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High speed machining modelling: SPH method capabilities

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***Abstract*— The purpose of this work is to evaluate the use of the Smoothed Particle Hydrodynamics (SPH) method within the framework of high speed cutting modelling. First, a 2D SPH based model is carried out using the LS-DYNA® software. SPH is a meshless method, thus large material distortions that occur in the cutting problem are easily managed and SPH contact control allows a "natural" workpiece/chip separation. The developed SPH model proves its ability to account for continuous and shear localized chip formation and also correctly estimates the cutting forces, as illustrated in some orthogonal cutting examples. Then, The SPH model is used in order to improve the general understanding of machining with worn tools. At last, a milling model allowing the calculation of the 3D cutting forces is presented. The interest of the suggested approach is to be freed from classically needed machining tests: Those are replaced by 2D numerical tests using the SPH model. The developed approach proved its ability to model the 3D cutting forces in ball end milling.**

I. INTRODUCTION

Machining is the most used process in industrial components production. The development of accurate and reliable machining process models has received considerable effort in the past years, but physical phenomena involved in industrial cutting cases are fully 3D and very complex. Thus, the orthogonal cutting framework is generally used in order to allow a 2D plain strain study. Orthogonal cutting conditions are reached when the cutting edge is rectilinear, perpendicular to the chip flow in each point, and perpendicular to the tool feed. In these conditions, the cutting parameters are summarized by cutting speed (Vc) and feed (f) (see figure 1).

In orthogonal cutting conditions and in stationary regime, the tool/workpiece interaction and the chip generation process can be represented in a simple way. Three principal shearing zones appear, see figure1: the primary zone (shearing causing the chip formation), the secondary zone (shearing due to tool/chip friction), and the tertiary zone (shearing due to tool/generated surface friction).

For years, significant effort has been devoted to the development of computational models of high-speed machining in order to overcome analytical models limits. Most of the machining numerical models are based on Lagrangian or Arbitrary Lagrangian Eulerian (ALE) Finite Element Methods (FEM) [3, 13].These approaches imply two major difficulties. First of all, the friction model must account for all the tribological complexity of machining. In most cases, the Coulomb model is used; it is very simple but limited [3]. Moreover, the friction parameter is often used in order to readjust the cutting forces obtained by FEM compared to experimental results [3, 13]. The workpiece/chip material separation model is the second aspect of the modelling difficulties. Lagrangian FE methods present the disadvantage of leading to large grid distortions. This implies the use of ALE methods and time consuming remeshing techniques.

Here, we present an approach based on the Smoothed Particle Hydrodynamics (SPH) method in the frame of the LS-DYNA® hydrodynamic software [12].

The paper is organized as follows. In section 2, our 2D SPH cutting model is introduced. In section 3, SPH cutting model applications are outlined and compared with other numerical or experimental data. The use of SPH as a numerical tool for a better understanding of the chip formation with worn tools is also presented. Finally, a developed 3D milling model based on 2D SPH model results is presented.

II. SPH CUTTING MODEL

A. *Basic principles of the SPH method*

SPH method is a meshless Lagrangian technique. Material properties and state variables are approximated by their values on a set of discrete points, or SPH particles. This avoids the severe problems of mesh tangling and distortion which usually occur in Lagrangian analyses involving large deformation. For more details on the method used, the reader can refer to [12].

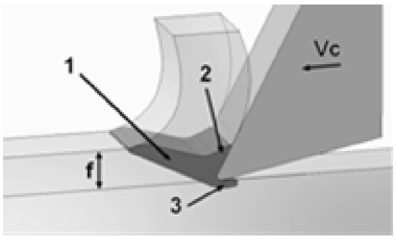


Figure 1. Shear zones definition

B. Model description

Several assumptions were made in order to reduce the model size and the computation time, allowing the development of a useful tool.

The model is implemented in the orthogonal cutting framework, thus in 2D (3D model can easily be developed, see figure 3). The tool is supposed rigid and has an imposed velocity. During the process, the computation time is reduced by using an imposed tool velocity ten times higher than the real velocity. This assumption is usually used in simulation of stamping processes. It is valid as long as the accelerated mass is low and the material behaviour is slightly influenced by the strain rate.

Accurate and reliable flow stress models are highly necessary to represent work material behaviour under high speed cutting conditions. In our model, the constitutive material law proposed by Johnson and Cook [4] is used and all associated parameters result from the literature.

C. SPH cutting model capabilities compared to classical FEM approach

An overview of the main specificities of the SPH cutting model approach compared to classical Lagrangian FE models is summarised in Table 1.

SPH method applied to machining modelling involves several advantages.

First, high strains are easily handled. The particles move relatively to each other in a disordered way during the deformation. This can be considered as a particles rearranging without topological restriction, thus no remeshing is needed.

Another advantage induced by SPH is the "natural" chip/workpiece separation. The relative motion of the particles creates the opening. The new free surfaces are given by the particles positions. Thus, the workpiece matter "flows naturally" around the tool tip.

In the same way, the SPH method presents an original aspect regarding contact handling. Indeed, when a workpiece particle "sees", in its neighbouring, tool particles, then workpiece particle circumvents the tool. Thus, friction is modelled as particles interactions and friction parameter does not have to be defined. SPH friction modelling must be studied in-depth but it offers a very interesting alternative to traditional definitions.

The last aspect of the SPH method presented in this part is related to the computational time. Lagrangian methods using adaptive remeshing are as expensive as SPH methods. Moreover, one advantedge of the SPH method is that 3D models are sometimes faster than FE models, it is the case in the 3D oblique cutting modelling (Figure 3).

D. Some specificities of the SPH model implementation

The implemented SPH model within the framework of LS-DYNA reveals some specific aspects.

1) Artificial viscosity

A viscosity term is classically introduced in FE to preserve the stability of the method when shocks are occuring. SPH method uses the same approach. Artificial viscosity is introduced into the equation of conservation of momentum. This term is controlled in LS-DYNA by two parameters: Q1 and Q2 (Cf. CONTROL_BULK_VISCOSITY). Technical details are compiled in [11]. Figure 4 shows the influence of artificial viscosity on an orthogonal cutting example. Let us note that the artificial viscosity parameters were selected in order to smooth in a coherent way the phenomena. All the calculations presented in the continuation were carried out with the same parameters.

TABLE I. SPH AND CLASSICAL APPROACH COMPARISON

	Lagrangian FE models	**SPH cutting model**
Large deformation process	Adaptative remeshing algorithm	SPH meshless nature
New free surfaces creation	Continuous remeshing and fracture model	Particles separation
Contact	Friction Coulomb approach	Particles interactions

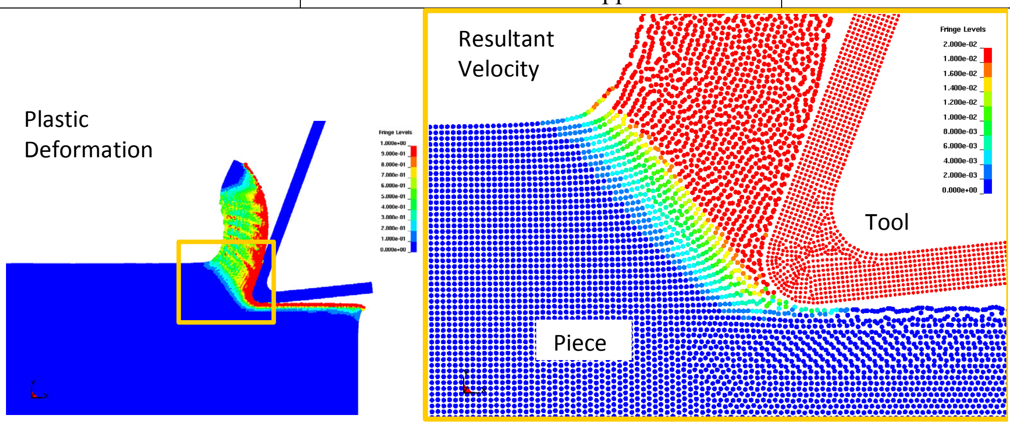


Figure 2. Chip separation

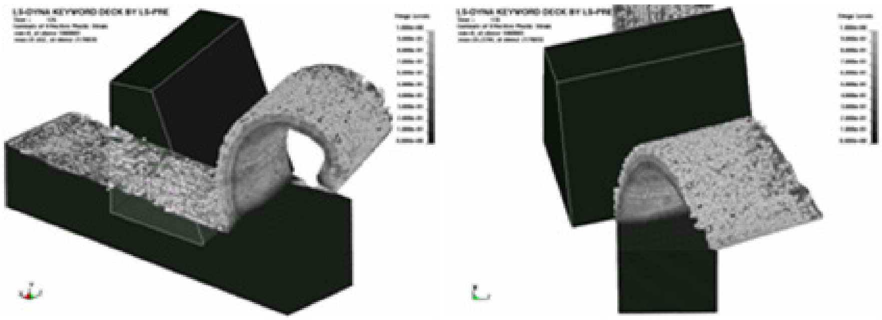
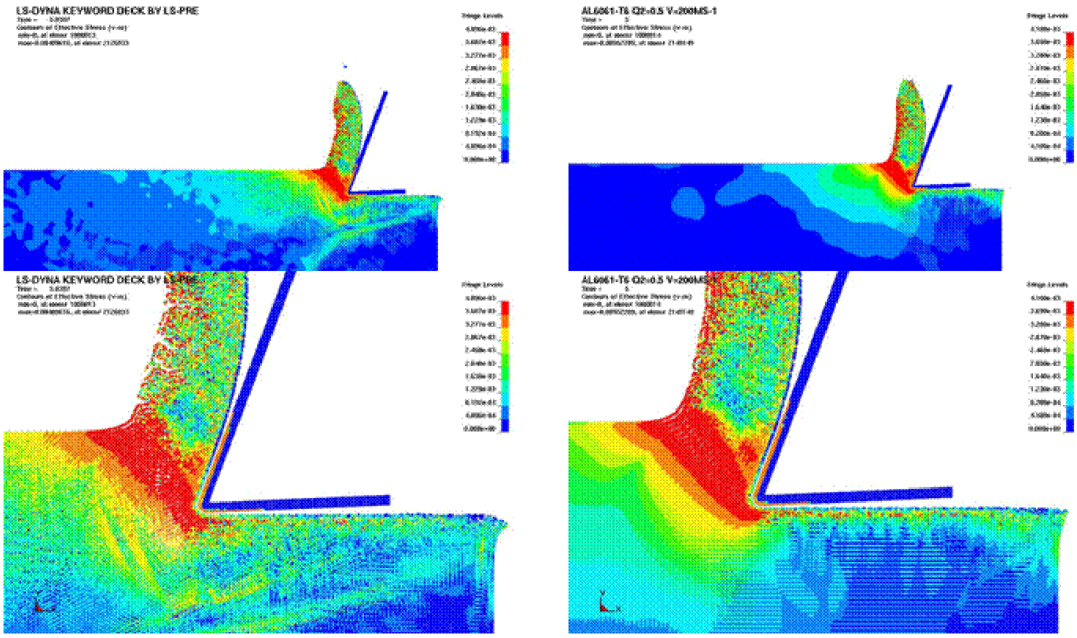


Figure 3. Al6061-T6 Oblique cutting case: 3D SPH model a. iso view b. top view



Von Mises Stress
Default FE parameters Q1=1.5 **Q2=0.06**

Von Mises Stress
Q1=1.5 **Q2=0.5**

Figure 4. Artificial viscosity effect

2) Renormalized SPH formulation

Due to the lack of neighbours, classical SPH approximation is not correctly calculated on the boundaries. Indeed, a particle located on a free edge only interacts with existing particles located on one side of the free edge, see Figure 5.

LS-DYNA proposes an alternative formulation to particle SPH approximation which corrects this deficiency. This formulation is called renormalization. It is based on [14] and [15] work. The renormalized formulation improves the SPH method consistency (order 1). Two advantages are obtained: a better precision when the particles are disordered and a better approximation of the calculated quantities at the boundary.

In the machining modelling case, standard SPH underestimates the chip curve (Figure 6). The use of the renormalized formulation allows a better modelling of the chip curve and a better evaluation of the matter state on the surface (Figure 6).

3) Numerical instabilities

The SPH method is prone to two types of numerical instabilities: tensile instability and zero energy modes. These aspects are discussed in details in [2].

We faced numerical instability of the SPH method for the cutting model. Figure 7 shows an example of numerical fractures. Increasing the physical velocity of the tool decreases these instabilities. Currently, the SPH method in LS-DYNA does not provide any advanced solution to solve this problem but a work is in progress.

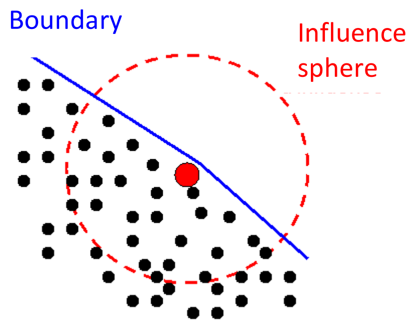


Figure 5. Standard SPH problem at the frontier

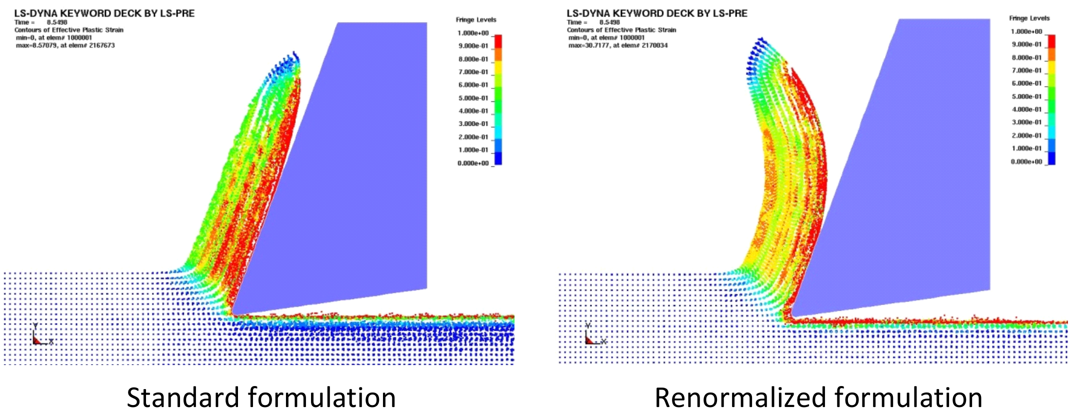


Figure 6. Standard/Renormalized SPH formulation in metal cutting

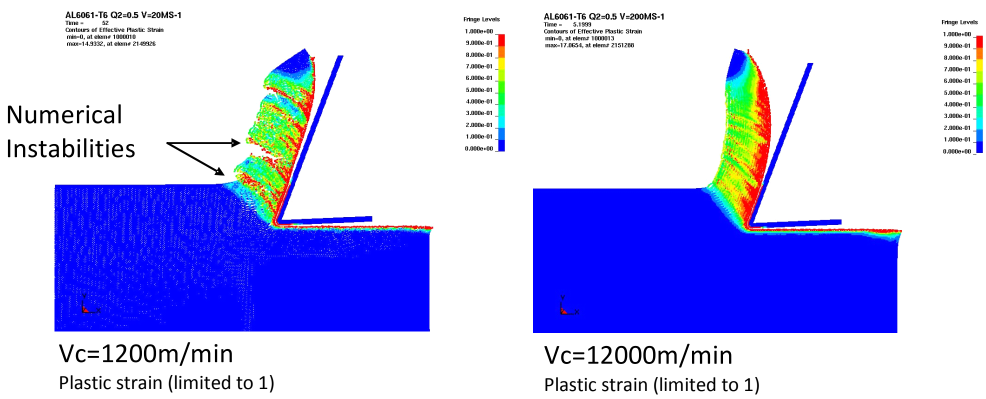


Figure 7. Numerical instabilities

III. SPH CUTTING MODEL APPLICATIONS

Two applications are presented here: the first one reproduce a continuous chip process and the second one a shear localized chip. They are studied and compared to experimental results and numerical FEM (AdvantEdge [13]) results. AdvantEdge is a reference in machining simulations. It is an explicit dynamic, thermo-mechanically coupled FEM package specialized for metal cutting. Here, comparisons are carried out on the chip morphology, stress distribution and the specific cutting forces. Other comparisons can be found in [8].

A 3D milling forces model based on the 2D SPH model is also introduced.

A. *Continuous chip: Al6061-T6*

We first present the result of a cutting problem using material Aluminium alloy Al6061-T6. The process parameters are defined as follows: speed 10m/s, rake angle 5°, feed 250µm and edge radius 25µm.

The material model parameters result from Lesuer, Leblanc and Kay [7].All the AdvantEdge and experimental results presented in this part are based on [13].

1) Chip morphology and stress distribution

LS-DYNA and AdvantEdge chip morphology results are presented in figure 8. The considered Aluminium alloy produces continuous chip in the speed and feed range studied [13]. LS-DYNA and AdvantEdge models results are in agreement with these experimental observations. The AdvantEdge model overestimates the chip thickness and the LS-DYNA SPH model underestimates it. Figure 8b shows the Von Mises stresses during the continuous chip formation. Primary and secondary shear zone described in figure 1 can be easily identified.

2) Cutting forces

Normal (or feed) and tangential (or cutting) forces are compared in figure 3.

LS-DYNA predicted cutting forces agree within 10% and 30% of the measured values for tangential and normal components respectively. These differences can be explained by chip separations criteria, friction model and SPH velocity assumption. It is important to recall that the SPH model does not use a numerical friction. Thus the predicted cutting forces are not adjusted. On the other hand, the AdvantEdge model used a Coulomb parameter fixed to 0.2 without any information on how to choose this value.

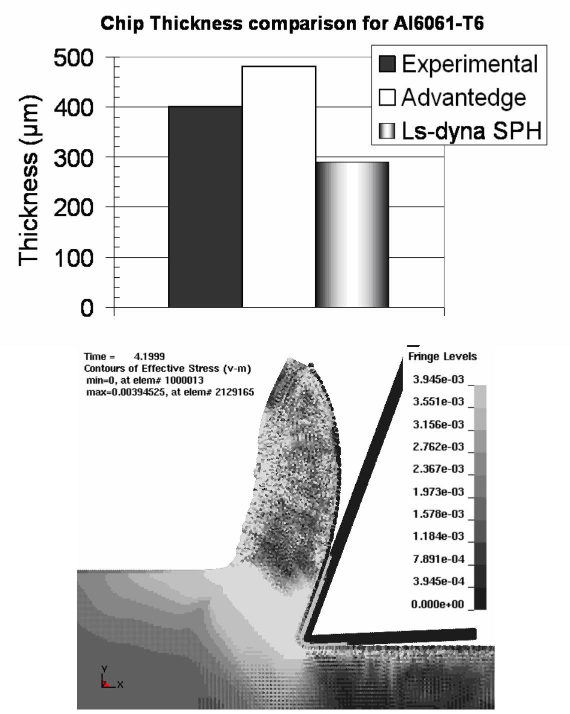


Figure 8. Al6061-T6 a.Chip thickness AdvantEdge/LS-DYNA comparisons b. SPH model VM stress

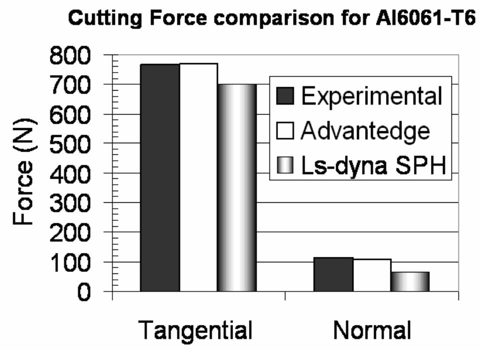


Figure 9. Al6061-T6 predicted cutting forces comparisons AdvantEdge/LS-DYNA

B. *Shear localized chip: Ti6Al4V*

In this section, the Ti6Al4V alloy machining is used under dry conditions. When machining titanium alloys with conventional tools, the tool wear rate progresses rapidly, and it is generally difficult to achieve a cutting speed of over 60m/min. The tool wear analysis method developed here is based on a chip formation analysis using experimental and numerical results. The main idea is to use the developed SPH model to study the cutting forces and the chip formation with new and worn tools and compare these results to available experimental data. This work was completed in collaboration with the Lamefip ENSAM Bordeaux France [10].

The studied cutting conditions are summarized in Table 2.

TABLE II. CUTTING CONDITIONS

Tool material	Tungsten carbides Grade H13A WC-6Co K20
Rake angle	0°
Clearance angle	11°
Cutting speed	60m/min
Feed	0.3mm

The tool geometry before and after machining are shown in Figure 10.

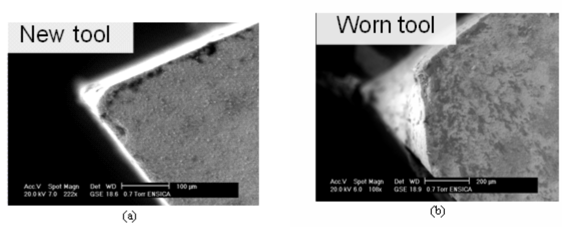


Figure 10. SEM images of (a) a new and (b) a worn tool.

1) Chip morphology

Under the cutting speed and feed range studied, Ti6Al4V alloy produces shear localized chips (see Figure 11). Shear localized chips are characterised by oscillatory profiles. They result from adiabatic shear band formation in the primary shear zone of the workpiece material. The chip type obtained for the SPH model is in accordance with experiments (Figure 11). The SPH model shows a shear band thickness increase and a decrease of frequency of chip segmentation with wear, which is also observed experimentally.

It is possible to identify a metal dead zone in the chip formation mechanisms with worn tools. This area is reduced to a triangular zone in front of the tool tip which moves with the tool. This physical mechanism was already observed in experiments [5]. The SPH approach is able to predict this stagnation zone because of its meshless nature.

2) Cutting forces

Experimental results, illustrated in Figure 13, show a great influence of wear on the feed force (about 90%) and a less important increase of the cutting force (about 20%). The SPH cutting model results show a mean feed force increase of about 95% with tool wear and of the cutting force of about 10% (Figure 13). So, the SPH model is able to correctly predict these variations, induced by the tool wear by only taking into account the tool tip shape changes. We think that the metal dead zone formed in front of the tool tip is the main cause of the large feed force increase [10].

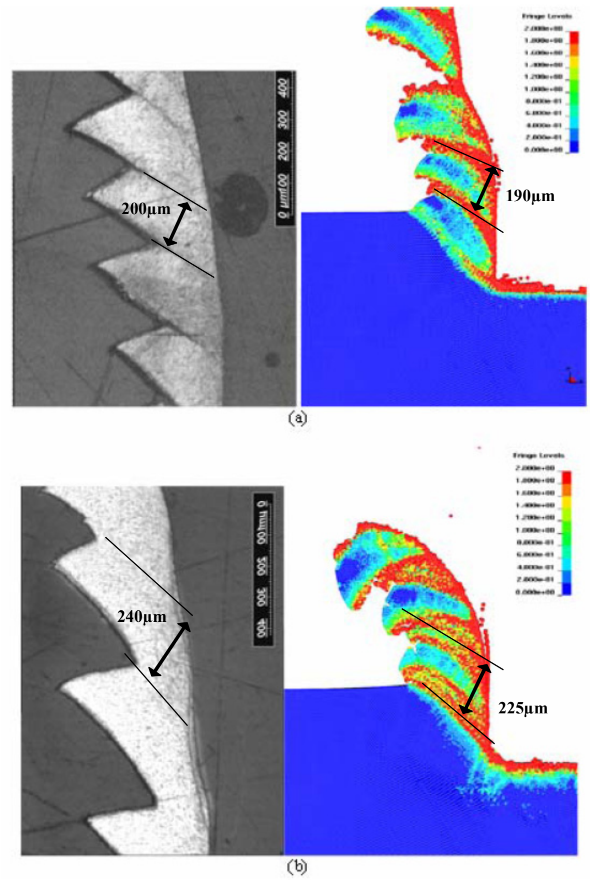


Figure 11. Experimental / numerical chip formation using (a) a new and (b) a worn tool geometry

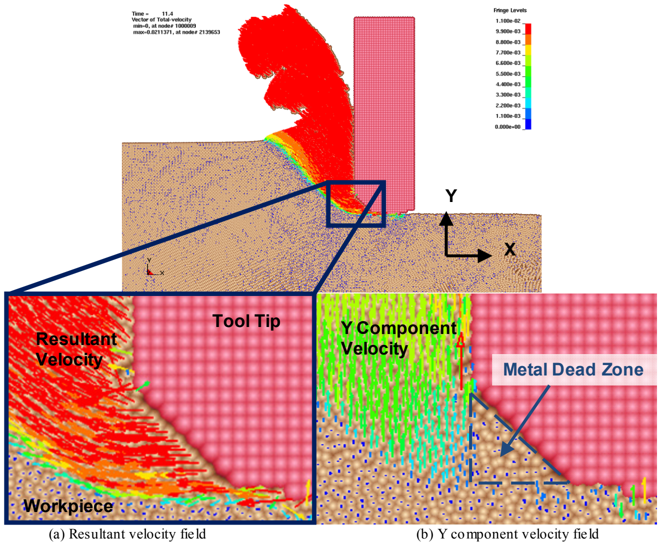


Figure 12. Velocity field at tool tip: Metal dead zone identification

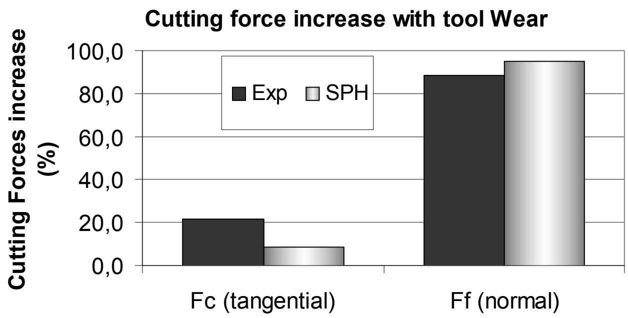


Figure 13. Tool wear influence on cutting forces: SPH model compared to experimental data

C. Milling 3D cutting forces modelling via 2D SPH

The validated 2D SPH model can be the basis of 3D milling force model. The proposed approach is based on a 3D mechanistic model developed by Altintas et al. [1]. This model connects chip thickness to cutting forces via cutting coefficients that are experimentally obtained by series of orthogonal cutting tests. These machining tests can be replaced by 2D numerical tests using a SPH model (more details can be found in [9]). A validation example is presented in figure 14. Experimental and Lamikiz model (cutting coefficients experimentally obtained) results are compared to the fully predictive proposed model (cutting coefficients numerically obtained via 2D SPH model). The proposed numerical approach, strongly limits the experimental phases necessary and comparable results to a model based on an experimental determination of the cutting coefficients are obtained.

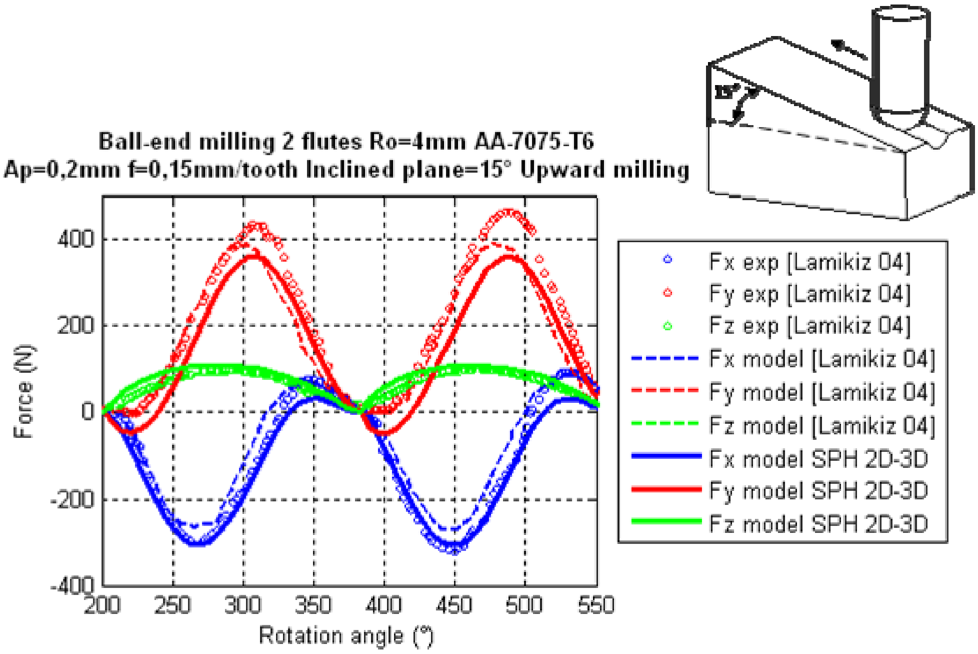


Figure 14. 3D developed model compared to Lamukiz work [6]

IV. 4. Conclusion

The results of the LS-DYNA SPH model were compared with experimental and numerical data. This study shows the relevance of the selected numerical tool. The SPH model is able to predict continuous and shear localized chips. The model also correctly estimates the cutting forces without introducing an adjusting friction parameter. Thus, comparable results compared to machining dedicated codes are obtained.

The SPH 2D cutting model has also been implemented as a helpful tool for understanding chip formation. The meshless nature of the method makes possible to represent a dominating physical phenomenon in the chip formation with strongly worn tool: the metal dead zone.

We also show that validated 2D SPH model can be the basis of 3D milling force model.

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