FEM TOOLS FOR CUTTING PROCESS MODELLING AND SIMULATION

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În ultimele decenii modelarea şi simularea proceselor de prelucrare a devenit foarte importantă pentru cercetători. Această lucrare prezintă analiza modelării şi simulării procesului de aşchiere ortogonală utilizând metoda elementelor finite aplicate la aliajul de titan Ti6Al4V. În lucrare se face o comparaţie între mai multe programe ce folosesc metoda FEM (DEFORM 2D, FORGE 2D şi AdvantEdge FEM) şi se încearcă sublinierea avantajelor şi dezavantajelor folosirii acestor programe de modelare şi simulare. În final se face o comparaţie a rezultatelor obţinute, cu privire la forţele de aşchiere, formarea aşchiei, deformaţii, temperaturi.

In the last decades, the modelling and simulation of machining processes be came very important for researchers. This paper presents the modelling and simulation analysis of the orthogonal cutting process using the finite element method applied to the machining process of Ti6Al4V. The paper makes a comparison between seeral finite element packages (DEFORM 2D, FORGE 2D and AdvantEdge FEM) and tries to emphasize the advantages and disadvantages when using these commercial codes. In the end, a comparison of the obtained results is made regarding cutting forces, chip formation, strains, and temperature.

Keywords: cutting, Titanium alloy, FEM, software packages, 2D modelling, simulation, results, comparison

1. Introduction

Orthogonal cutting means cutting of a plane surface that meets the following conditions: the cutting edge is normal to the main cutting motion; the length of the cutting edge is larger than the cutting width; during cutting, the cutting speed remains constant.

Among the first orthogonal cutting models are those of Merchant, Lee and Schaffer, Oxley, and Armarego. Merchant developed the earliest steady state or-

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thogonal cutting model; then Lee and Shaffer proposed another model, which uses a slip line theory. Armarego and Oxley developed and proposed analytical orthogonal cutting models, in which Oxley investigated the flow stress variable and Armarego investigated the shear relation.

An extensive bibliography related to the development of orthogonal cutting process and a revision of the actual stage in modelling of cutting processes can be read in the papers of T. Tyan et al. [1], K. Ueda et al. [2], and C. Constantin and E. Strajescu [3]. In time, extensive researches regarding the study of fundamental elements and performances of the orthogonal cutting process have been made [4; 5; 6; 7]. Lately the finite element modelling and simulation of orthogonal cutting process is more and more encountered in scientific papers [8; 9; 10; 11; 12]. This technique has captured the interest of researchers due to the appearance during the machining processes of high strain rates, high temperatures and also to the need of including the material behaviour and the non-linear contact when modelling the process [13].

Nowadays, the finite element analysis is the main tool regarding the metal cutting process modelling and simulation. It has important advantages [14], such as: the prediction of cutting forces and chip shape; it solves contact problems between bodies; it uses bodies made from different materials, etc.

This article is motivated by the desire to make a detailed presentation of the possibilities of modelling and simulation using the finite element method applied using three commercial codes. It is a well known fact that machining, especially orthogonal cutting is a common process in industry. Creating accurate models using the finite element method results in optimizing these processes, thereby a reduction of the experiments number results, implicitly of the time and costs related to these operations. In addition, a comparative study of the commercial software packages that use the finite element method help researchers to choose the most suitable software which can meet their needs.

The scope of this paper is to present the modelling and simulation techniques using the finite element method and also to make a comparison between three commercial codes which use the finite element method when simulating the orthogonal cutting of titanium alloy Ti6Al4V. These commercial codes are DEFORM 2D, FORGE2D, and AdvantEdge FEM.

2. Brief presentation of the finite element software codes

In this paper, the commercial software DEFORM 2D, FORGE 2D and AdvantEdge FEM have been used in order to create finite element models of an orthogonal metal cutting operation.

DEFORM 2D is a finite element method based process simulation system which is designed to model, simulate and analyze various forming and heat treatment processes [15]. Among the advantages of using this software are [15]: improving tool and die design to reduce production and material costs; reduce the need for costly shop floor trials and redesign of tooling and processes; shorten lead time in bringing a new product to market etc.

The creator of the FORGE software, a veritable tool of reference for major players in the automotive and aeronautics industry [16], is Transvalor. FORGE 2D is a code which offers the ability to simulate a wide range of processes, from the traditional (forging, stamping etc.) to more specific (rolling etc.) [16].

AdvantEdge FEM is an explicit commercial code for designing, improving and optimizing machining processes. The solver is optimized for metal cutting processes. Some advantages of using this software are [17]: it reduces cutting tests, extends tool life and reduces tool breakage, uses complex geometries of tools and workpieces, faster machining processes, efficient productivity, increases material removal rates and machine utilization, etc. This software has a high level of details and a simple and user friendly interface which allows users to easily set the modelling and simulation data. It is capable to model complex interactions between tool and workpiece, and covers a wide range of cutting types from turning to milling.

Compared to DEFORM 2D and FORGE 2D, AdvantEdge FEM contains:

- an extensive standard tools library, but also gives user the possibility of creating, within the program, new tool geometries and also importing them from CAD files;
- an extensive material library, but also gives to the user the possibility of introducing new materials, based on known material properties.

The structure of the three codes is similar: pre-processor module, simulation module and postprocessor module, Table 1. The pre-processor module is departure support. It contains data input for the models and also the simulation controls. The simulation module is the module where the actual simulation takes place. Once the necessary data for the modelling and simulation have been entered, the solver makes calculations using the finite element method. These computations are hidden from user. After the calculations are made, in the postprocessor module, the results are processed and displayed in various forms, such as graphs and images. Among the results obtained, we can enumerate: chip formation, chip and tool temperature, stresses, strains, cutting forces, tool wear, damage etc.

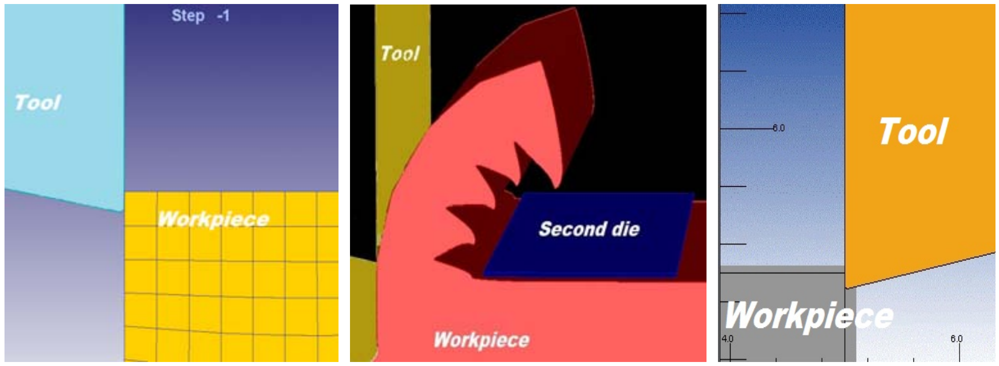
3. Finite element modelling and simulation

Most physical phenomena can be described by differential equations, but sometimes impossible to obtainit is the solutions.In this case, the finite element methodis used. This method is one of the most widely used numerical methods, being known since 1970 and used for analyzing forming processes and designing tools [18]. In order to help modelling machining processes, the computer-based simulation and the finite element analysis (FEA) were developed.

Table 1

Comparison of the structure of the three software codes

	DEFORM 2D	***FORGE 2D***	***AdvantEdge FEM***
Pre-processor module	The Preprocessor - allows users to setup the entire simulation, including defining tool geometries, material conditions and machining parameters It contains: -a simple tool library, -a simple material library -offers the possibility of importing complex CAD geometries tools and workpieces -offers the possibility of introducing new materials	The GLPre allows users to setup the entire simulation, including defining tool geometries, material conditions and machining parameters It contains: -a primitive CAD module where simple tool and workpiece geometries can be created -a basic material library -offers the possibility of introducing new materials	The Simulation Setup Interface allows users to setup the entire simulation, defining tool geometries, material conditions and machining parameters It contains: -a user friendly interface -an extensive standard tools library -an extensive material library -offers the possibility of creating new tool and workpiece geometries within the program and also to import complex geometries form other CAD files -offers the possibility of introducing new materials
Simulation module	The Simulator performs all the hidden calculations from the setup inputs.	The Solver performs all the hidden calculations from the setup inputs.	The AdvantEdge Engine performs all the hidden calculations. Simulations can run in: -Demonstration mode, decreases the simulation time but is less accurate -Standard mode, requires longer simulation time but is more accurate
Post-processor module	The Post-Processor displays and assists in analyzing the simulation results. -among the displayed results , there can be enumerated: chip formation, chip and tool temperature, cutting forces, state variables, etc.	The GLview Inova displays and assists in analyzing the simulation results. -among the displayed results there can be enumerated: chip formation, chip and tool temperature, cutting forces, state variables, etc.	The Tecplot displays and assists in analyzing the simulation results. -among the displayed results there can be enumerated: chip formation, chip and tool temperature, cutting forces, steady state variables such as: strain, stress, strain von Misses, etc.



a b c

Fig.1. Model description: a. DEFORM model; b. FORGE model; c. AdvantEdge FEM model.

Nowadays a right choice of the finite element software code has a big importance for the aim, scope, and quality of the performed analysis.

In this paper three different commercial software codes using the finite element method were used to model and simulate two dimensional orthogonal metal cutting operations. DEFORM 2D and FORGE 2D are implicit codes, while AdvantEdge is a dynamic explicit code. Implicit finite element software solves the set of finite element equations through iterations until the convergence criterion for each increment is satisfied [19]. It is assumed that this type of finite element analysis is more accurate. In dynamic explicit software the finite element equations are reformulated so that they can be solved directly to determine the solution at the end of the increment, without iterations [20], but this kind of analysis is time consuming.

For generating the finite element models, in this case of cutting, we consider a rigid tool and a deformable workpiece, see Fig. 1, a, b, and c. In the case of modelling and simulation with FORGE 2D the software must be adapted for orthogonal cutting, that is why in addition to the workpiece and tool the user must insert a second die, see Fig. 1, b.

All models have the same workpiece, dimensions 7 mm length and 4 mm width, only the tool geometry changes. Four tools are used, with four different tool tip radii, 10 μm, 20 μm, 30 μm, and 40 μm.

The tool material is tungsten carbide/cobalt (WC-Co), which is widely used for cutting tools, metal forming tools, mining tools, and wear resistance surfaces, because is high melting (≈ 2 900 °C) and extremely hard [21].

The workpiece material is the most common titanium alloy known in industry, Ti6Al4V. This alloy is hard to be machined, that is why the tool of uncoated WC-Co is used, because is the most recommended for machining titanium workpieces.

Table 2

Workpiece material properties [23]

Physical properties		***Chemical composition of Ti6Al4V***	
Type	Value	Element	Value
Density [kg/m^3]	4.43	Aluminium	6.00
Mean coefficient of expansion [m/m·°C]	20°C – 200°C: 9.00 × 10^{-6}	Vanadium	4.00
Modulus of elasticity [N/mm^2]	at 20°C: 110 × 10^3	Carbon	< 0.08
Shear modulus [N/mm^2]	45 000	Iron	< 0.30
Thermal conductivity [W·m/m^2·°C]	at 20°C: 6.7	Oxygen	< 0.20
Electrical resistivity [μΩ·cm^2/cm]	at 20°C: 170	Nitrogen	< 0.07
Absolute magnetic permeability [H/m]	1.26 × 10^{-6}	Titanium	Base
Poisson's ratio	0.3		

This titanium alloy has received great interest in the past years due to its excellent high strength at elevated temperatures, good corrosion resistance and also excellent biocompatibility, especially when direct contact with tissue or bone is required, but its usage is limited because of the high production costs [22]. The workpiece material properties are presented in Table 2.

All three commercial codes have a material library containing the most used materials: steel, aluminium, stainless steel, titanium and other, from which the users can choose the needed one. DEFORM 2D and FORGE 2D have basic material libraries but also give users the possibility of creating new materials. AdvantEdge FEM has an ever-expanding library of standard materials, also has the possibility of creating new materials or importing them.

The workpiece material is modelled as elastic-plastic and requires a mesh. The tool is considered rigid in case when using DEFORM 2D and FORGE 2D. In AdvantEdge FEM tools and coatings are modelled only as elastic bodies and do not plastically deform. Tool meshing is not required.

The friction between tool and chip is of shear type for DEFORM 2D and Coulomb type for FORGE 2D and AdvantEdge FEM.

After choosing the material, the workpiece should be meshed. DEFORM 2D and FORGE 2D use four-node quadrilateral elements for the mesh and AdvantEdge FEM uses six-node triangular elements by default. The material separation from the workpiece, for chip formation, is possible because of the remeshing method. DEFORM 2D uses a remeshing criterion different from FORGE 2D and AdvantEdge FEM.

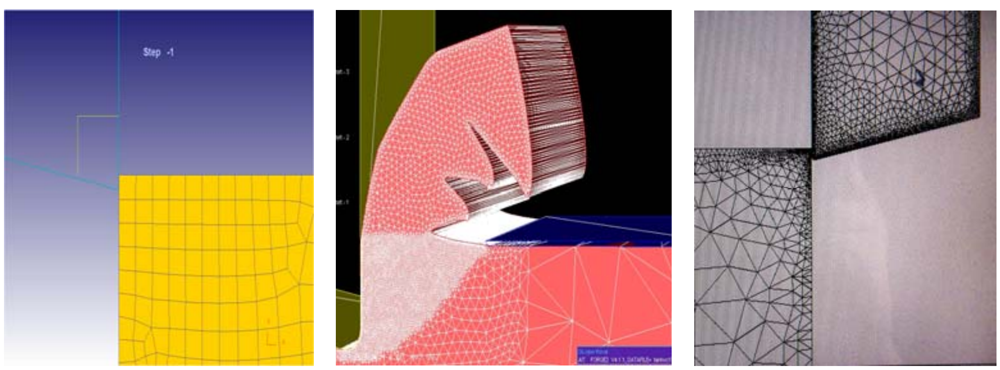
AdvantEdge FEM uses the continuous remeshing in order to separate the chip. During metal, cutting the workpiece material flows around the cutting edge of the tool and the remeshing takes place whenever the elements from the cutting edge area change their initial shape. Due to automatic remeshing, these programs allow also the modelling and simulation of complex geometry workpieces.

In FORGE 2D the mesh is very fine when the tool tip enters the workpiece material and the size of the mesh elements increases in the piece depth, this kind of mesh can be achieved using meshing windows with different element sizes. On the other hand, AdvantEdge FEM makes the mesh automatically, after introducing the input process parameters. The software sets the mesh parameters to create a balance between the calculation time and the accuracy of the results. AdvantEdge FEM gives the possibility to change the mesh, but only advanced users should change it, based on their experience.

In DEFORM 2D the elements at the tool tip are erased during remeshing, when they reach a critical value. After that, the remeshing takes place, see Fig. 2 a, b, and c.

As for the boundary conditions, in FORGE 2D and DEFORM 2D the user must set the left, right and bottom boundary nodes as fixed in *x* and *y* directions, so the workpiece cannot move. In AdvantEdge FEM the user can set the boundary conditions just in the case when using a custom tool. If the tool is chosen as a standard one, the user has no access to this information and it is enough to enter the input process parameters for achieving the 2D simulation.

In the last step of the pre-processor module, before starting the simulation, the process parameters must be set, see Table 3, the tool penetrates the workpiece with a constant cutting speed and a constant feed rate.



a b c

Fig. 2. Mesh form: a. DEFORM 2D model; b. FORGE 2D model; c. AdvantEdge FEM model.

Table 3

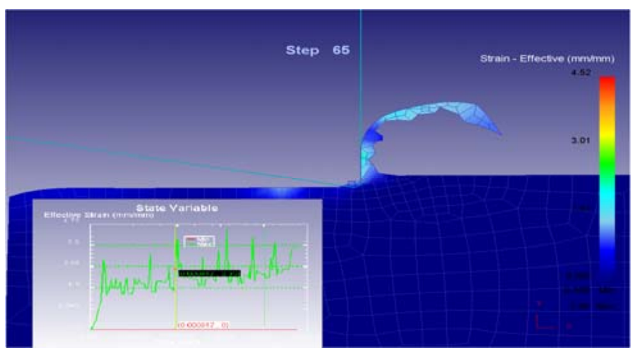
Process parameters

Parameter	***Value***		
Initial temperature	25 [˚C]		
Cutting speed	150 [m/min]		
Feed	0.1 [mm/tooth]		
Friction model	DEFORM 2D	FORGE 2D	AdvantEdge FEM
	Shear model	Coulomb model	Coulomb model

4. Simulation results

Before starting the simulation, the user must know that in FORGE 2D and DEFORM 2D the material behaviour law can be also introduced. The Johnson-Cook material behaviour model is widely used in finite element modelling but in this case it cannot predict the phenomena responsible for the appearance of the segmented chips, also known as saw-tooth chips, during the machining of titanium alloys. Calamaz et al. [25] developed a new material law which considers the strain rate, the temperature and also the strain softening effect when analyzing the chip formation and shear localization during machining of titanium alloy Ti6Al4V. This new material law is introduced in FORGE 2D.

For this study, finite element simulations were carried out for four cases by using four different tool tip radii: 10 µm, 20 µm, 30 µm, and 40 µm, the clearance angle remaining constant at 11 deg. These simulations were carried out by



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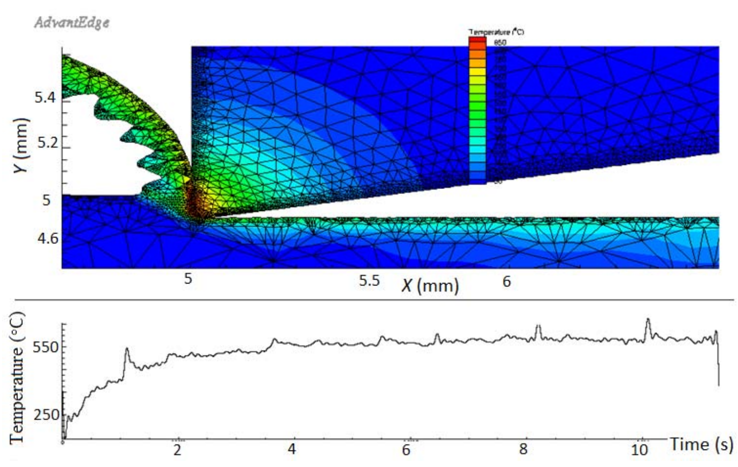

b

Fig. 3. Presentation forms of the same result, graph and image: a. DEFORM 2D effective stress presentation, b. AdvantEdge FEM temperature presentation.

DEFORM 2D, FORGE 2D, and AdvantEdge FEM separately. From these simulations, different kind of variables can be obtained such as temperature variation in chip, state variables, cutting forces etc. and also the chip form can be predicted. Among the state variables, we can enumerate: strain, effective strain rate, stress, effective stress rate, damage, etc.

AdvantEdge and DEFORM 2D offer the possibility to present results in graphical form and also in form of images, see Fig. 3a, and b. AdvantEdge FEM allows user to easily switch the isplayedresults d and also offers the possibility to compare simulations.

AdvantEdge FEM and FORGE 2D can create animations with results and save them as .avi files.

All three software have also job monitors, which update permanently the simulation progress and also keep a log of all simulations that have been modelled.

AdvantEdge FEM and FORGE 2D have the ability of parallel processing, this means the simultaneous run of simulations. AdvantEdge FEM allows the simultaneous run of eight simulations while FORGE 2D only four.

4.1. *Chip formation*

When machining with high cutting speeds, the appearance of segmented chips is imminent. Ti6Al4V is one of the materials that generate saw-tooth chips at law cutting speeds [26]. The modelling and simulation using FORGE 2D and AdvantEdge FEM can predict the chip form, but DEFORM 2D cannot because of the Johnson-Cook material law used, see Fig. 4 a, b, and c. Also a detailed analysis of the size of the chip can be obtained, regarding the number of the chip segments, and the width and height of a chip segment.

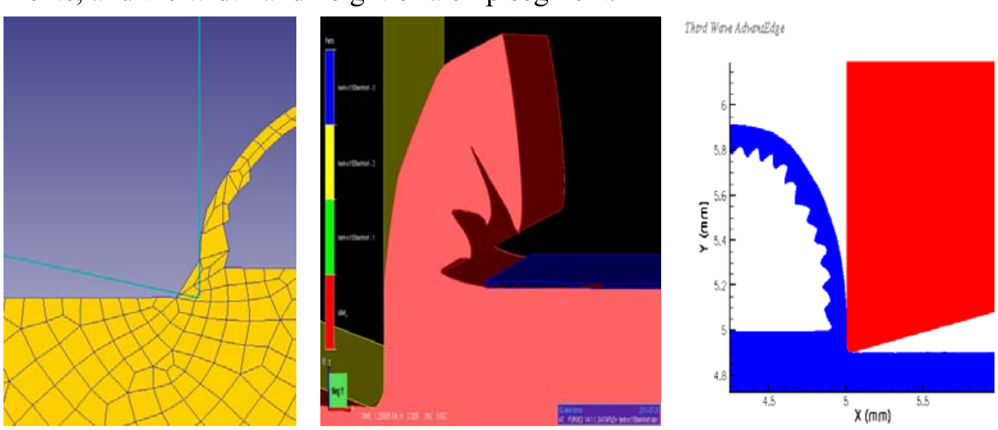

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Fig. 4. Saw-tooth chip formation: a. DEFORM 2D chip; b. FORGE 2D chip; c. AdvantEdge FEM chip.

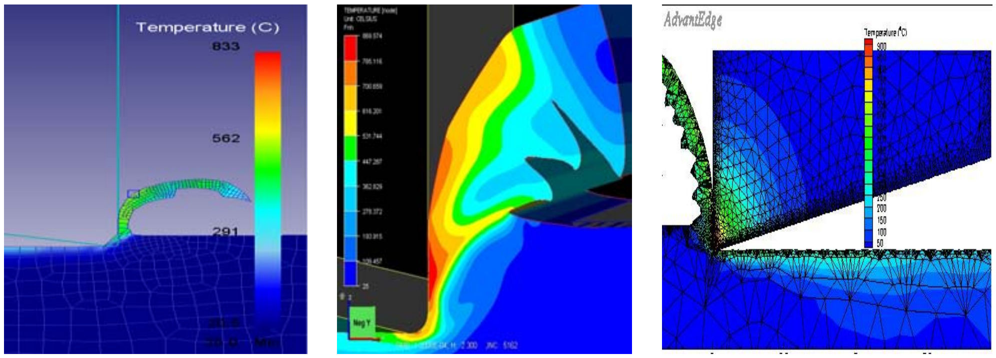

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Fig. 5. Temperature distribution in chip: a. DEFORM 2D; b. FORGE 2D; c. AdvantEdge FEM.

Table 4

Average temperature

Average Temperature	*Tool radius* 10 μm	*Tool radius* 20 μm	*Tool radius* 30 μm	*Tool radius* 40 μm
FORGE 2D	460 °C	500 °C	520 °C	550 °C
DEFORM 2D	450 °C	500 °C	550 °C	570 °C
AdvantEdge	450 °C	500 °C	550 °C	550 °C

4.2. *Temperatures*

After simulation and data processing, the temperature distribution can be seen in postprocessor. Fig. 5 shows the temperature distribution in the chip, in case when the tool has a radius of 20 µm. Table 4 presents the calculated average temperature in each simulation case. One can see that the temperature increases when the tool tip radius raises. The differences between the three software codes are not significant.

4.3. *State variables and cutting forces*

The state variables predicted after the finite element simulations are: tool wear; deformations such as damage, strain, stress, strain rates, velocity; normal pressure etc. In Fig. 6 the average strain is presented. Strain means a measure of deformation representing the displacement between particles in the workpiece relative to a reference length [24] while stress is a measure of the internal forces acting within the deformable body [24].

The three software codes are also capable to predict the cutting forces, see Figs. 7 and 8.

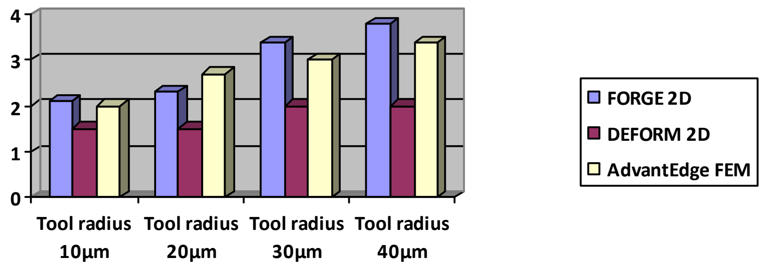

Fig. 6. Average strain [mm/mm].

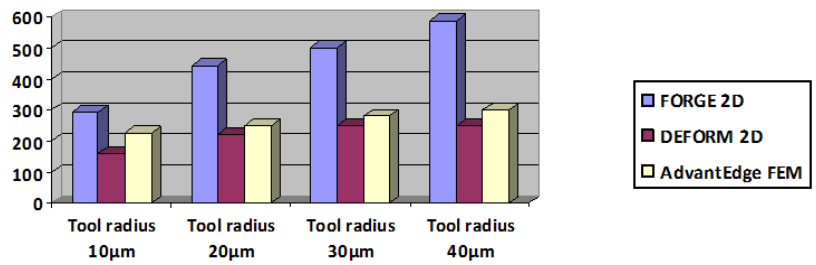

Fig. 7. Cutting forces on x-axis [N].

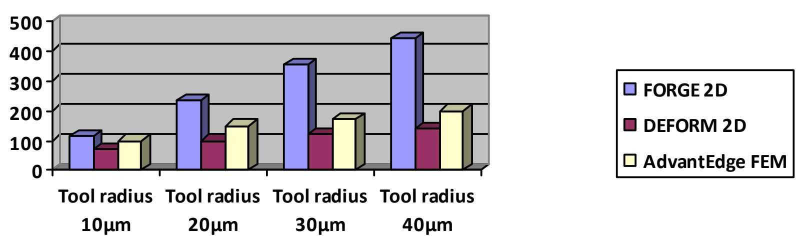

Fig. 8. Cutting forces on y-axis [N].

5. Conclusions

This paper presents an overview of the finite element modelling and simulation technique. Three commercial finite element codes: FORGE 2D, DEFORM 2D and AdvantEdge FEM are used for modelling and simulation. FORGE 2D and DEFORM 2D are implicit codes and AdvantEdge FEM is a dynamic explicit code.

Table 5

Comparison of the three commercial codes

	FORGE 2D	***DEFORM 2D***	***AdvantEdge FEM***
Formulation	Implicit	Implicit	Dynamic explicit
Chip separation	Through remeshing	Through element erase due to damage	Through remeshing
Friction Modelling	Coulomb law	Constant shear	Coulomb law
Boundary Conditions	Left, right, bottom edges fixed in 2 directions	Left, right, bottom edges fixed in 2 directions	Automatic (hidden to users)
Geometry	2D	2D	2D
Material	Chosen from the library	Chosen from the library	Chosen from the library
Mesh element type	4-node quadrilateral	4-node quadrilateral	6-node triangular
Remeshing	Element	Element	Periodic
Analysis of results in	GLview Inova	Post-Processor	Tecplot

The results obtained after the simulations show similar results predicted by the three programs regarding the temperature in chip and also the average strain. FORGE 2D and AdvantEdge FEM are able to predict the saw-tooth chip formation of the TiAl6V while DEFORM 2D cannot predict it accurately. A reason for the inaccurately chip prediction in DEFORM 2D might be the material law, Johnson-Cook law, which is not suitable here.

Regarding the cutting forces, those predicted by FORGE 2D are bigger than the others because in FORGE the used material behaviour law is a special law developed by the researchers at the University Bordeaux I, France [25]. DEFORM 2D generally predicts different values than FORGE 2D and AdvantEdge FEM because of the fact that DEFORM 2D uses a different chip separation method.

A comparison between the commercial codes is made further and the results are presented in Table 5.

Regarding the computational time, meaning the time used to complete the finite element simulation, it can be concluded the following: DEFORM 2D: 5-7 hours to complete one simulation, so, around 3 days to complete all four simulations; FORGE 2D: at least two weeks to complete four parallel simulations; and AdvantEdge FEM: about 3 hours to complete one simulation, so, around 2 days for all four simulations.

The use of finite element modelling techniques as design and optimization tools is growing nowadays when speaking of machining processes but the existent commercial software packages are not able to predict accurately different aspects such as surface integrity of the workpiece, a fact regarding the safety when using for critical components, such as aero-engine parts. Table 6 shows the most

Table 6

Advatages and disadvatages when using FORGE 2D, DEFORM 2D and AdvantEdge FEM

	Advantages	*Disadvantages*
FORGE 2D	-possibility to import complex geometries from other CAD software -possibility to create new materials -possibility of using the meshing windows for a better meshing of the workpiece	-must be adapted for machining processes -the CAD module is rudimentary and hard to work with -the solver runs slowly, a simple simulation takes days
DEFORM 2D	-possibility to adjust solver parameters -uses adaptive meshing controls -primitive creator module for simple geometries -possibility to import complex geometries from other CAD software -possibility to create new materials	-must be adapted for machining processes -tool and workpiece orientation is time consuming -simple standard material library, other materials must be created - complex simulation runs very slow and sometimes stops
AdvantEdge FEM	-simple, user friendly interface -the solver is optimised for metal cutting processes -offers the possibility of creating new geometries and also of importing them -extensive material library and also possibility of creating new materials -the solver runs fast	-gives user less flexibility in configuring the solver controls

important advantages and disadvantages when using the three commercial codes presented in this paper.

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