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Procedia CIRP 58 (2017) 245 – 250

www.elsevier.com/locate/procedia

16th CIRP Conference on Modelling of Machining Operations

The CEL method as an alternative to the current modelling approaches for Ti6Al4V orthogonal cutting simulation

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Abstract

The finite element approach is often adopted to study the machining process. The Lagrangian and Eulerian formulations or even Arbitrary Eulerian-Lagrangian (ALE), one of their combinations, are the most employed in the current literature; each having their pros and cons. One of the most challenging issue in finite element modelling is the large strains during the cutting process that induce high deformation levels in the elements of the mesh. Remeshing contributes to decreasing mesh deformation but the criterion adopted to control it influences the results.
The Coupled Eulerian-Lagrangian (CEL) method proposes to combine the Lagrangian and Eulerian formalisms without any element deformation problem. This paper studies its implementation in Ti6Al4V orthogonal cutting. The results are then compared to an experimental reference, as well as more standard models: an ALE model developed with Abaqus, an implicit Lagrangian model developed with Deform and an explicit Lagrangian model developed with AdvantEdge. The comparison is mainly based on the cutting forces and the chip morphology. It shows that the CEL formulation is a competitive alternative to the more standard models.

Peer-review under responsibility of the scientific committee of The 16th CIRP Conference on Modelling of Machining Operations

Keywords: Finite element method (FEM), Machining, Titanium

1. Introduction

Titanium and its alloys are widely used materials in aerospace industry due to their excellent mechanical properties that are maintained at high temperature, such as, high specific strength, fracture toughness and corrosion resistance [1]. However, other properties, thus, low thermal conductivity, which inhibits the heat dissipation from the workpiece causing a temperature increase in the cutting zone, and high chemical reactivity, which produced BUE (Build Up Edge), entails a reduction in the machinability [2]. Those fabrication problems added to the high extraction cost carry a high price of the material in comparison to other metals [3].

Nevertheless, a precise numerical model able to make accurate predictions of temperature, chip morphology, strain and stress contributes to the cost reduction by optimizing the machining process without carrying out a large number of experimental tests. First approaches of numerical modelling were done in Eulerian and Lagrangian mathematical formulations on 2D orthogonal cutting in the seventies [4]. The main difference between those formulations is that in the Eulerian formulation the mesh is fixed and the material moves through it, while in Lagrangian the mesh and the material moves together. The main disadvantage of the Lagrangian formulation is that as the material suffered large deformations the mesh is distorted inducing a lower accuracy of the results [5]. In order to overcome inexactness, the remeshing [6-8] and element deletion [9] techniques have been widely adopted. However, it leads to a computational time increase as well as to an accuracy reduction due to the approximations done to transfer the values between meshes [10]. The Eulerian formulations drawback is that it only can be used in steady-state simulations and required to establish the final chip morphology [11].

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doi:10.1016/j.procir.2017.03.188

The Arbitrary Lagrangian Eulerian (ALE) formulation takes the best of both Lagrangian and Eulerian formulations by permitting the independent movement of the mesh and the material with a reduced computational time [12]. Due to the separation of the mesh and material movements, the element distortion is reduced avoiding the necessity of using remeshing or other simulations strategies. When Eulerian and Lagrangian boundaries are introduced, it allows a longer simulation duration as well as a more refined mesh in primary and secondary shear zones [13, 14]. Nevertheless, a first prediction of the chip morphology need to be introduced and it does not obtain segmented chip as it happens with Lagrangian models [15]. When only Lagrangian boundaries are used, no initial chip prediction is needed but the resulting morphology is usually far from the experimental one or that of a Lagrangian model [15].

So as to overcome the disadvantages of the ALE model, the Coupled Eulerian-Lagrangian (CEL) model was developed for orthogonal cutting. However, typically its use has been limited to the fluid-structure interactions. Nevertheless, there has been some researches that conclude that CEL formulation is suitable for large deformations [16-20]. In orthogonal cutting, the formulation is based on a cutting tool modelled according to a Lagrangian formulation, where the mesh follows the material displacement, and an Eulerian workpiece represented by a non-translating and material deformation independent mesh [9, 16, 17]. Zhang et al [20] have adopted the CEL formulation to compare it towards Lagrangian and ALE formulations and to select the best set of Johnson-Cook parameters between two sets. No experimental validation was performed and they concluded that none of the sets of Johnson-Cook parameters was best suited for the three formulations considered.

In this paper different formulations have been applied to simulate the orthogonal cutting of the titanium alloy Ti6Al4V with a carbide tool in a variety of software, in order to be able to analyze the accuracy of each study. For that, the commercial software AdvantEdge and DEFORM-2D™ are used with the Lagrangian formulation and the Abaqus software is adopted for the CEL and ALE formulations.

2. Models characteristics

The four models (ALE, CEL, Deform and Advantedge) simulate the same orthogonal cutting tests to allow the comparison of the results. The numerical results will also be compared to an experimental reference obtained in orthogonal cutting conditions [21]. All the cutting parameters are the same as for the finite element models. One cutting speed is adopted for three different uncut chip thicknesses. Table 1 summarizes the cutting conditions and the tool geometry.

The models show common characteristics: the physical and mechanical materials properties are the same, as well as the material constitutive model of Ti6Al4V, the carbide tool geometry and friction at the tool – workpiece interface.

The material constitutive model of Ti6Al4V is the Johnson-Cook model [22]. This well-known model in finite element simulation of machining dissociates the plastic, viscous and thermal contributions in three independent terms:

$$\sigma = \left[A + B\varepsilon^n\right]\left[1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right]$$

The materials parameters are A, B, C, m and n, $\dot{\varepsilon}_0$ is the reference strain rate, and T_{melt} and T_{room} are, respectively, the melting and the room temperatures. The values adopted in the models are given in Table 1. They were previously determined as the most suited to model Ti6Al4V cutting in the adopted cutting conditions [23]. Friction is modelled with Coulomb's model. All the assumptions on the plastic and the friction energies conversion to heat, as well as heat partition between tool and workpiece are provided in Table 1. The faces of the models are supposed to be adiabatic.

Table 1. Materials physical and mechanical properties, cutting conditions and tool geometry [24-30].

JC constitutive model	A (MPa)	997.9
	B (MPa)	653.1
	C	0.0198
	m	0.7
	n	0.45
	$\dot{\varepsilon}_0$ (s^{-1})	1
	T_{room} (K)	298
	T_{melt} (K)	1,878
Young's modulus, E (GPa)	Ti6Al4V	113.8
	Carbide	800
Poisson's ratio, ν	Ti6Al4V	0.3
	Carbide	0.2
Density, ρ (kg/m³)	Ti6Al4V	4,430
	Carbide	15,000
Conductivity, k (W/mK)	Ti6Al4V	7.3
	Carbide	46
Expansion, λ (1/K)	Ti6Al4V	8.6 e^{-6}
	Carbide	4.7 e^{-6}
Specific heat, c_p (J/kgK)	Ti6Al4V	580
	Carbide	203
Friction coefficient	0.2	
Friction energy to heat (%)	100	
Inelastic heat fraction	0.9	
Heat partition to workpiece (%)	50	
Cutting speed, V_c (m/min)	30	
Uncut chip thickness, h (mm)	0.04, 0.06, 0.1	
Rake angle, γ (°)	15	
Clearance angle, α (°)	2	
Cutting edge radius, r (μm)	20	

The initial geometry of the four models is the same: the workpiece is a rectangular block of Ti6Al4V fixed in space and the tool moves horizontally from the right to the left at the cutting speed to remove the upper layer of the workpiece.

The models exhibit some differences due to the software and the formulations adopted. Abaqus [31] is used for the ALE and CEL models. The number of elements of the ALE model is

11,473. In the CEL model, the space initially filled with void and in which the chip will form needs to be meshed as well [19]. To limit the number of elements, the height of the model is adapted to the value of the uncut chip thickness. By doing so, the number of elements ranges from 13,675 to 20,075. In the ALE model, the ALE formulation and so the ability of the nodes to move to reduce mesh distortion is applied to the workpiece; the tool is Lagragian. For the CEL model, the tool is described by the Lagrangian formulation and the workpiece by the Eulerian one. For the two Abaqus models, the size of the elements in the whole workpiece is the same (0.005 mm at the beginning of the computation). The size of the elements does not change during the computing for the CEL model, while it is modified in the ALE model by the nodes relocation. These combinations of Lagrangian and Eulerian formulations avoid to introduce a criterion to allow for the chip to form. Such a criterion should be avoided as much as possible as it can strongly influence the results and then becomes a parameter of the models that use it [15]. Both Abaqus models include an elastic tool and an elasto-plastic workpiece.

The software AdvantEdge is also used to simulate the orthogonal cutting by a Lagrangian formulation with adaptive meshing and continuous remeshing [32]. The model is composed of a rigid tool and a plastic workpiece. The mesh is established by the minimum and the maximum element, 0.02 mm and 0.1 mm respectively. The standard constitutive model in the software is the Power Law [32], so a user routine is established to be able to introduce Johnson-Cook parameters. However, the software does not provide much flexibility so the user is restricted to the pre-set controls of it.

Focusing on the model developed with the commercial software DEFORM-2D, it uses a Lagrangian implicit code with remeshing [33]. The model consists of a rigid tool and a plastic workpiece, meshed with 3,000 and 6,000 isoparametric quadrilateral elements respectively. A local remeshing criteria based on the strain and strain rate is established. A plane strain coupled thermomechanical analysis is performed. In comparison to AdvantEdge, it allows more flexibility to the user. Thanks to remeshing, the size of the elements in the cutting area is refined during computing. This allows to use very small elements in that area (close to 0.001 mm in Deform and to 0.002 mm in AdvantEdge).

A major difference between the models is the way the chip separates from the workpiece is handled. Deform and AdvantEdge models allow the chip formation thanks to a remeshing criterion that strongly limits the mesh deformation. The ALE model only allows a small relocation of the nodes, while the CEL model takes advantage of the Eulerian formulation of the workpiece to completely avoid mesh distortion.

3. Comparison

The numerical chips are shown in Figure 1. They are all continuous, like the chips of the experimental reference in Figure 2. The chip thickness and the shear angle of each model are compared to the experimental reference in Table 2. Both values are globally better modelled by the ALE and CEL models. The difference is larger with Deform and AdvantEdge models. All the numerical chip thickness values are larger than the experimental ones and thus the modelled shear angles are smaller than the reference from the experiments.

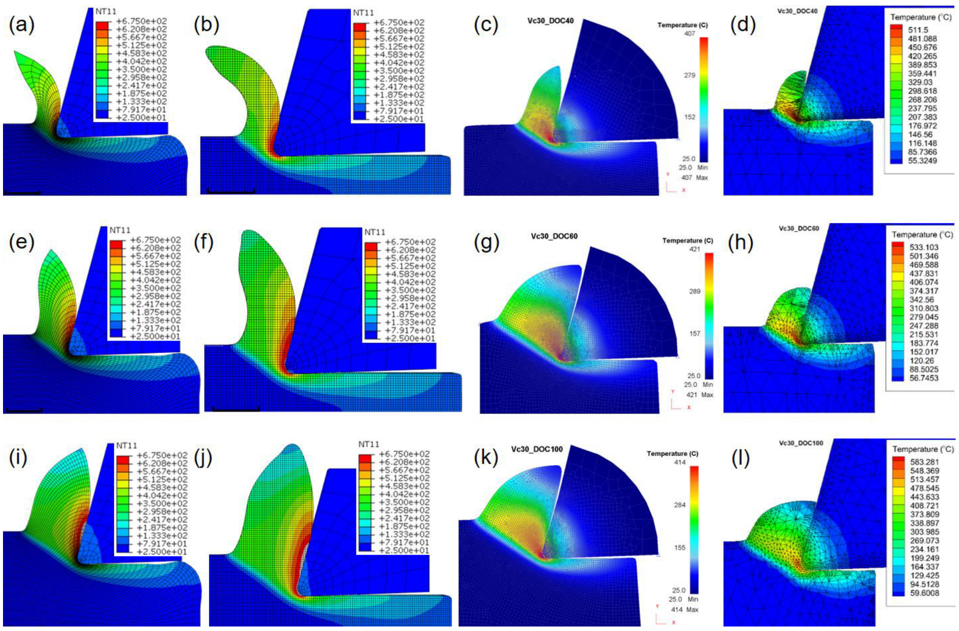

Fig. 1. Temperature contours (in °C) of the numerical chips (a) ALE h = 0.04 mm, (b) CEL h = 0.04 mm, (c) Deform h = 0.04 mm, (d) AdvantEdge h = 0.04 mm, (e) ALE h = 0.06 mm, (f) CEL h = 0.06 mm, (g) Deform h = 0.06 mm, (h) AdvantEdge h = 0.06 mm, (i) ALE h = 0.1 mm, (j) CEL h = 0.1 mm, (k) Deform h = 0.1 mm and (l) AdvantEdge h = 0.1 mm.

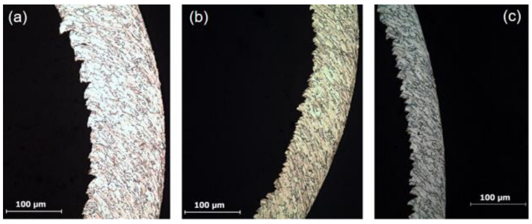

Fig. 2. Experimental chips: (a) h = 0.1 mm, (b) h = 0.06 mm and (c) h = 0.04 mm [21].

Table 2. Summary of the results for the chip morphology (h': chip thickness, φ: primary shear angle and Δ_x: difference with the experimental values).

Case	h' (mm)	$\Delta_{h'}$ (%)	φ (°)	Δ_φ (%)
		h = 0.04 mm		
Experiments	0.059	–	38	–
ALE	0.064	8	36	7
CEL	0.066	12	35	9
Deform	0.090	53	24	38
AdvantEdge	0.080	36	23	40
		h = 0.06 mm		
Experiments	0.080	–	42	–
ALE	0.101	26	34	18
CEL	0.100	25	35	17
Deform	0.130	63	27	34
AdvantEdge	0.120	50	25	41
		h = 0.1 mm		
Experiments	0.135	–	42	–
ALE	0.171	27	34	19
CEL	0.166	23	35	17
Deform	0.200	48	29	42
AdvantEdge	0.200	48	27	34

The quality of the mesh in the chip is different depending on the model considered. The elements are not deformed in the Deform and CEL models. Elongated elements are noticed in AdvantEdge and the mesh is completely unstructured. Some kind of defects linked to the quality of the mesh are observed on the free side of the chip near the workpiece. Deformed and elongated elements are observed as well for the ALE model. The mesh remains however globally structured. However, at the end of the chip, the mesh movement is not intense enough to avoid the distortion of the elements. This is particularly noticed for h = 0.04 mm. As the size of the elements is the same for the different uncut chip thickness values, less elements compose the chip when h = 0.04 mm than when h = 0.1 mm, resulting in more deformed elements at h = 0.04 mm. This leads to a kind of material accumulation at the end of the chip and thus a reduction of the chip thickness in the area in contact with the tool, influencing the results.

The contact length between the chip and the rake face of the tool is given in Table 3 for each model. It increases with the uncut chip thickness value, as expected. Values with Abaqus are rather close, except at h = 100 µm. Deform and AdvantEdge values are larger, and especially with AdvantEdge: the chips stick more to the tool. This is coherent with a larger chip thickness.

Table 3. Contact lengths between the tool and the chip, lc_h.

Case	$lc_{0.04}$ (mm)	$lc_{0.06}$ (mm)	$lc_{0.1}$ (mm)
ALE	0.041	0.075	0.133
CEL	0.044	0.072	0.124
Deform	0.060	0.080	0.120
AdvantEdge	0.070	0.087	0.140

The cutting and feed forces values are given in Table 4. As for the chip morphology, the Abaqus models provide values closer to the experimental reference for both forces; the cutting forces values can be considered equal to that of the experiments. The difference is larger for the feed force, but still lower than with Deform and AdvantEdge.

Table 4. Summary of the results for the forces (CF: cutting force, FF: feed force and Δ_x: difference with the experimental values).

Case	CF (N/mm)	Δ_{CF} (%)	FF (N/mm)	Δ_{FF} (%)
		h = 0.04 mm		
Experiments	86	–	40	–
ALE	85	1	42	5
CEL	84	2	36	10
Deform	80	7	26	35
AdvantEdge	120	40	60	50
		h = 0.06 mm		
Experiments	113	–	44	–
ALE	114	1	36	18
CEL	113	0	34	23
Deform	106	6	25	43
AdvantEdge	150	33	80	82
		h = 0.1 mm		
Experiments	174	–	50	–
ALE	173	1	33	34
CEL	171	2	31	38
Deform	150	14	22	56
AdvantEdge	250	44	90	80

Deform models give lower forces values. The difference with the reference is larger for the feed force than for the cutting force. Both forces are underevaluated, contrary to that of AdvantEdge models. Indeed, all the forces obtained with AdvantEdge are significantly larger than the reference. It is however important to note that the feed forces of the

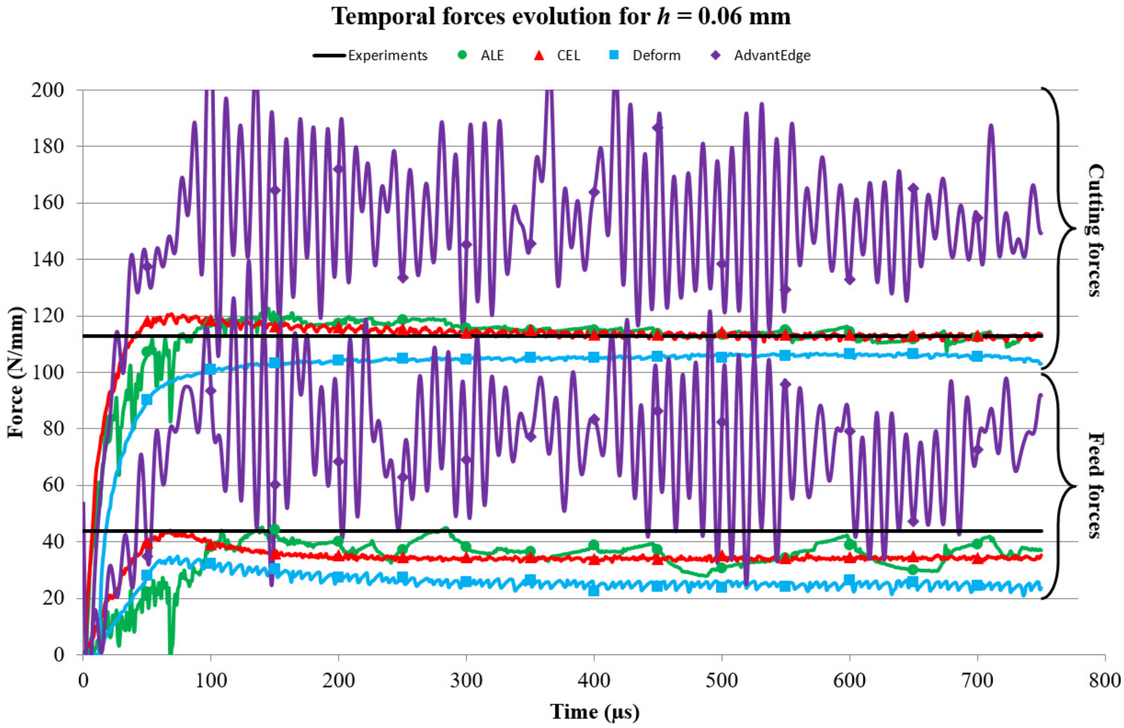

Fig. 3. Temporal forces evolution for the four software and mean experimental values when the uncut chip thickness is 0.06 mm.

AdvantEdge models are the only ones to follow the increasing trend of the reference values when the uncut chip thickness increases. The three other models indeed lead to a feed force decreasing when the uncut chip thickness increases.

A representative example of the forces evolutions for the four models is provided in Figure 3 when the uncut chip thickness is set to 0.06 mm. It shows that the forces are globally constant when steady-state is reached, i.e. after 150 µs. The forces variations are however high with the AdvantEdge model. At that uncut chip thickness, the minimal and maximal cutting force values with the AdvantEdge model are 105 N/mm and 229 N/mm, while they are 107 N/mm and 119 N/mm for the ALE model, 111 N/mm and 116 N/mm for the CEL model and 101 N/mm and 107 N/mm for the Deform model. This clearly shows the significant difference between the results from AdvantEdge and the other models. The high forces variations in the AdvantEdge model are assumed to be mainly due to the remeshing criterion. The feed force with the ALE model tends to vary more than with the CEL and Deform models, but to a far lower extent than with the AdvantEdge model.

4. Conclusions

Four models have been developed with three different software to analyze the accuracy of each of them by comparing them amongst themselves and against an experimental reference. The main highlights of the study are the following:

- The ALE and CEL models produced results that were very close.
- The chip morphology and the forces were closer to experimental results with the CEL and ALE models than with the Deform and AdvantEdge models.
- Mesh distortions were observed with the ALE model. They influenced the results and can lead to the premature termination of the computation.

The main output of this study is that the CEL formulation is a competitive alternative to the formulations widely used so far. Its application to metal cutting modelling should be expanded to other materials, cutting conditions and to study more specific issues such as tool wear.

Acknowledgements

Computational resources for Abaqus have been provided by the supercomputing facilities of the University of Mons (Dragon1/UMONS) and the Consortium des Équipements de Calcul Intensif (CÉCI), funded by the Fonds de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under Grant No. 2.5020.11. François Ducobu gratefully acknowledges Sébastien Kozlowskyj, System Manager of Dragon1, for his help and support to run Abaqus on the cluster. The authors thank the projects MICROMAQUINTE (PI_2014_1_116) and EMULATE (DP12015-67667-C3-3R) for their funding to the research presented in this paper.

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