

SPH Simulation of single grain action in grinding

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Abstract. The paper presents a study of chip formation in single grain grinding using a convenient FEM formulation, the Smooth Particle Hydrodynamics (SPH) method. The chip formation process was geometrically idealized. It was simulated as an inclined linear scratching of a cuboid part. After a systematic study, the results prove that this approach is useful to study the influence of grinding speed, friction conditions and uncut chip thickness on grinding forces, stresses and strains occurring during the grain action.

1 Introduction

Grinding is a cutting surface generation procedure using a multi-cutting edges tool with undefined geometry. These cutting edges belong to a large number of abrasive grains connected by a special property bond and remove the material from the workpiece surface with a high cutting speed. The goal of grinding is the acquiring a new surface with high accuracy (dimensional, of form and of position), high surface finish and texture, special behaviour in functioning (endurance, corrosion resistance, interchanging capability) and even aesthetic qualities.

In the last decades, research efforts were made to improve the results of grinding, envisaging the increasing removal rate, increasing the cutting speed, optimizing the grinding wheel geometry and topography, reducing the thermal influence on machined surface, protecting the industrial environment by minimizing the grinding fluid and raising its efficiency, looking for new abrasive materials with high wear resistance, finding efficient dressing methods for grinding wheels, and manufacturing grinding machines with high quality dynamics.

All these achievements were based on careful studies on the single grain cutting mechanism. The particularities of chip formation were studied experimentally and theoretically to achieve satisfactory models with the ability to prognosticate the influence of grinding factors on grinding results.

The experimental studies on chip formation are difficult because of microscopic size, small forces, high cutting speeds, and very quick phenomena, so a useful tool in studying abrasive grain cutting is the simulation using finite element method (FEM).

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2 SPH simulation and grinding

A literature review revealed that grinding and especially single grain grinding were in the attention of several researchers with the aim of finding a detailed description of grain action [1-6]. A useful tool in such studies, besides of experimental research, proved to be Smooth Particle Hydrodynamics (SPH), [7-10]. This is a meshless method implemented in LS-Dyna software [11].

2.1 Single grain process modelling

2.1.1 Model geometry

The general geometry of the SPH model is presented in figure 1. With the help of Ls-PrePost [12], the single grain grinding has been reproduced. The abrasive grain has been designed as a conical frustum with dimensions convenient to the scale of the process ($D_g = 0.05$ mm, $d_g = 10\%$ D_g , and $H_g = 40\%$ D_g) (fig 1). The grain was meshed via the automatic mesher into solid elements. The workpiece has been designed as a box filled with particles evenly distributed in the 3-D directions. To simplify the simulation and to keep it in convenient computer time, the adopted dimensions were $L= 0.05$ mm, $B= 0.04$ mm and $H= 0.01$ mm. The number of considered particles within the workpiece volume was $N=160,000$.

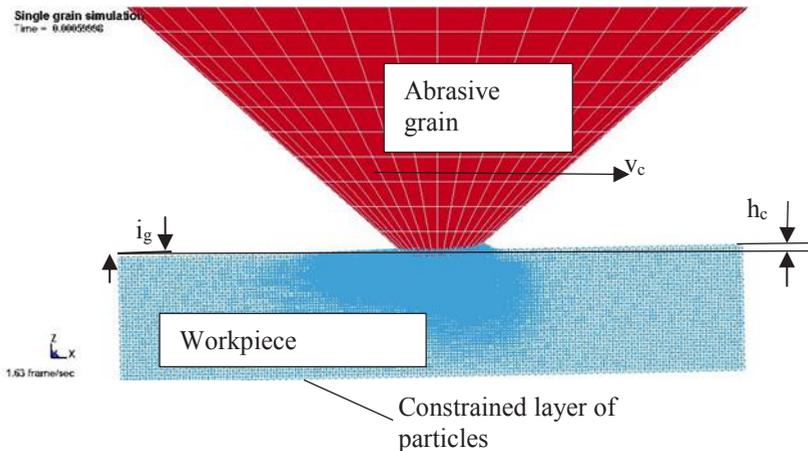


Fig. 1 Single grain grinding model in Ls-Prepost

2.1.2 Boundary conditions of the simulations

The grain movement is constrained to one degree of freedom translation along the X axis and is achieved as the movement of the rigid part (abrasive grain) with constant velocity, namely the grinding speed v_c . The different uncut chip thicknesses h_c were obtained by rotating the workpiece around the Y axis with different i_g angles. All particles from the base of the workpiece were constrained to be immobilized by constraining all the degrees of freedom for them. An automatic surface to nodes contact algorithm with different friction coefficient was consequently used for modelling grain-workpiece contact.

2.1.3 Materials modelling

The grinding grain was considered made from a conventional abrasive material, Al_2O_3 and was modelled as a perfectly rigid material (*MAT_RIGID), with mechanical properties listed in Table 1.

Table 1. Aluminium oxide grain properties [13]

Mechanical Property	Units of Measure	Value
Density	g/mm ³	0.00389
Flexural Strength	MPa	379
Elastic Modulus	GPa	375
Shear Modulus	GPa	152
Bulk Modulus	GPa	228
Poisson's Ratio	—	0.22
Compressive Strength	MPa	2600
Hardness	Kg/mm ²	1440
Fracture Toughness K _{IC}	MPa m ^{1/2}	4
Thermal Property		
Thermal Conductivity	W/m °K	35

The workpiece was taken as hardened VSIMoCr52H13 chromium hot-work steel SR NE ISO 4957:2002, equivalent to AISI H13 steel, which is widely used in hot and cold work tooling applications due to its excellent combination of high toughness and fatigue resistance. Its composition is displayed in Table 2 and its thermo-mechanical properties in Table 3.

Table 2. Steel chemical composition [min-max%] [14]

C	Si	Mn	P	S	Cr	Ni	Mo	W	Co
0.37-0.43	0.9-1.20	0.30-0.50	0.030	0.030	1.20-1.50	1.90-1.10	0.35	0.3	4.8-5.50

Table 3. Workpiece material properties [14]

Mechanical Property	Units of Measure	Value
Density	g/mm ³	0.00783
Young's Modulus	GPa	206.84
Shear Modulus	GPa	8.0.172
Bulk Modulus	GPa	164.161
Poisson's ratio		0.2900
Yield stress at offset	GPa	0.85495
Engineering ultimate stress	GPa	1.0342
Yield offset	%	0.2000
Thermal Properties		
Specific Heat Capacity	J/g°C	0.460
Thermal conductivity	W/m °K	37

The constitutive Johnson-Cook material model was involved in modelling the workpiece material. This plasticity model is widely employed in simulations of high-speed metal cutting or hardened materials cutting because it can accommodate high strain rate and temperature effects which are definitory features for chip formation in grinding. This material model is implemented in Ls-Dyna as *MAT_JOHNSON_COOK (*MAT_15) and has the general form:

$$\bar{\sigma} = [A + B\bar{\epsilon}_p^n] \left[1 + C \ln \frac{\dot{\bar{\epsilon}}_p}{\dot{\epsilon}_0} \right] \left[1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m \right] \quad (1)$$

where $\bar{\sigma}$ is the effective stress, $\bar{\epsilon}_p$ is the effective plastic strain, $\dot{\bar{\epsilon}}_p$ and $\dot{\epsilon}_0$ are the effective and reference strain rates, and T , T_r , and T_m are the current, room and melting temperatures.

The separation of the chip was simulated by using the damage law of the Johnson-Cook model. This considers strain, strain rates and temperatures as in equation (2):

$$\epsilon_f = [D_1 + D_2 \exp(D_3 \sigma^*)] \left(1 + D_4 \ln \frac{\dot{\bar{\epsilon}}_p}{\dot{\epsilon}_0} \right) \left[1 - D_5 \left(\frac{T - T_r}{T_m - T_r} \right)^m \right] \quad (2)$$

where: σ^* is the ratio of pressure divided by effective stress. Fracture is then allowed to occur when damage parameter D defined by equation (3) reaches unity ($D=1.0$) and so all the concerned particles are removed from the computation.

$$D = \sum \frac{\Delta \epsilon_p}{\epsilon_f} \quad (3)$$

The Johnson-Cook model strength and damage constants considered in achieved simulations are displayed in Table 4

Table 4. J-C Model input constants [15]

A	B	n	C	m
715 MPa	329 MPa	0.28	0.03	1.5
D1	D2	D3	D4	D5
-0.8	2.1	-0.5	0.0002	2.57

2.2 Computer simulations

The software used to achieve the numerical simulation was the Ansys LS-Dyna solver R9.00 on a win64 machine and LSPrePost v 4.3 as specialized pre and post-processing interface. As hardware, a conventional system using Intel® Core™ i7-4702-MQ @ 2.20GHz CPU with 16 Gb RAM was used. All references and keywords used by LS-Dyna solver are detailed in [17].

Due to the fact that SPH simulation in metal cutting was used especially when high cutting speeds were involved the screening simulations covered the usual range of grinding speeds. The values of uncut chip thickness were considered as the maximum values that can be produced during conventional grinding. Different friction conditions between SPH particles and the grain (rigid body) had been considered too. Figure 2 displays the results of such simulations, emphasizing the outputs as stress and strain distributions and grinding forces. The groove produced by the grain action on the surface of the work piece is visible and the pile up of material during the ploughing stage also.

2.3 Factors analysis

A full factorial DOE program with three factors and two levels (Tab. 5), was designed to analyse the influence of friction coefficient μ , cutting speed v_c and uncut chip thickness h_c on the levels of forces F_x and F_z , produced during the virtual chip formation due to the grain cutting movement on the workpiece.

Table 5. Parameters for single grain grinding simulations

Simulation parameters	Units	Low level	High level
Cutting speed v_c	m/s	50	100
Uncut chip thickness h_c	mm	0.001	0.002
Friction coefficient μ		0.1	0.6

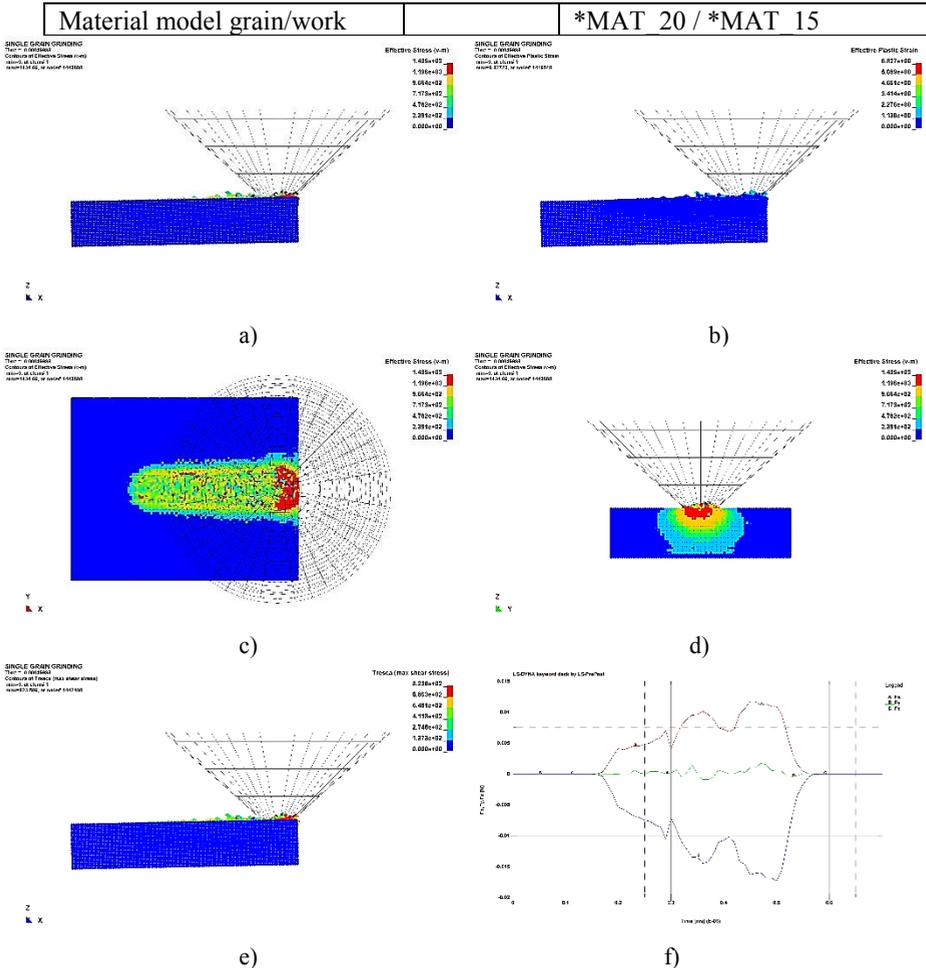


Fig. 2 SPH simulations results for $\mu=0.1$, $v_c=100$ m/s and $h_c=1$ μm : a) effective stress; b) effective strain, c) effective stress - top view; d) effective stress - front view; e) maximum shear stress (Tresca); f) grinding forces F_x , F_y and F_z versus grinding time

After running the planned simulations and the response variables F_x and F_y were obtained, ANOVA analysis was done. The significant factors were then identified, the modified factorial model was finally used for both grinding forces and the following regression equations were obtained in terms of actual factors:

$$F_x = -0.0184 + 2.97 \text{ E-}004 v_c + 0.0335 h_c - 3.19 \text{ E-}004 v_c h_c \quad (4)$$

$$F_z = -0.01237 - 0.0148 \mu + 3.02 \text{ E-}004 v_c + 0.0362 h_c - 3.34 \text{ E-}004 v_c h_c \quad (5)$$

Analysing the achieved equations (4) and (5), one may observe that the "tangential" force (F_x) is mainly influenced by grinding speed v_c and uncut chip thickness h_c , while the "normal" force (F_z) is influenced also by the friction coefficient μ . Both forces are influenced by the combination of v_c and h_c factors.

Figure 3 displays the grinding forces per grain F_x , and F_z , versus the main factors, uncut chip thickness h_c and grinding speed v_c , considering an average friction coefficient $\mu = 0.35$. One may observe that increasing in grinding speed produces a slight decrease in grinding forces while the increase in uncut chip thickness produces a significant increase of forces.

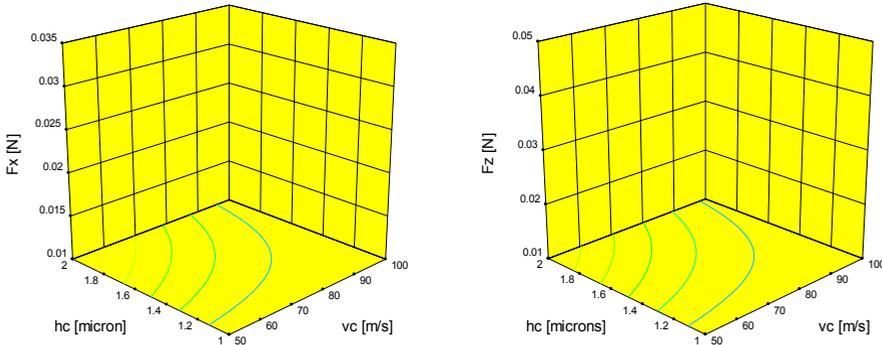


Fig. 3 Variations of simulated grinding forces

3 Conclusions

The present approach to simulating the chip formation in single grain grinding, using a numerical engineering method, FEM with a special meshless formulation, Smooth Particle Hydrodynamics (SPH), proved to be a useful instrument in studying the chip formation mechanics. It was demonstrated that the method is sensitive to the kinematic parameters of the process, grinding speed v_c and uncut chip thickness h_c , and in a smaller account to friction (μ). The method proved to be useful for getting the 3-D, stress and strain distributions in this complex deformation process. The method may be directed to study the geometry of the formed chip, because it permits to identify the ratios between rubbing, ploughing and cutting action of the grinding grain, also. Due to the sensitivity to the material formulation, it may be directed to grindability studies too.

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