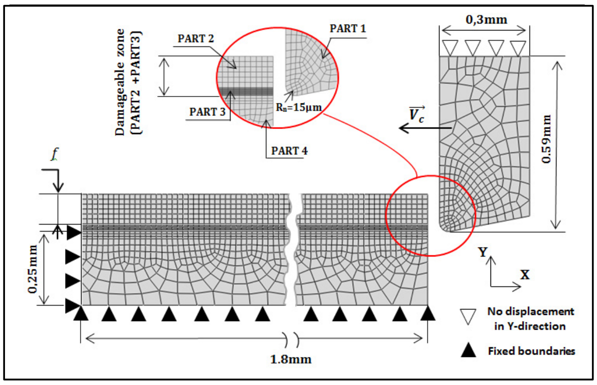

Fig. 1. Mesh and boundary conditions of the cutting model

2.2. Material behavior

To simulate chip formation, the Johnson-Cook [13] material constitutive law is adopted. Von Mises stress is given by the equation 1.

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n)\left[1 + Cln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_f - T_0}\right)^m\right] \quad (1)$$

For AISI 4140 steel, Johnson-Cook parameters are mentioned in the table 1 [14].

Table 1. Johnson-Cook parameters for AISI 4140

A (MPa)	B (MPa)	n	C	m
1098	1092	0.93	0.014	1.1

2.3. Decreasing computational time

To simulate tool wear, high simulation times (few minutes) need to be reached, which consumes high computational times. In fact, in machining simulations, computational time is divided mainly between calculating strains inside the material and managing contacts between surfaces. It depends also on the formulation adopted. The lagrangian approach adopted in this study is the one consuming the less computational time.

Inspired by previous works [9,10,11], a new approach called "vertical modelling" is proposed in this paper; to increase machining time simulated (Fig.2).

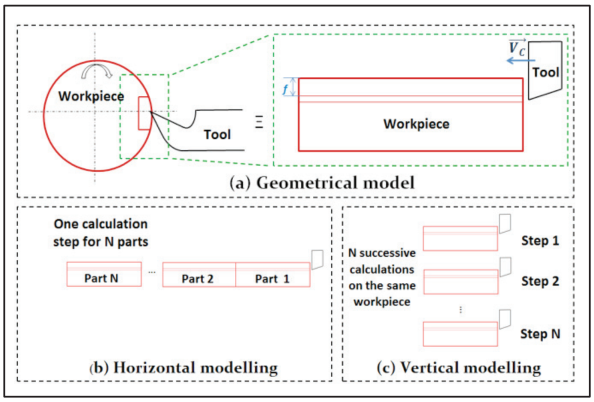

Fig. 2. Strategies of modelling to increase simulated time

In fact, many calculations are performed successively on a reduced length of the machined surface (1.8 mm). To insure the continuity from one calculation to another, the thermal state in the cutting tool is taken into account. For that, a procedure is set up and consists primarily on saving the thermal distribution in the cutting tool at the last increment of each calculation in the ODB file (result file). This distribution is then used as the initial temperature (at t=0 s) in the following calculation instead of having a constant temperature of 25 °C on the whole tool.

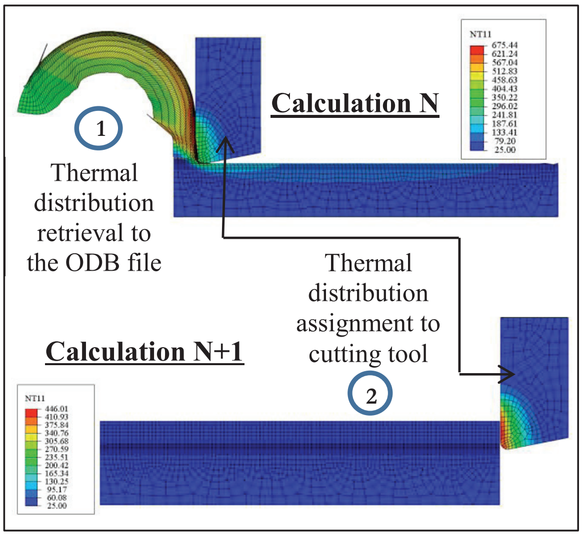

Fig. 3.Thermal loading on tool initially

This assumption can be made since the tool is considered elastic (Fig.3).

Table 2 shows the evolution of computational time as a function of the machined length when adopting the vertical approach or the horizontal approach. The cutting conditions are a cutting speed of 120 m/min, a feed rate of 0.1 mm/rev and a cutting depth of 3 mm.

Calculations were performed on a laptop having the following characteristics:

- Processor Intel® Core™ i5-4300M CPU @ 2.6 GHz
- 8 Go RAM.

Table 2. Evolution of computational time and simulated time as a function of machined length

Workpiece length (mm)	Computational time with horizontal modelling (min)	Computational time with vertical modelling (min)	Simulated time (ms)
1.8	15	15	0.85
3.6	91	30	1.7
5.4	234	45	2.55

It is noticed that the vertical modelling strategy allows reducing considerably computational times for the same machining simulation times. A python algorithm is developed to launch automatically successive calculations in order to reach a sufficient simulation time allowing the implementation of a tool wear law.

Fig. 4 shows the evolution of tool temperature as a function of time during six successive calculations.

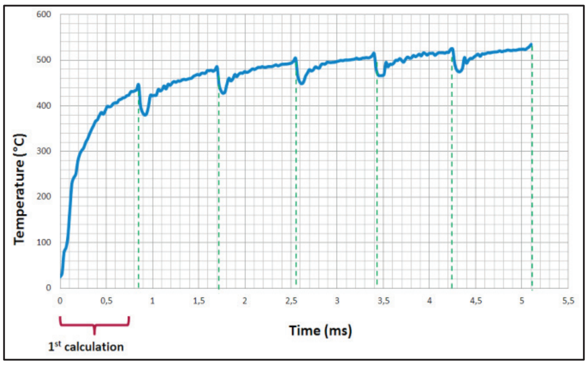

Fig. 4. Evolution of tool temperature in vertical modeling during 6 calculations

According to Fig. 4, it is noted that tool temperature is increasing continually which prevent from reaching steady state. So, it's recommended to modify the boundary conditions imposed on the tool taking into account the convection between the insert and the tool holder.

This convective condition will be applied, initially, by imposing a constant temperature equal to the ambient temperature on the tool borders that are in contact with the tool holder.

It's important also to study the impact of the initial temperature of the workpiece, equal to 25 °C, at the beginning of each new step on cutting tool temperature (Fig. 5).

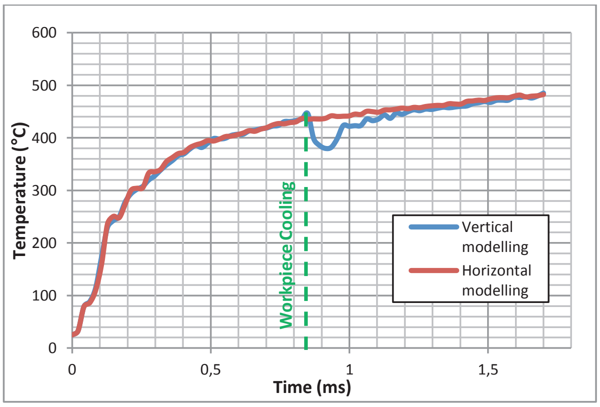

Fig. 5. Evolution of tool temperature in vertical and horizontal modeling

It is noted that initial temperature of 25 °C of workpiece creates a discontinuity in the evolution of tool temperature (Fig.5). Hence, it is important to take into account workpiece temperature at the last increment of computation following the same strategy adopted for the cutting tool.

After taking into account the thermal continuity in the workpiece and imposing a temperature equal to 25 °C to tool borders, many calculations are launched in order to reach 10 milliseconds of machining (Fig. 6).
It is noticed that the temperature begins to stabilize after about 8 ms (about 526 °C). However, thermal discontinuity remains when moving from one step (Fig. 2) to another in spite of getting less marked.

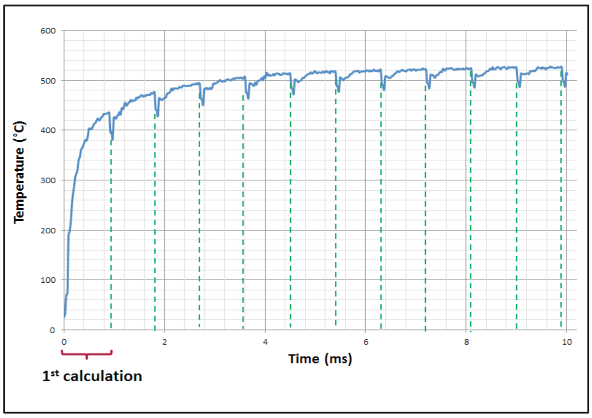

Fig. 6. Evolution of tool temperature in vertical modeling during 10 calculations after model improvement

2.4. Comparison between numerical and experimental results from literature

To ensure the validity of the model developed, in terms of temperature, numerical results are compared to experiments provided by Arrazola et al [15]. In fact, in his contribution, he provides the thermal fields of AISI 4140 machining with a tungsten carbide tool. For that, he had used a custom infrared microscope. Machining is performed on a high speed machining center with surface speeds up to 500 m/min and uncut chip thicknesses ranging from 0.1 mm to 0.3 mm.
In Fig.7, temperature measurements in the tool-chip-interface are provided. Cutting parameters are as following: V_c=100 m/min and ap=0.2 mm.

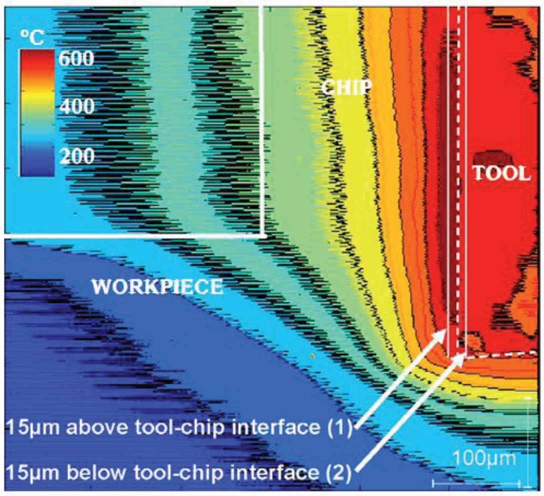

Fig. 7. Temperature measurements just above and below the tool–chip interface [15]

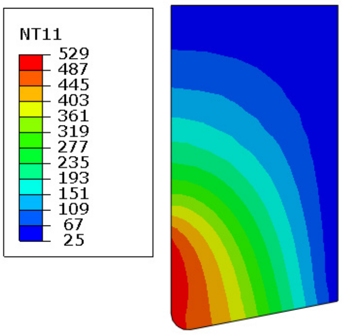

Fig. 8. Numerical temperature distribution in the tool in °C

It is noted that, the model developed in this study have coherent results in terms of thermal fields in the tool (Fig.8).

Conclusion

In this study, a FE model was developed in order to reach high simulated times in machining with moderate computational times in the case of orthogonal cutting.

An important step is achieved which is simulating a long machining time by creating a continuity in thermal distribution on the tool from one step to another.

Taking into account workpiece temperature is also important to afford a thermal continuity to the whole model.

Boundary conditions imposed have also been reviewed in order to reach steady state. Thermal results have been validated by experimental results from literature.

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