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# FVPM simulation of a single-particle scratching surface

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## Abstract

This article investigates the benefits of using Finite Volume Particle Method (FVPM) to simulate grinding process. This meshless particle technique employed to simulate the specimen behaviour is a variant of the well-known Smooth Particles Hydrodynamics (SPH). Indeed, FVPM method has been successfully used for the simulation of elasto-plastic material deformation induce by silt impacts. The presented analysis is based on the simulation and experimentation of a single particle damaging a specimen. The numerical approach is coherent with the literature. Both simulated and measured damage geometries have been compared. The presented results consist in a first step toward simulating more complex surface finishing operations and towards producing industrially relevant outcomes.

## 1. Introduction

Performances of high added value mechanical parts are closely linked to the functional surface quality. Whether these surfaces are designed to provide friction, optical or aerodynamic functions, the geometry must be controlled from the conception to the realization of the part. Grinding operations are commonly used to obtain smooth surfaces after machining and to control surface aspect. This finishing process is characterized by complex interactions between the machined surface and the grinding tool to remove and repel matter. Within this context, manufacturers meet their requirements relying on empirical rules combined with an experienced based know-how. Several techniques have been developed for modelling the material removal mechanism of abrasive processes. Klocke identifies from a literature review four different types of interaction responsible for material removal [1]. Jourani [2] combines experimental observations in a numerical model to induce surface characteristics. From a macroscopic point of view, the model of Preston [3] allows to determine the material removal rate based on an empirical rule. Indeed, relevant results are obtained using these methods and assumptions. Thus, relating these observations to process outcomes is not yet straightforward besides considering experimental testing. Moreover an experimental insight of these local interactions during manufacturing remains unreachable. The increasing computing capabilities offers the opportunity to overcome these hurdles. The concept of continuum mechanics has been proven relevant in numerous industrial applications. It defines a framework of equations available to model the inner mechanical equilibrium structuring matter. A better understanding of the mechanisms of abrasion and a relevant simulation tool to visualize the resulting topography, strain and stresses could lead to improve the computer aided manufacturing at all involved steps. Whereas the surface topography resulting from the machining operation is well known, a realistic prediction of the grinding geometry resulting from a real abrasion process is not yet achievable [4, 5]. The article is structured as follows: Section 2 gives an overview of the numerical scheme used to simulation material behaviour. Two test cases have been numerically implemented. In section 3, the simulation of a Brinell hardness measurement have been carried out while a single indenter scratching a sample material have been simulated in section 4. Experimental and literature comparison showed the relevance of the implemented method.

## 2. Theory

Mechanical simulations rely on the discretization of the volume and the time range in order to solve the partial differential equations arising from the local mechanical equilibrium. Among all the numerical techniques available, one can divide them in two main categories. Mesh-based techniques features connectivity information between the interpolation points whereas meshless methods rely on a set of uncorrelated points. The abrasion process simulation includes large deformations so that it is often needed to apply a regeneration algorithm to handle element distortion. Concerning meshless methods, the particle distribution used to interpolate vector fields inside the specimen allows to take into account any amount of deformation whether small or large. That's why particle-based methods are a suitable choice for wear simulations. Finite Volume Particle Method (FVPM) is a meshless method which includes many of the attractive features of both particle methods, such as SPH, and conventional mesh-based Finite Volume Methods (FVM) [6]. In FVPM, the Sheppard function is used as the interpolating function defined by equations [3] and [2]:

$$\mathbf{U} = \sum_i \psi_i \mathbf{u}_i \quad [1]$$

$$W_i = \begin{cases} 1 & \|\mathbf{x} - \mathbf{x}_i\|_\infty \leq h_i \\ 0 & \|\mathbf{x} - \mathbf{x}_i\|_\infty > h_i \end{cases} \quad [2]$$

$$\psi_i = \frac{W_i(\mathbf{x})}{\sum_k W_k(\mathbf{x})} \quad [3]$$

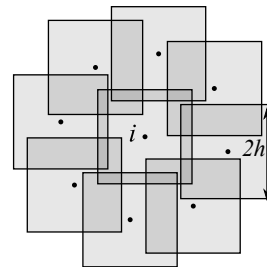


Figure 1: rectangular support kernels

The scheme composed of overlapping particles as pictured in figure 1 is used to interpolate any spatial field. Whether the considered quantity, it's value  $U$  at any given point  $\mathbf{x}$  is the result of a summation over all the nearest neighbours as shown in equation [1]. Compared to a mesh-based technique, additional computational cost is required to retrieve the closest points since the particle cloud does not carry any connectivity information. Nevertheless spatial hashing algorithms allow to reduce the addressed complexity. In FVPM, like in SPH, computational nodes usually move with the material velocity, which is compatible with the Lagrangian form of the equation of motion. This enables the method to handle moving interface problems without issues of mesh deformation or tangling. Contrary to mesh-based methods, whose core functions rely on generating a rigidity matrix to be inverted, working with particles as interpolation points implies to compute internal forces exerted on each particle at each time step. The forces are correlated to accelerations which are integrated as time passes from one frame to another. The propagation of acoustics waves in the specimen is part of the outcomes of the simulation. Thus, using this force based framework raises numerical instabilities against the chosen time step.

The presented study has been implemented using *SPHEROS*. This computational code has been developed by the Laboratory for Hydraulic Machines (LMH) based in Lausanne to simulate free surface flow using particle-based discretization scheme. It has been successfully used to simulate erosion resulting from the impact of silt particles on a surface [7]. The presented article aims at assessing this numerical implementation against elasto-plastic deformations induced by a rigid particle moving along the specimen surface. The main difference between erosion and abrasion lies

in the amount of plastic strain reach by the specimen.

### 3. Indentation simulation

One of the most common material characterizing tests is hardness measurement. This test involves complex material behaviour and interactions, yet features simple experimental outcomes. A spherical indenter penetrates the specimen until a yield normal load is reached. The hardness is determined against the dimensions of the indentation and the corresponding force. Among all hardness measurement techniques available in the literature, the Brinell hardness scale has been chosen due to the spherical indenter shape. The model for such a shape is straightforward in *SPHEROS*, as the raw geometric primitives used are spherical particles. As a consequence, there is no additional modeling constraints related to the indenter. Furthermore, the macroscopic experimental outcomes are easily comparable to simulation outputs. The ability of a simulation tool such as *SPHEROS* to produce relevant results within these conditions remains a prerequisite for more complex scenarios.

The simulation features a multi-scale cloud of particles. The spacing length is refined in the interested areas to balance relevance against computing time while the largest particles aim at extending the size of the simulation area. The boundary conditions consist in a set of particles that have been fixed at the bottom of the simulation bounding box. This ensures the specimen position and recreates artificially the indentation table interaction with the specimen. Only the interest area has been populated with particles not to penalise computational complexity. The particles are coloured according to their relative spacing in figure 2.

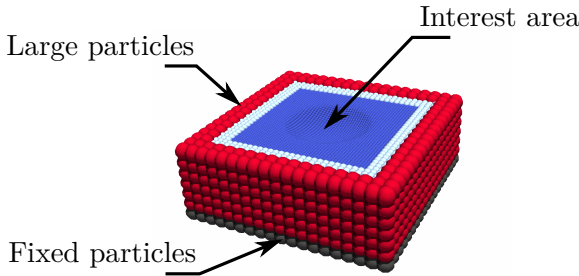


Figure 2: Discretization scheme

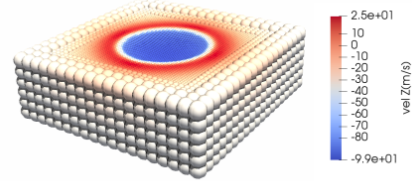


Figure 3: Vertical velocity

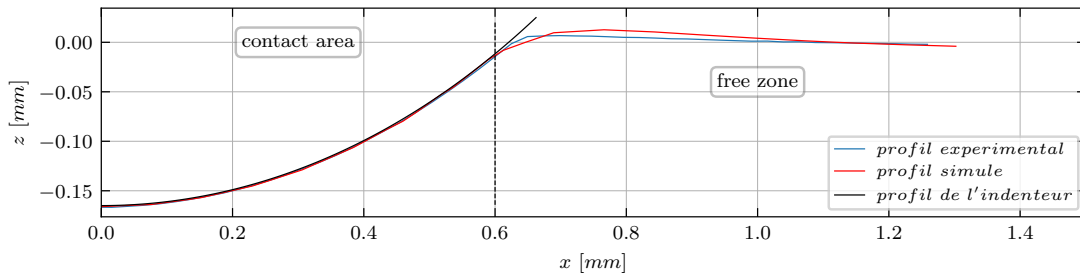


Figure 4: Indentation profiles

The Brinell test has been carried out on aluminum AU4G. The Johnson-Cook material parameters have been identified from tensile tests whose

material	A[MPa]	B[MPa]	n	e
AU4G	218	570	0.32	0.0029

Table 1: Johnson-Cook material parameters

values are listed in table 1. The indenter diameter is  $2.5 \text{ mm}$  under a load of  $1840 \text{ N}$ . The figure 2 pictures the spatial distribution of the particle and the simulated mark. The finest particles are set to 32 times smaller than the indenter. In the simulation, the velocity of the indenter is set to  $100 \text{ m.s}^{-1}$ . This configuration leads to a total computational time of  $4 \text{ h } 25 \text{ min}$ . The vertical velocity during the indentation is shown in figure 3 to highlight the formation of the bugles at the edge of the indentation. This behaviour arises from the volume conservation condition which defines plastic flow during the simulation. The macroscopic parameters are retrieved with good agreement, the global shape of the indentation mark is respected in the numerical environment. While the simulated profile fits the experimental data at the bottom of indentation, the bulges on both sides of the indentation have been found sensitive to boundary conditions and to particle size.

## 4. Scratching simulation

Scratching a specimen consists in moving an indenter under a normal load which creates a small channel. The indenter kinematics is more involved than in the previous case as it changes from normal penetration to tangential sliding. The groove left is both the result of the indenter repelling and removing matter. In this simulation, the sliding tool geometry is still spherical, which focuses efforts on the specimen behaviour. The interaction between the specimen and the spherical particle modelling the indenter consists in a penalty force computed against the interpenetration depth. This force is directed from the center of the indenter toward the specimen constituting particles. The numerical results obtained have been compared with the article of Leroch [8] as shown in the figure 6. The indenter size in this simulation has a  $400 \mu\text{m}$  diameter. The surface has been extracted from the points cloud using a level set of an implicit function defined by the sum of spherical kernels associated with each of the specimen particle. The extraction parameters are set from the initial spatial distribution. The penetration depth reached by Leroch which is  $60 \mu\text{m}$  has not been implemented without encountered instabilities in our model. As a consequence, it has been reduced to  $35 \mu\text{m}$  as shown is figure 5. A higher depth-to-radius ratio is not yet reachable by the FVPM model implemented. Nevertheless, the bulges on both sides of the scratching groove are observed in the simulation output.

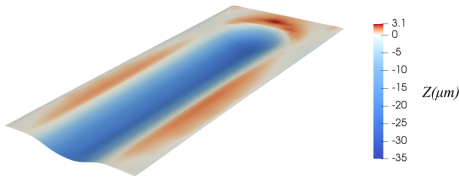


Figure 5: Scratching simulation

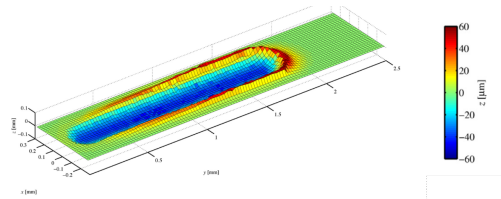


Figure 6: Leroch et al. [8]

## 5. Conclusion

An indentation and a scratching experiment have been simulated using a meshless particular method. In this context, the visco-elastic FVPM solver implemented in *SPHEROS* for surface erosion under silt particles impacts have been tested. The chosen simulations conditions aimed at replicating the main raw interactions encountered during the abrasion process. These preliminary results aims at assessing the FVPM method toward simulated more complex scenarios. The surface geometry of the indentation has been found in good agreement with the experimental measurements. Compared the literature, the penetration depth allowed during the scratching simulation has to be reduced. During the implementation of these test cases, numerical instabilities arise while large plastic strain was reached by the most damaged specimen areas. The numerical stability should be improved to allow larger plastic strain to be simulated without fault. This issue need to be considered before investigating the implementation of a several particles grinding process. The simulation framework is suitable for taking into account abrasive tool wear during the process. An increased computing time is expected against the problem complexity, which will need to be addressed.

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