3D FEM Analysis of Cutting Processes

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Abstract: - This paper presents a modeling and simulation analysis with FEM for the following processes: turning, drilling and milling. The authors describe, first of all, the finite element method. Secondly, a comparison between the most important commercial software that uses FE method is made. The most important part of this paper represents the describing of FEM analysis steps: pre-processing, simulating and post-processing of data for the established machining processes. An analysis of the most important simulation results is made: cutting forces, stresses, chip formation, tool wear and temperature.

Key-Words: - FEM formulation, cutting, turning, drilling, milling, 3D modeling, simulation, data processing.

1 Introduction

Finite Element Analysis (FEA) is known since 1960-1970 and has been used to analyze forming processes and designing tools [1]. Finite Element Method (FEM) permits the prediction of cutting forces, stresses, tool wear, and temperatures of the cutting process so that the cutting tool can be designed. With this method the best cutting parameters are determined. FEM has some advantages such as [2]: it solves contact problems, bodies made from different materials are used, a curvilinear region can be approximated by means of finite elements or described precisely, etc. There are two types of finite element formulations to describe a continuous medium: Lagrangian and Eulerian.

The Lagrangian is widely used. In a Lagrangian analysis, mesh grid deforms with the material, while in Eulerian analysis the grid is fixed in space [3]. The Lagrangian analysis simulates the entry, exit, intermittent and discontinuous chip formation phases while the Eulerian cannot simulate the intermittent and discontinuous chip formation phases. However, Eulerian formulation eliminates the need for a chip parting criteria and avoids mesh distortion [4]. Lagrangian formulation was used by most of the researchers, except Strenkowski, Moon, and Athavale [5, 6] that prefer to use the Eulerian formulation.

The right choice of finite element software is very important in determining the scope and quality of the analysis that will be performed. The most important software codes used for simulation of metal cutting are: Abaqus, Deform and AdvantEdge (Table 1).

Applications of FEM models for machining can be divided in six groups: tool edge design, tool wear, tool coating, chip flow, burr formation plus residual stress and surface integrity [7].

This paper makes an overview of possibilities when using FEM. An incremental Lagrangian formulation is used to simulate the following cutting processes: turning, drilling and milling. The main objective of this research is to apply FEM, to study and describe the data obtained.

The FEM analysis consists of three steps: pre-processor, simulation and post-processor.

2 Setting the initial data for modeling and simulation and processes simulation

2.1 Process setup and conditions

Before modeling and simulation, the user should set the initial data, namely process parameters and conditions: cutting speed, depth of cut, feed rate, environment temperature, whether a coolant will be present or not and friction coefficient. These parameters will be described and set up in the first step, pre-processor.

This paper makes an overview of possibilities when using FEM. This method is used to simulate the following cutting processes: turning, drilling and milling. The process parameters and cutting conditions are described in Table 2.

Table 1. Comparison between Abaqus, AdvantEdge, and Deform [8]

	Advantages	Disadvantages
Abaqus	- high level of detail - manual design of workpiece and tool, free modeling - allows configure the material - very fine control of mesh	- has no support for any materials - it takes a lot of time to "setup" simulations as the user has to manually set many of the simulation parameters
AdvantEdge	- the solver is optimized for metal-cutting processes - simple tool and workpiece geometries, - allows import of complex geometries - extensive material library, - allows specifying new materials - uses adaptive meshing to increase the accuracy of solution	- gives the user less flexibility in configuring the controls of the solver, this means that the user is restricted to the preset controls of the software - the software also has no support for drilling operations
Deform	- set up of standard machining processes - adjusts solver parameters - extensive material library - capability of defining new materials - uses adaptive meshing controls	- some tool geometries need to be imported - the drilling module has a few deficiencies: the simulation solver runs very slow and stops periodically

When setting the process conditions, the user must choose the environment temperature, coolant with the convection coefficient, shear friction factor and heat transfer coefficient.

2.2 Tool and workpiece setup

For the tool setup the user has two possibilities. First, the user can choose the tool geometry from the software tool libraries. Second, if the tool geometry is complex, such as a drill or a milling insert, this can be imported from CAD systems. There should be: one surface, no free edges, no invalid edges and no invalid orientations.

Table 2. Process and condition setup

Process and condition parameters	Turning	Drilling	Milling
Cutting or rotational speed	250 mm/sec	400 rpm	75.36 m/min
Feed	0.35 mm/rev	0.15 mm/rev	2.4 mm/sec
Depth of cut	0.3mm	0.3mm	0.5mm
Shear friction coeff.	0.5	0.6	0.5
Interface heat transfer coeff.	45°C	40°C	45°C
Convection coeff.	0.02	0.02	0.02
Environment temperature	20°C	20°C	20°C

Table 3. Tool properties

Tool properties	Turning	Drilling	Milling
Diameter	-	6mm	80mm
Tip taper	-	1.5mm	-
Material	WC	WC	WC
Tool holder	Chosen from the toolholder library. In our case TNMA 332	-	-

Table 4. Workpiece properties

Workpiece parameters	Turning	Drilling	Milling
Geometry	Modeled as plastic	Round model	Modeled as plastic
Thickness	-	1.7mm	-
Length	7mm	-	20mm
Diameter	-	7mm	-
Material	AISI1045 (Steel)	AISI1045 (Steel)	AISI1045 (Steel)

For example, for modeling the milling process, an insert was designed in AutoCAD/Inventor (Sandvik milling head R365-080Q27-S15M).

Some tools, like those used in turning processes, need a toolholder. This can be created or loaded from the library. If the database does not contain the toolholder needed, the user should know some parameters in order to create a new one: side cutting angle, back rake angle, and side rake angle. The tool properties used in simulations are shown in Table 3.
The workpiece geometry can be also imported from CAD systems. The used software (Deform 3D) can design a variety of simple or curved geometries based on some workpiece properties, such as:

Table 5. Material properties

Plastic	Flow stress
	Creep
	Yield function type
	Hardening rule
Elastic	Young's modulus
	Poisson's ration
	Thermal expansion
Thermal	Conductivity
	Heat capacity
	Emissivity
Grain	Recrystalization model
Elec./Mag.	Electrical resistivity
	Relative magnetic permeability
	Relative magnetic permittivity

length, width, diameter, etc. Table 4 contains the workpiece properties for the turning, drilling and milling processes.

2.3 Boundary conditions

The boundary conditions help the user to establish the interaction of the workpiece with other objects present in simulation. The most used boundary conditions are: heat exchange with environment and velocity at contact between objects in the model, etc.

2.4 Tool and workpiece material

A material should be assigned for the tool and another one for the workpiece. The material can be loaded from the library, starting from aluminium, and beta materials up to steel and superalloys, even composites [16]. Most of the tools are made from carbide or WC. If the user needs a special material, the software gives the opportunity to create it. The user has to know some material properties. You can find a list of material properties in Table 5 [9].

2.5 Mesh generation

FEM uses Lagrangian or Eulerian meshing criteria. The Lagrangian mesh is reformulated at nearly every time step, in order to manage the material deformation. If a simulation crashes, for any reason, a new simulation can start where the other one stopped.

Tool and workpiece meshing are very important for an accurate process simulation. A finer mesh gives a finer accuracy. If the number of elements increases, time also increases.

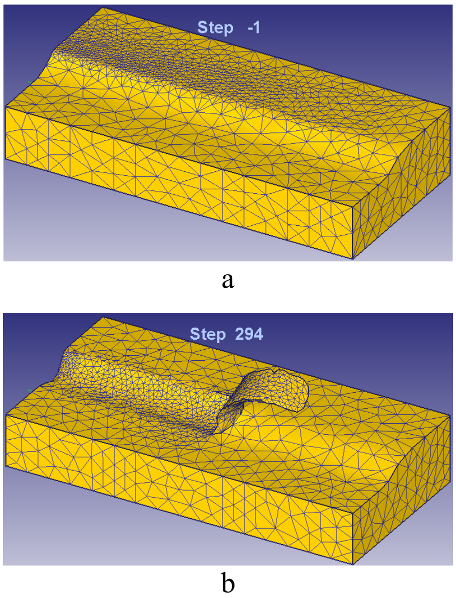


Fig. 1. Workpiece mesh for turning process: *a* - undeformed mesh; *b* - deformed mesh.

Meshing the workpiece is much more important. In general workpieces are modeled as plastic objects, they can be easily deformed and cut by tools. When the mesh deforms, it must be frequently regenerated. During the simulation, the mesh helps reconstruction the distorted material. The new meshes are generated based on user defined parameters to keep fine elements where they are needed for resolution.

Fig. 1 shows an example of undeformed and deformed workpiece meshes for the turning process.

2.6. Simulation controls and database generation

The end of the pre-processor step and also the beginning of the simulation step contain the simulation controls and database generation. The simulation controls (Table 6), namely the number of simulation steps, step increment to save, and tool wear calculation are the last pre-processing data that has to be set before running the simulation.

The tool wear can be also calculated. The structure and material properties influence the cutting forces (Fig. 2) and so the wear rate. Tool-chip interface means first of all cutting parameters, friction and coolants, these reducing tool wear and cutting temperature if they are properly set. The tool needs to be appropriate chosen for an operation subject for FEM modeling and simulation (turning, drilling, milling). The optimal performance of a tool means a correct combination between the cutting conditions and the tool properties.

Table 6. Simulation controls

Simulation co trols	Turning	Drilling	Milling
Nr. of steps	10 000	7 000	10 000
Steps to save / steps def.	25	5×10^{-4}	25
Secondary sto ping control	3.5mm	drill reaches 3.5mm	-

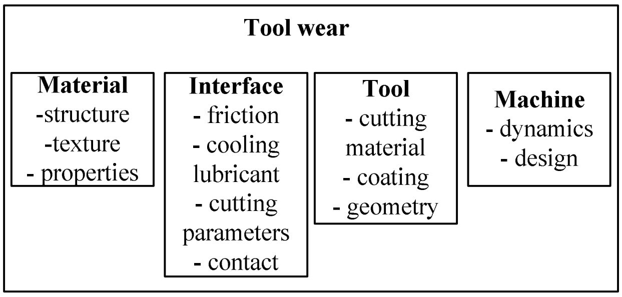


Fig. 2. Functional elements that influence tool wear in machining processes [11].

Table 7. Summary of selected empirical tool life models and tool wear rate models [12-15]

Empirical tool life models	Tool wear rate models
Taylor's basic equation: $VL^n = C_1$ Taylor's extended equation: $L = \frac{C_2}{V^p f^q d^r}$ Taylor's extended equation: $V = \frac{C_3}{L^m f^p d^q (BHN/200)^r}$ Temperature- based equation: $TL^n = C_4$	Takeyama & Murata's wear model (abrasive and diffusive wear): $dW/dt = G(V,f) + D\exp(-E/RT)$ Usui' s wear model (adhesive wear): $W = \int aPve^{-b/T}dt$ Archard's wear model: $W = \int K\frac{P^a * v^b}{H^c}dt$
L = tool life, P = interface pressure, σ_n = normal stress, *T* = cutting temperature, f = feed rate, *V* = cutting speed, *E* = process activation energy, V_s or v = sliding velocity, d = depth of cut, *R* = universal gas constant, H = hardness of tool material, *BHN* = workpiece hardness, *a*, b, c, K = experimentally calibrated coefficients, d*W* / d*t* = wear rate (volume loss per unit contact area per unit time)	

The machine dynamics and design are also important in cutting processes, because chatter or excessive tool wear can appear. The common used wear model is Usui's model, see Table 7.

The simulation data entered in the pre-processor has to be written as a database. This database is used in the following step.

2.7 Simulation

The simulation uses the database generated in the pre-processor. It initiates a series of operations and generates new meshes if necessary.

3 Processing data obtained from numerical simulation

The last step is the post-processor. In the post processor the user can check the simulation results. The data obtained from simulation are easy to be extracted from the database. The user can access all the steps that were saved during the simulation process.

The following information is available after the simulation:

A. Geometry of workpiece and tool after the simulation, tool movements and deformed mesh at each step saved, see Fig. 1.

B. Distribution of state variables: stress, strain, temperature, wear, damage etc, Fig. 3.

Interpreting state variables. Damage generally relates to fractures in a part and is not a good indicator of fracture in tooling. Stress components should be used for die failure analysis. The damage value at which fracture initiates varies substantially from material to material, and can even varies for a given material with different annealing treatments.

Strain is a measure of the degree of deformation in an object. Engineering strain is defined as:

$$\frac{\Delta l}{l}, \quad (1)$$

where Δl is the length change and l is the original length. This is a good approximation for small deformations, but loses accuracy when deformations become large.

For large deformation analysis, it is better to use true strain:

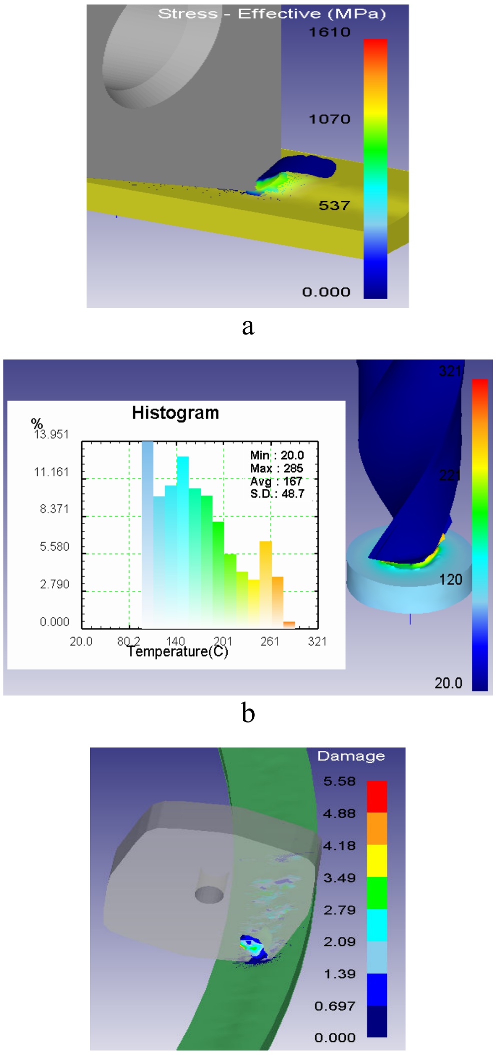
$$\varepsilon = \ln\frac{l_f}{l_0}, \quad (2)$$

where ε is the true strain, l_0 is the initial length and l_f is the final length. A change in volume relative to initial volume is stored as mean strain. The strain rate is a measure of the rate of deformation with respect to time.

The stress is defined as the force acting on a unit area of material. The effective stress $\bar{\sigma}$ is defined as:

$$\bar{\sigma} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}, \quad (3)$$

where σ_1, σ_2 and σ_3 are the principal stresses.



a

b

c

Fig. 3. State variables: *a* - effective stress in turning process; *c* - temperature in drilling process; *d* - damage in milling process.

The temperature plot displays nodal temperature at each step.

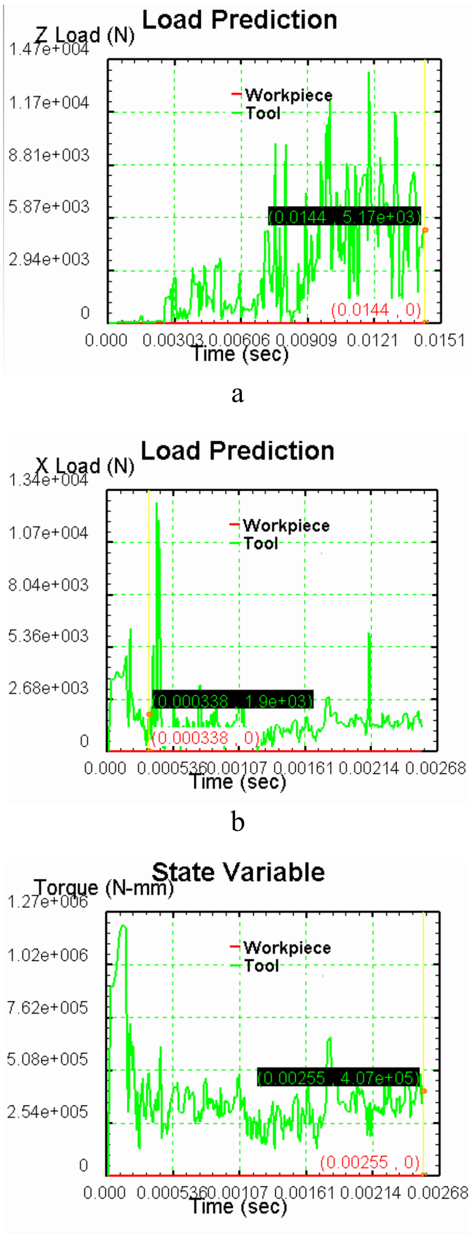
C. Displacement and velocity.

D. Graphs of load, volume, states variables between two points, etc;

E. Point tracking for showing the movement of the material;

F. Chip formation;

G. Predicted cutting forces and torque.



a

b

c

Fig. 4. Predicted cutting forces and torque: *a* - *Z* load in turning; *b* - mean *X* load in milling; *c* - torque in milling.

After simulation users can obtain cutting forces on the three directions *x*, *y* and *z* and torque around the *z* axis. Fig. 4 presents some examples of predicted cutting forces and torque.

4 Conclusions

This paper proposed an overview of the approach of FEM analysis of the machining process considering 3D modelling. The cutting models can be studied starting from classical analytical models up to complicated finite elements models.

The bibliographic study of the 3D FEM cutting modelling established that there are two main formulations for describing a continuous medium – Lagrangian (widely used) and Eulerian.

Among the features of FEM one can emphasize

- the possibility of considering material properties as function of strain, strain rate and temperature (using material libraries and having the possibility of defining new materials);
- contact between tool and workpiece can be modeled as sticking or sliding with the friction coefficient constant or variable.
- workpiece material can be considered elastic-plastic, plastic, viscoplastic, elasticviscoplastic, and rigid-plastic;
- cutting tool is considered as a rigid body;
- it is considered the thermal effect in cutting by thermo-mechanically algorithms;
- mesh optimization during simulation by mesh rezoning technique and continuous remeshing to overcome mesh distortion.
- many post-processing options can be used after simulation such as: geometry of workpiece and tool after the simulation; distribution of state variables - stress, strain, temperature, wear, damage etc; displacement and velocity; graphs of load, volume, states variables between two points, etc; Point tracking for showing the movement of the material; chip formation; predicted cutting forces and torque.

The 3D FEM models were applied to turning, drilling and milling operations in certain cutting conditions in Deform for highlighting the most important aspects involved in setting the initial data for modelling, simulation and also for obtaining information after simulation.

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