# A new approach of high speed cutting modelling: SPH method

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**Abstract.** The purpose of this study is to introduce a new approach of high speed cutting numerical modelling. A lagrangian Smoothed Particle Hydrodynamics (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 permits a “natural” workpiece/chip separation. Estimated chip morphology and cutting forces are compared to machining dedicated code results and experimental data. The developed SPH model proved 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.

## 1. INTRODUCTION

Machining is the most used process in industrial components production. Machining modelling is becoming an increasingly important tool in gaining understanding and improving machining processes. The development of accurate and reliable machining process models has received considerable attention from both academic researchers and industry practitioners in recent years, but the physical phenomena involved in industrial cutting cases are fully 3D and very complex. Thus, most of the prior researches were carried out within the orthogonal cutting framework in order to permit a 2D plain strain study. It remains today an interesting study framework because it can be the base of industrial cases studies. 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.

Comprehension of the chip formation mechanisms is still partial but important information was identified. 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) [1,8].These approaches imply three major difficulties. First of all, the material model must represent the complex material behaviour under high strain, strain rate and temperature. Next, the friction model must account for all the tribological complexity of machining. In most cases, the Coulomb model is used in cutting models; it is very simple but limited [8]. Moreover, the friction parameter is often used in order to readjust the cutting forces obtained by FEM compared to experimental results [1,8]. The workpiece/chip material separation model is the third 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 remeshing techniques which are known to be time consuming and to loose energy through a loss of stresses during remapping.

Here, we present a new approach of the metal cutting modelling by using Smoothed Particle Hydrodynamics (SPH) method in the frame of the Ls-Dyna hydrodynamic software [4, 10]. SPH is a meshfree Lagrangian method. Material properties and state variables are approximated by their values at a discrete set of disordered points, or SPH particles. The developed model introduces a new approach of material separation in cutting modelling.

The paper is organized as follows. In section 2, our SPH cutting model is introduced and, in section 3, SPH cutting model applications are outlined and compared with other numerical or experimental data.

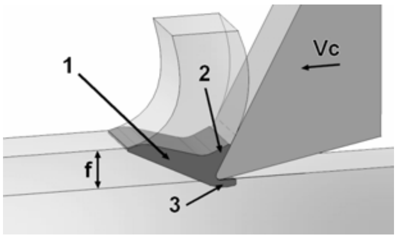


**Figure 1**. Shear zones definition

## 2. SPH CUTTING MODEL

### 2.1 Basic principles of the SPH method

Smoothed Particle Hydrodynamics (SPH) method is a grid-less Lagrangian technique that originated in 1977. The main advantage of the method is to bypass the requirement for a numerical grid to calculate spatial derivatives. This avoids the severe problems associated with mesh tangling and distortion which usually occur in Lagrangian analyses involving large deformation and extreme loading events. Grid based methods such as Lagrange and Euler FE assume connectivity between nodes to construct spatial derivatives. SPH uses a kernel approximation which is based on randomly distributed interpolation points with no assumptions about which points are neighbours to calculate spatial derivatives. For more details on the method used, the reader can refer to [4].

### 2.2 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. But, one can note that it is not very difficult to develop a full 3D model using the SPH method (see figure 7).

The tool is supposed to be non deformable and its velocity is imposed. 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 as the material behaviour is slightly influenced by the strain rate. These two conditions will be used in section 3.

Accurate and reliable flow stress models are considered as highly necessary to represent work material constitutive behaviour under high speed cutting conditions. In our model, the constitutive model proposed by Johnson and Cook [3] is used and all associated parameters result from the literature.

### 2.3 SPH model particularities

The SPH method applied to machining modelling involves several advantages. First, no remeshing is needed when deformations are high, even due to shear. Another advantage induced by SPH method is the “natural” chip/workpiece separation: no rupture criterion is necessary. The creation of the new free faces is directly managed by the SPH method. Indeed, when a workpiece particle “sees” in its neighbours particles of the rigid moving too, the workpiece particle circumvents the tool. Then, the workpiece matter “flows naturally” around the tool tip.

In the same way, the SPH method presents an original aspect concerning contact handling. Indeed, it does not require the definition of surfaces. So, it does not involve a friction parameter. This SPH friction management 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 relates to the computational time. The experienced computational time allow industrial use of the developed tool.

## 3. APPLICATIONS

Two applications are presented here: these are two cutting cases that are known to produce respectively continuous and shear localized chip. They are studied and compared to experimental and numerical FEM (AdvantEdge [9]) data. AdvantEdge is often taken as reference. It is an explicit dynamic, thermo-mechanically coupled FEM package specialized for metal cutting [8]. Here, comparisons are carried out on the chip morphology, stress distribution and the specific cutting forces. Other comparisons can be found in Limido [6].

### 3.1 Continuous chip: Al6061-T6

The first application concerns 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 Marusich [8].

#### *3.1.1 Chip morphology and stress distribution*

Ls-Dyna SPH and AdvantEdge chip morphology results are presented in figure 2. Al6061-T6 is known to produce continuous chip in the speed and feed range studied [8]. SPH and AdvantEdge models results are in agreement with these experimental observations. As expected, the deformation is largely confined to the primary shear zone and to a boundary layer adjacent to the tool.

The AdvantEdge model overestimates the chip thickness and the Ls-Dyna SPH model underestimates the chip thickness. Figure 2b shows the Von Mises stresses map during the continuous chip formation. Primary and secondary shear zone described in figure 1 can be easily identified.

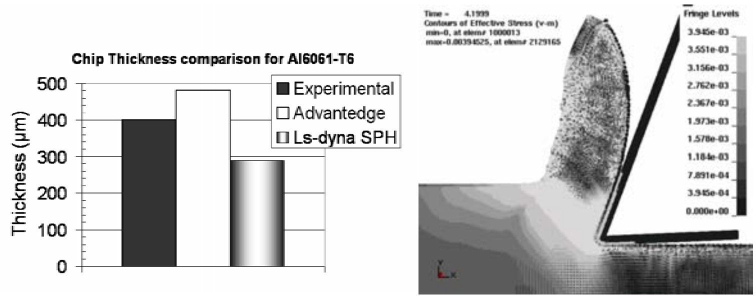


**Figure 2**. Al6061-T6 a.Chip thickness AdvantEdge/Ls-Dyna comparisons b. SPH model VM stress

### *3.1.2 Cutting forces*

Normal and tangential components of the cutting forces are compared. All simulations were performed with a 25µm edge radius in order to minimize the introduction of an additional length scale. The Ls-Dyna and AdvantEdge cutting forces are compared in figure 3.

Ls-Dyna predicted cutting forces agree within 10% and 30% of the measured values for respectively tangential and normal components. These differences can be explained by difference in chip separation criteria, friction model and SPH tool increased velocity assumption. It is important to recall that the SPH model does not have numerical parameter making it possible to control friction. Thus the predicted cutting forces were not adjusted. On the other hand, the AdvantEdge model used a Coulomb parameter fixed to 0.2 without any precision on how or why to choose this value.

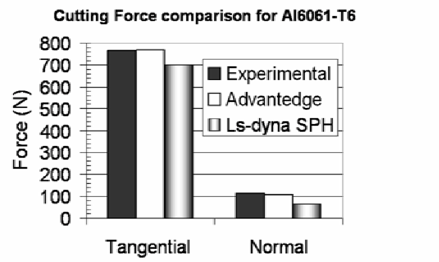


**Figure 3**. Al6061-T6 Presticted cutting forces comparisons AdvantEdge/Ls-Dyna

## 3.2 Shear Localized Chip: AISI4340

The second application concerns AISI4340 high strength steel. The process parameters are as follows: speed 2m/s, rake angle -5°, feed 400µm and edge radius 25µm.

The material model parameters result from Mabrouki work [7]. AdvantEdge and experimental results presented in this part are also based on [7].

### *3.2.1 Chip morphology and stress distribution*

In the speed and feed range studied, AISI4340 produces shear localized chips (see figure 4a). Shear localized chips are characterised by oscillatory profiles. They are the result of adiabatic shear band formation in the primary shear zone of the workpiece material. The local plastic shear instability arises from a competition between the tendency of the material to harden as it deforms, and the opposing tendency of the material to soften if local heating due to plastic dissipation is large enough [2].

Ls-Dyna SPH chip formation results are presented in figure 5. SPH and AdvantEdge models results are in agreement with the experimental observations (see figure 4b).The SPH method correctly models all the steps of the cyclic adiabatic shear band formation. This phenomenon was also very well observed and described in M.A. Davis and T.J. Burns [2]. A cycle is described here:

- The tool tip imposes pressure to the cold material ahead of it, and stresses and plastic strains grow in the primary shear band, figure5a.
- The loads reach the cold yield stress of the material and shear begins in the primary shear band, figure5b.
- The great majority of the plastic work is dissipated as heat and the material starts to heat up locally in the primary shear zone, figure 5c.
- The heating causes thermal softening of the material localized in a narrow deformation zone, figure 5c.
- The new formed deformation zone falls behind the tool tip and the zone is carried away into the flow, figure 5d. This is the end of the cycle.

In order to model shear localized chip, AdvantEdge uses a fracture model which allows for arbitrary crack initiation and propagation. An original aspect of the SPH model presented is that it does not implement a fracture model. Indeed, the fracture due to the shear localization is carried out naturally by the SPH method.

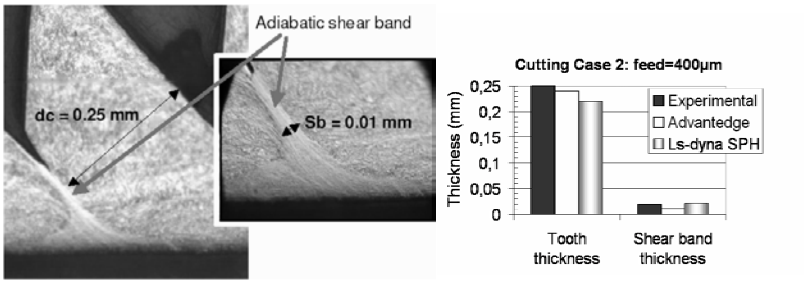


**Figure 4**. AISI4340 a.Chip morphology [7] b.comparisons

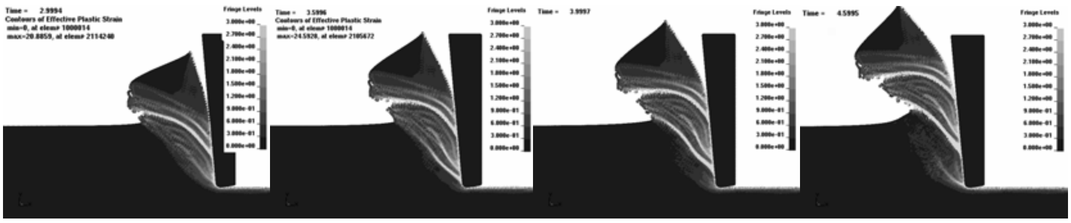

**Figure 5**. Shear localized chip formation steps a. b. c. d.(Plastic strain visual max limited to 3)

### *3.2.2 Cutting forces*

Normal and tangential components of the cutting forces are compared. The Ls-Dyna and AdvantEdge cutting forces are compared in figure 6. Ls-Dyna predicted cutting forces agree within 15% and 35% of the measured values for respectively tangential and normal components. Here again, the AdvantEdge model used a chosen Coulomb parameter of 0.25 without any comment on how and why to choose value.

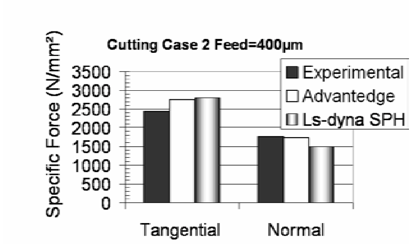


**Figure 6**. AISI4340 Predicted cutting forces comparisons AdvantEdge/Ls-Dyna

## 4. CONCLUSIONS

The results of the Ls-Dyna SPH model were compared with experimental and numerical data. The defined validation criteria were the chip morphology, mechanical state in the shear band and the cutting forces. This study shows the relevance of the selected numerical tool. The SPH model is able to predict continuous and shear localized chips and all the steps of its formation. The model also correctly estimates the cutting forces (approximately 10% and 30% errors on respectively tangential and normal components) without introducing an adjusting parameter like Coulomb friction. Thus, comparable results compared to machining dedicated codes are obtained. The SPH model advantages are the total transparency of the assumptions made and the use of not adjusted numerical parameters (friction coefficient, fracture control parameter). Another important aspect is the meshless nature of the SPH. Indeed, no remeshing is needed to deal with high transformations problems and a “natural” workpiece / chip separation is thus possible. Future work will concentrate on 3D SPH model implementation in order to deal with oblique cutting problems (see figure 7) and more specific research on the free faces, friction and heat exchange in SPH method.

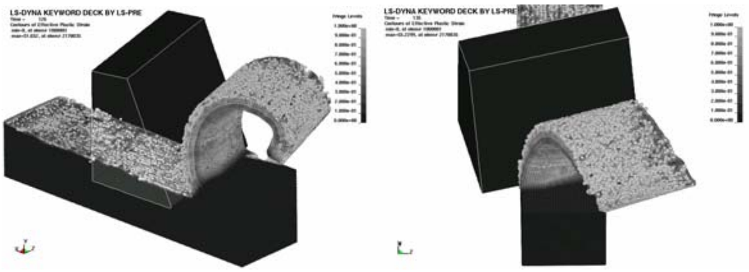

**Figure 7**. Al6061-T6 Oblique cutting case: 3D SPH model a. iso view b. top view

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