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Procedia CIRP 8 (2013) 105 – 110

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14th CIRP Conference on Modeling of Machining Operations (CIRP CMMO)

# A Sensibility Analysis to Geometric and Cutting Conditions Using the Particle Finite Element Method (PFEM)

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**Abstract**

The (PFEM) is employed to simulate orthogonal metal cutting of 42CD4 steel. The objectives of this work are mainly three: The first one is to validate PFEM strategies as an efficient tool for numerical simulation of metal cutting processes by a detailed comparison (forces, stresses, strains, temperature, etc.) with results provided by commercial finite element software (Abaqus, AdvantEdge, Deform) and experimental results. The second is to carry out a sensibility analysis to geometric and cutting conditions using PFEM by means of a Design of Experiments (DoE) methodology. And the third one is to identify the advantages and drawbacks of PFEM over FEM and meshless strategies.
Also, this work identifies some advantages of PFEM that directly apply to the numerical simulation of machining processes: (i) allows the separation of chip and workpiece without using a physical or geometrical criterion (ii) presents negligible numerical diffusion of state variables due to continuous triangulation, (iii) is an efficient numerical scheme in comparison with FEM.


Selection and peer-review under responsibility of The International Scientific Committee of the "14th CIRP Conference on Modeling of Machining Operations" in the person of the Conference Chair Prof. Luca Settineri

*Keywords:* Particle Finite Element Method, orthogonal cutting, design of experiments

## 1. Introduction

Metal cutting is a very complex process involving large strains, high shear and friction mechanisms and thermomechanical couplings. The experimental approach to study machining processes is expensive and time consuming, especially when a wide range of parameters is included. Therefore, numerical simulations appear as an alternative.

Literature review shows that large part of the research in the numerical simulation of metal cutting has been carried out using FEM [2, 3]. However, some new numerical techniques as the meshless strategies [4-7] have been recently developed. Meshless strategies might be an alternative tool to the numerical simulation of metal cutting processes in a near future.

Therefore, the capability of PFEM (Particle Finite Element Method) to predict the influence of cutting conditions on forces, stresses, temperatures inside the workpiece, the chip and the tool is the focus of this work. Several advantages are worth mentioning: (i) Continuous Delaunay Triangulation minimizes the

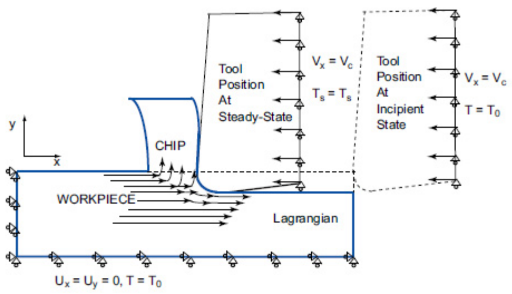


Fig. 1. Mechanical and thermal boundary conditions used in the cutting simulation of 42CD4 steel[1].


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doi:10.1016/j.procir.2013.06.073

Table 1. : Experimental and numerical results (PFEM, Abaqus, AdvantEdge, Deform).

| | T (k) | h (mm) | V.M. (MPa) | e () | $t_2$ (mm) | $F_c$ (N) | $F_f$ (N) |
|---|---|---|---|---|---|---|---|
| PFEM | 1173 | 0,26 | 1400 | 13 | 0,35 | 383 | 105 |
| Abaqus/Explicit | 1240 | 0,32 | 1348 | 5.2 | 0,35 | 412 | 135 |
| AdvantEdge | 1442 | 0,29 | 2343 | 7 | 0,27 | 647 | 228 |
| Deform | 1107 | 0,24 | 1210 | 3,57 | 0,3 | 365 | 129 |
| Experimental | | 0,49 | | | 0,32 | 395 | 170 |

angular distortion of the finite element mesh and (ii) PFEM does not need a chip workpiece separation criterion and (iii). PFEM is able to predict results that are in good agreement with numerical simulations and experiments.

In this research the (PFEM) is applied to the numerical simulation of metal cutting of 42CD4 steel in orthogonal conditions. Comparisons are made against empirical and numerical results obtained with other software: AdvantEdge, Deform and Abaqus/Explicit

## 2. The Particle Finite Element Method (PFEM)

**The basis:** The PFEM, originally developed in[8], is a numerical technique for modeling and analysis of complex multidisciplinary problems in fluid and solid mechanics involving thermal effects, interfacial and free-surface flows, and fluid-structure interaction, among others. PFEM is a particle method in the sense that the domain is defined by a collection of particles that move in a Lagrangian manner according to the calculated velocity field, transporting their momentum and physical properties (e.g. position, displacement, velocities, strain, stresses, internal variables, etc).

**How it works?** The PFEM, as was initially formulated, uses a finite element mesh to discretize the physical domain and to integrate the differential governing equations. In contrast to classical finite element approximations, the nodes of the mesh move according to the equations of motion in a Lagrangian fashion. At the end of each time step the mesh has to be re-build as the nodes have been moved to their new time step position. For this reason a fast and robust algorithm to build the new mesh is essential. The Delaunay Tessellation is chosen to connect all the particles at the new time step position giving a new mesh. The resulting

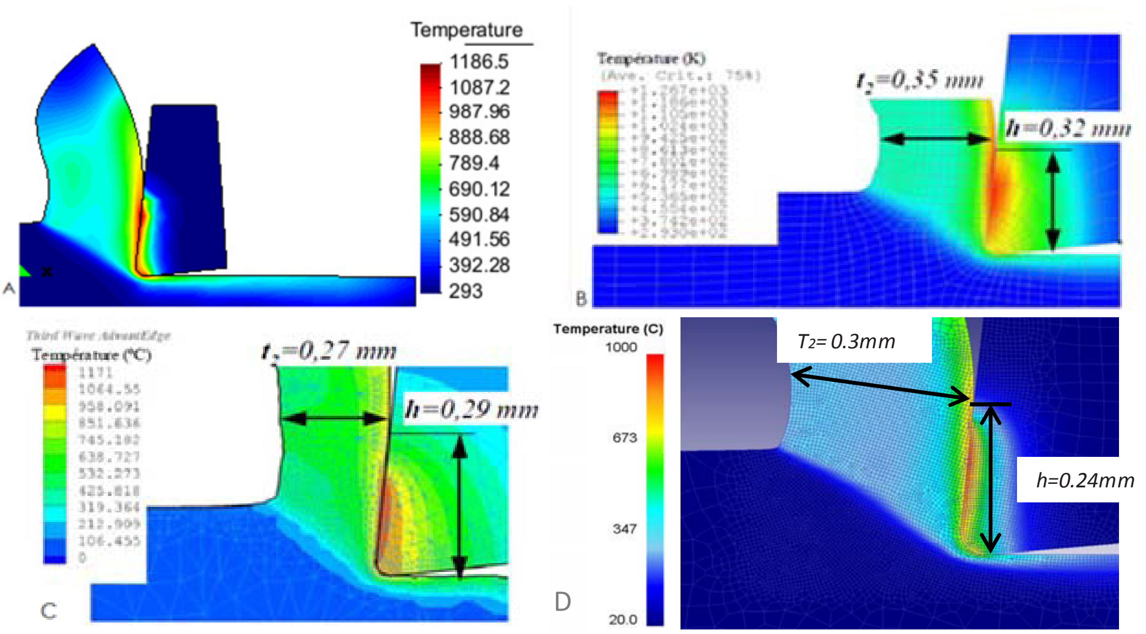


Fig. 2. Comparisons of temperature fields given by A. PFEM, B. Abaqus, C. AdvantEdge and D. Deform.

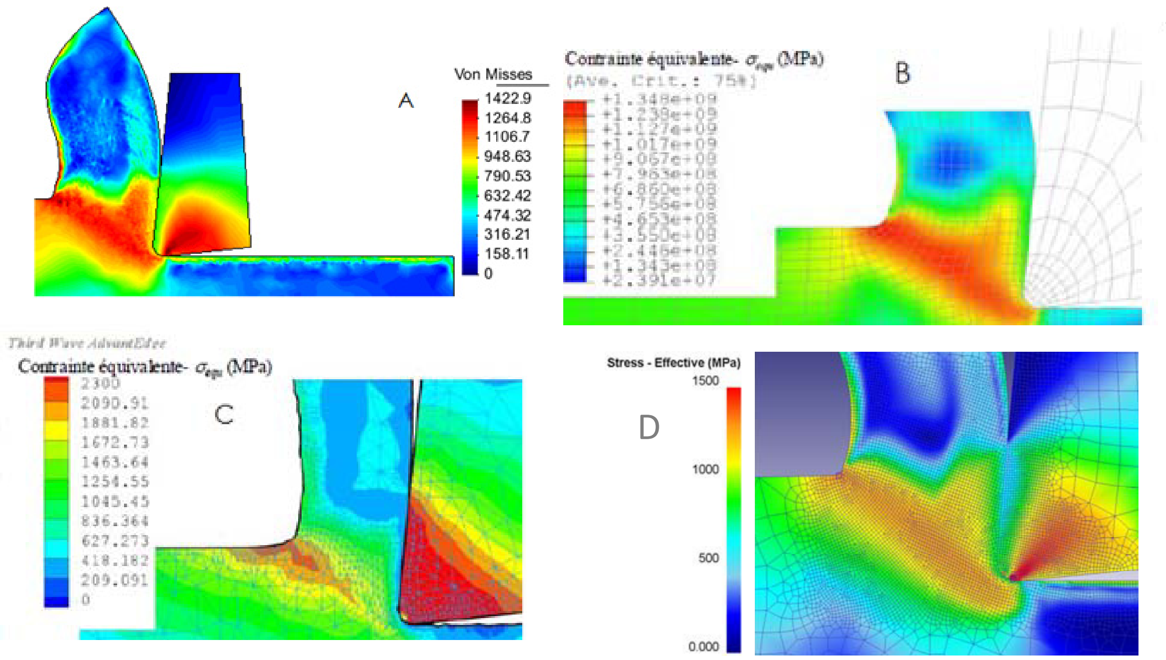


Fig. 3. Comparisons of Von Mises stress fields given by A. PFEM, B. Abaqus, C. AdvantEdge and D. De-form.

mesh not only works as a support where the differential equations are integrated, it is also used to identify the contacts and to track the free surface. The track of the surface is accomplished with the help of a technique called alpha-shape.

**PFEM in metal cutting**: In contrast to the classical PFEM approximation described above, some modifications have to be introduced to apply it properly to the numerical simulations of cutting processes. In the case of the boundary, in which the free boundary was initially obtained by the alpha shape method, in this work the boundary is treated as a material surface. It is due to the high accuracy required to capture correctly the formation of the chip during the cutting process. This requirement is even higher when a serrated type chip is developed. The consequence is that a modified Delaunay constraint triangulation is required together with an insertion/deleting particle approach. Also the information transfer, between meshes, is done by means of a projection technique. Finally, the quality of the mesh is improved by introducing a Laplacian smoothing strategy.

## 3. Numerical Assessment

### 3.1 *Orthogonal cutting simulation of 42CD4 steel using the Particle Finite Element (PFEM)*

In Fig. 1 a 2D numerical model using PFEM is set up.

The Johnson-Cook thermo-elasto-visco-plastic law describes the workpiece material behavior.

In order to validate PFEM strategy, a cutting process of 42CD4 steel at 300m/min, with a tool radius of 0.04mm, a rake angle of 6º and a cutting depth 0.2 mm is proposed.

Materials and contact properties used are the same presented in[1]. A summary of all the inputs parameters can be found in Table 2

The time step used during the simulation was 1.1e-8 seconds; as a result 20000 steps were needed.

Fig. 2 (a) shows the temperature field after a cutting length of 1mm. The maximum tool temperature reached is about 1186K. It is located far from the cutting edge, and approximately at the distance of the 1.25 times the undeformed chip thickness (t1).

The maximum von Mises stress ( Fig. 3(a)) inside the chip-piece takes places in the primary shear zone, while the maximum von Mises stress inside the tool is close to the point where the tool loses the contact with the machined surface.

### 3.2 *Numerical and experimental validation of the PFEM strategy*

Data about experimental results have been obtained from data reported in the literature[1]. Also, data about numerical simulations using Advantage and Abaqus have been obtained in[1].

Table 2. Mechanical and thermal properties of the workpiece and the tool.

| | | | |
|---|---|---|---|
| Material Properties | Conductivity | Workpiece | 42,6 at 373K |
| | | | 42,3 at 473K |
| | | | 37,7 at 673K |
| | | | 33,1 at 873K |
| | | Tool(P10) | 25 |
| | Specific Heat | Workpiece (42CD4) | 473(423K-473K) |
| | | | 519(623K-673K) |
| | | | 561(823K-873K) |
| | | Tool(P10) | 200 |
| | Thermal expansion coefficient (1/K) | | 0 at 293K |
| | | | $14,5.10^{-6}$ at 673K |
| | Percentage of plastic power into heat | | 0,9 |
| | Density ($Kg/m^3$) | Workpiece (42CD4) | 7800 |
| | | Tool(P10) | 10600 |
| | Elastic Modulus (Gpa) (42CD4) | | 210 |
| | Poisson (42CD4) | | 0,3 |
| | Plasticity | A(Mpa) | 598 |
| | Johnson-Cook | B(Mpa) | 768 |
| | Workpiece(42CD4) | C | 0,0137 |
| | Tamb = 293K | M | 0,807 |
| | Tfus = 1793K | N | 0,2092 |

| | | | |
|---|---|---|---|
| Contact | Thermal Properties | Thermal Conductance ($W/(m^2K)$) | 1,00E+08 |
| | Mechanical Properties | Partition coefficient | 0,5 |
| | | Friction Coefficient | 0,23 |
| | | Norton Hoff Coefficient | 6,00E-05 |
| | | Percentage of friction Energy converted into heat | 1 |

Validation was carried out comparing PFEM results with experimental ones and numerical results obtained from the commercial software Abaqus, Deform and AdvantEdge.

Table 1 compares the numerical and the experimental cutting and feed forces results obtained for the reference cutting test. It is observed a good agreement between the experimental and the numerical cutting forces predicted by PFEM, Deform and Abaqus. Instead, comparing experimental cutting forces with AdvantEdge results, higher differences were found.

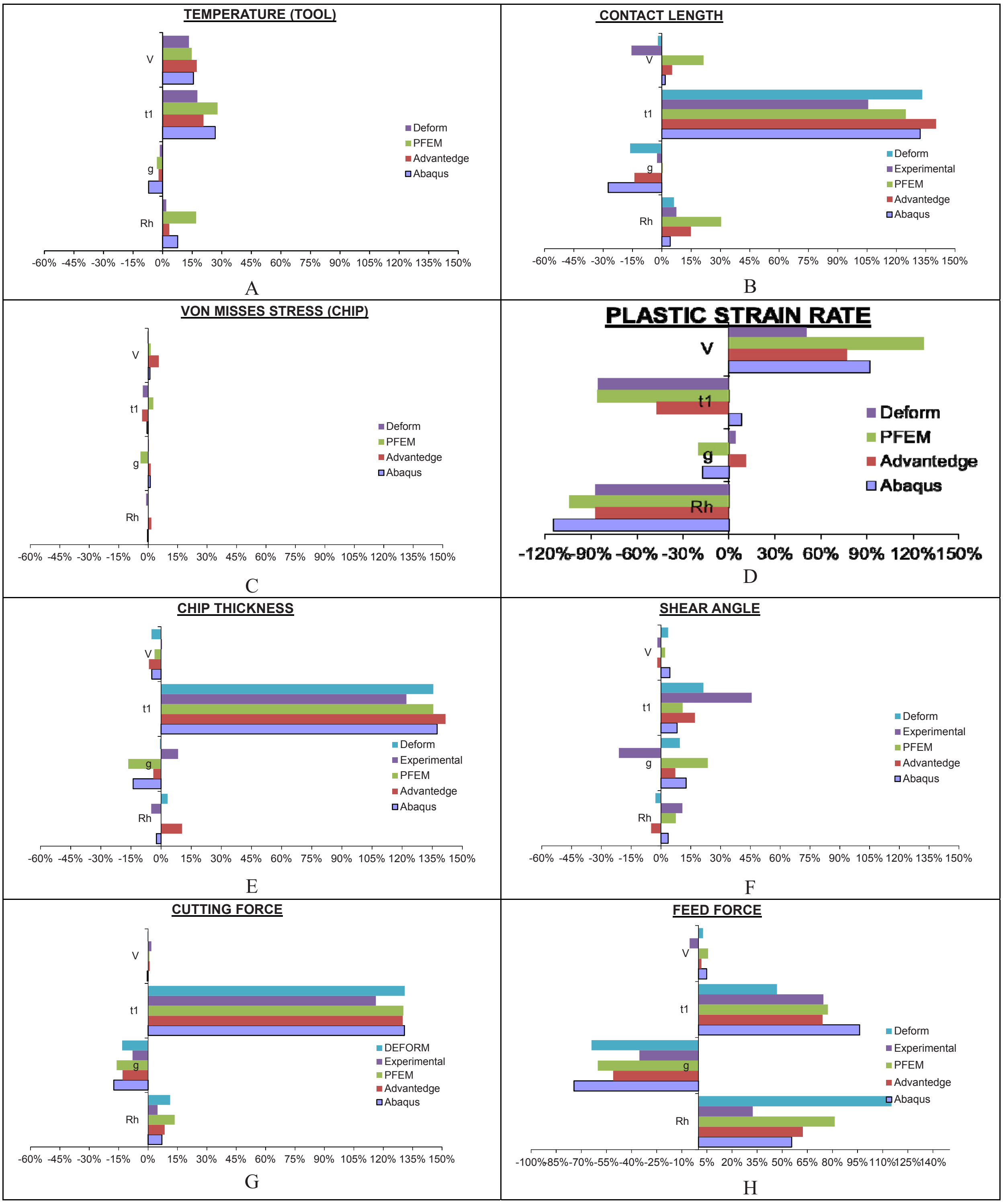


Fig. 4. Numerical and Experimental effects obtained after sensibility analysis.

Table 1 shows the large differences between the experimental and numerical feed forces.

Regarding to the chip thickness (t2) a relatively quite good agreement was found for all the results. However, the tool-chip contact length (h) measured in the experiments is about two times greater than the length predicted by the numerical simulations.

Fig. 2 and Fig. 3 show a comparison of the temperature, von Mises stress. The temperature predicted by PFEM, Abaqus, Deform and Advantedge are similar. The von Mises stresses are similar for PFEM, Deform and Abaqus, while AdvantEdge shows a different field possibly due to the constitutive model used.

Hence, the numerical model set up with PFEM is considered to be accurate enough to carry out a sensitivity analysis to process parameters.

### *3.3 A Design of experiments with PFEM and its comparison with a design of experiments with the commercial software (FEM)*

This section presents a (DoE) to study the influence of cutting conditions on output variables using the PFEM. Also, DoE's carried out using FEM and Experimental results. In Fig. 4, V (the tool velocity), t1 (undeformed chip thickness), g (the rake angle) and Rh (the tool radius).

PFEM predicts that increasing 6 times the chip thickness implies increasing 125% the contact length (Fig. 4B). The effect of the rake angle predicted by PFEM is opposite to other numerical simulations and experiments (friction law). The effect of the tool velocity predicted by PFEM, Abaqus and AdvantEdge is different from the effect given by the experiments.

PFEM predicts that the most significant effect on deformed chip thickness is the undeformed chip thickness (Fig. 4 F), quite similar to the effect predicted by the other numerical simulations. All the numerical simulations predict an opposite effect of the rake angle on deformed chip thickness. FEM and PFEM predict a decrease in the chip thickness increasing cutting speed, while experiments shows a negligible effect.

The effects on cutting forces of the cutting conditions predicted by the numerical simulations and experiments are similar (Fig. 4 G).

PFEM, FEM and experiments predict an increase in feed forces due to an increase in tool radius and chip thickness; while increasing rake angle implies decreasing the feed force (Fig. 4 H). The tool radius and the rake angle effect predicted by the simulations is two times the effects given by the experimental results.

## 4. Conclusions

The numerical simulations present PFEM as a promising strategy to simulate metal cutting processes, because PFEM overcomes some disadvantages of numerical schemes developed until now. For example, (i) allows the separation of chip and workpiece without using a physical or geometrical criterion, (ii) PFEM decreases the numerical diffusion due to re-meshing (transient mesh adaptivity is used instead of re-meshing, (iii) PFEM needs less degree of freedom than used in a numerical simulation using FEM. Furthermore, PFEM predicts similar result to the other software and experiments as shown in Fig. 4 and Table 1.

The computing time needed by PFEM under Matlab programming and exploding code vectorization (intuitive, concise and faster programming style) is similar to FEM software. It is expected, that PFEM under high level programming language needs less computing time than standard finite element software.

## Acknowledgments

The Spanish Ministry of Economy and Competitiveness, and the Catalan Government Re-search Department (AGAUR), are gratefully acknowledged for their financial support to this research under grants BIA2011-24258 and 2009 SGR 1510, respectively.

The authors thank the Basque and Spanish Governments for the financial support given to the projects PROFUTURE II (code IE11-308), INPRORET (code IE12-342) and METINCOX (DPI2009-14286-C02-0 and PI-2010-11).

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