Numerical modelling of the micro-cutting in the abrasion process with pyramidal indenter

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Abstract. A 3-D finite element model of abrasion process based on a CEL (Coupled Eulerian-Lagrangian) approach was developed. A scratch test on elastic-perfectly plastic materials with a pyramidal indenter was simulated. The influence of the interfacial friction coefficient *f*, the geometric parameters of the indenter and the cutting conditions on the overall friction coefficient μ were studied. Subsequently, the finite element simulation results were compared with an analytical model. It was found that the μ increases linearly with the friction coefficient f and the attack angle of grit β. The FE model results present a good agreement with the analytical model results.

Introduction

Grinding is a material removal process using a grinding wheel consisting of agglomerate grains. It enables surface quality and tight dimensional tolerances to be achieved on very hard materials. Almost all of the energy required is converted into heat, which can lead to high temperatures at the wheel/part interface, geometric defects and thermal damage. Thermal instrumentation with ground thermocouples allows the inverse determination of heat flow densities, partition coefficients, and convection exchange coefficients at the wheel/workpiece/lubricant interface [1]. Grinding forces can be used as an indicator to monitor the process. Indeed, these forces are related to the rise in temperature and the appearance of vibrations. Analytical modeling has great importance in order to analyze the work material and the grinding wheel. Therefore, modelling can be used to study the effects of cutting conditions in order to improve the quality of the grinding.

The grinding wheel is a complex tool consisting of abrasive grains with undefined cutting edges and geometry, which makes the modelling process much more complex than in conventional machining. The process of abrasion by a single grit grinding is broken down in the literature into several phases: elastic and then plastic deformations with the formation of microchips and side beads [2,3]. The production of microchips, with a thickness in the order of one micrometer, results from micro-cutting process due to the abrasive action of the active grains at the wheel/part interface for which the attack angle is larger enough.

Xie and Williams [4] modeled the local abrasion process with a pyramidal indenter, taking into account the angle of attack and the coefficient of interfacial friction. This model has been developed to predict the overall coefficient of friction (i.e. the force ratio: ratio of the tangential grinding force to the normal grinding force) and the wear rate when a surface is sliding against a randomly rough harder surface. They showed that the overall coefficient of friction of an asperity contact depend on the deformation mode, the operating condition and the mechanical properties of the soft surface. This model provides a qualitative prediction on the wear process and wear rate.

On a global scale of abrasion process, current approaches, such as those proposed by [5,6], takes into account the actual topography of the grinding wheel with statistical approaches to determine the height distribution of grain heights and slopes. In this context, Torrance and Badger [5] proposed a grinding forces model based on the 3D model of Xie and Williams [7,4], in combination with a statistical approach. The model was used to evaluate the likely effects of wheel grade, coolant, etc. on the grinding forces and roughness of the workpiece.

From the literature review, it can be noted that the model of Xie and Williams, based on various assumptions, is used by several authors [3,8,9,10]. Consequently, the validity analysis of the model is important, by comparing its results with those obtained from a more precise model such as a finite element model. In the present work, the model of Xie and Williams is compared with a numerical modelling of the abrasion process at grain scale based on a CEL (Coupled Eulerian-Lagrangian) approach. The aim of this study is to determine the effects of overlapping and indenter geometry on the formation of lateral ridges, taking into account the work material behavior, with respect to the cutting direction (feed direction), the tribological conditions and the operating conditions. Additionally, the study seeks to evaluate the validity of Xie and Williams's model [7,4] by comparing the obtained results with a finite element model of abrasion machining using a pyramidal indenter.

Finite element simulation

To analyze the grain/material interaction, a 3D finite element simulation of abrasion machining on a local scale is carried out by using ABAQUS/CAE software. The abrasive grain is modelled by using a rigid pyramid-shaped indenter with a square base, a pyramid angle of 2α, an attack angle β and a radius of 10 μm at the tip as shown in Fig. 1. The workpiece is modelled with a deformable part and dimensions of length 0.5 mm, width 0.5 mm and height 0.16 mm. The workpiece material is 42CD4 steel, whose elastic material properties are Young's modulus E=200 GPa, Poisson's ratio ν=0.3, Density ρ=7800 $Kg.m^{-3}$ and yield stresses are 612 MPa. A first scratch is pre-machined in the geometry of the workpiece. As for the FEM boundary condition, the workpiece bottom was set to encastre type. The displacement load of the indenter was loaded on reference point RP, while the indenter could only move in X and Z directions. The cutting path of single grain for FEM simulation is defined as in Fig. 2 to simulate different parameters of grain/material interaction.

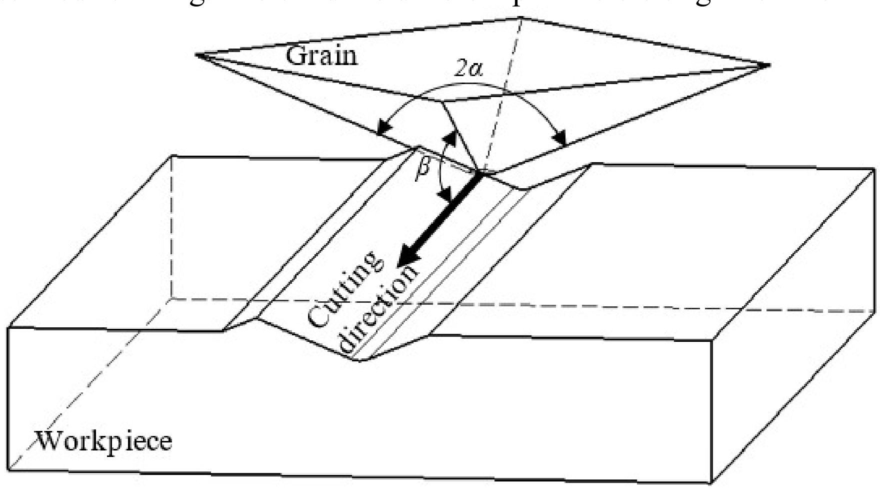

Figure 1. The workpiece and the pyramidal indenter used for the Finite Element Model (FEM)

In developed 3D FEM, a CEL (Coupled Eulerian-Lagrangian) approach and a progressive fine mesh for the interaction zone are used. Finer meshes over the interaction area provide better conformity of contact grain/material and maximum accuracy of FE results. The grain and Eulerian part (work material) are modelled by using quadratic tetrahedral elements of type C3D10M and linear hexahedral elements of type EC3D8R, respectively. For the numerical stability of the CEL approach, the rules for the orientation and the dimensions of the mesh, proposed by Ducobu et al [11, 12], have been adopted in the present work. The simulation conditions correspond to those used by Xie and Williams [7] in their 3D model for the interaction of single hard pyramid-shaped asperity in sliding contact with a softer surface [4]. In order to respect the assumptions of Xie's model and to decouple the grinding parameter effects during the grain/material interaction in the present work, the workpiece material behavior is assumed elastic-perfectly plastic.

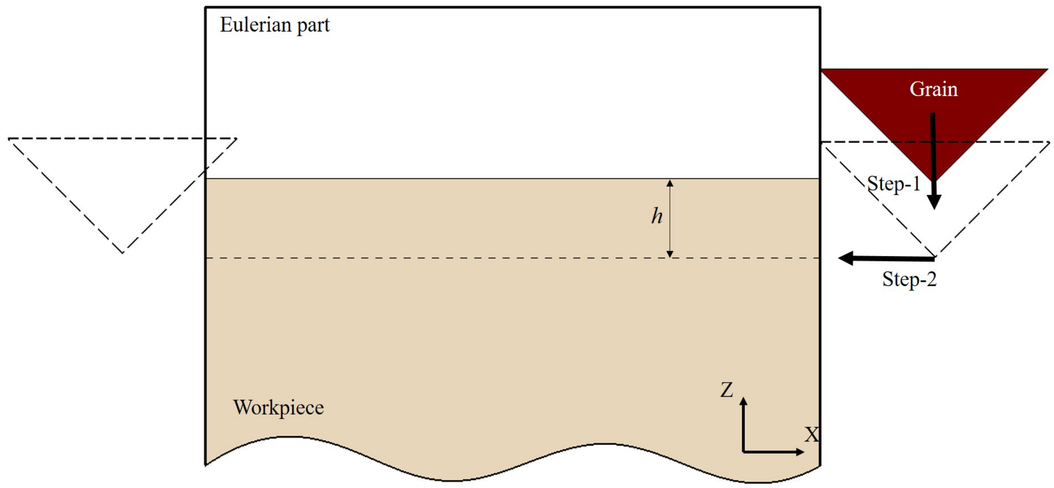

Figure 2. A single grain simulation path

Several numerical simulations were carried out according to the geometric parameters and the friction coefficient used in Xie and Williams's model. In this context, three modes of material deformation and three contact regimes were defined by Xie and Williams [7]: (i) elastic shakedown involves non-permanent elastic deformation of the material, (ii) ploughing involves permanent plastic deformation without material removal, and (iii) micro-cutting involves material being simultaneously sheared beneath the grit, being pushed sideways, and being removed as chips. For each mode, an abrasive wear coefficient K and a force ratio or an overall friction coefficient μ are developed. These models are defined as a function of the attack angle of grit β, the relative overlap of successive grinding scratches l, the shear yield strength of the work surface k, the ratio of the surface hardness H_s to the bulk hardness H_b and the Tresca's friction coefficient f (ratio between the shear strength of the rake interface to the shear strength of the workpiece).

$$\mu = \sqrt{2/\pi}\, \frac{\tan\beta}{l^{0.25}} \left(1 - \frac{f}{3\sqrt{3}}\left[1 + \frac{\pi}{4\,(\tan\beta)^2}\right]^{0.5}\right). \quad (1)$$

$$K = 0.003\, \frac{3\sqrt{3}\,(\tan\beta)^3}{f k \sqrt{l}} \sqrt{\frac{H_b}{H_s}} \quad (2)$$

$$l = \frac{L}{(h+h')\tan\alpha} \quad (3)$$

$$F_n = \frac{H_s h^2}{(\tan\beta)^2} \quad (4)$$

Torrance and Badger [5] have confirmed that the attack angles in a grinding wheel vary in the range of 5° to 30° (angles greater than 30° are quite rare). Thus, in this FE study, we have ignored some physical mechanisms considered by Xie and Williams (ploughing and rubbing; and rubbing alone). In the present work, the study is focused on the micro-cutting mode for a multiple-pass test when the model of K and μ are defined by equations (Eq.1) and (Eq.2). In this type of test, the relative overlap of successive grinding scratches l has an important role and a direct effect on the defined models. This parameter is defined as the distance between adjacent scratches L divided by the half-width of the plowed grooves, so it can be written as Eq.3, where h is the scratch depth and h' is the pre-existing ridge height, as shown below in Fig. 3.

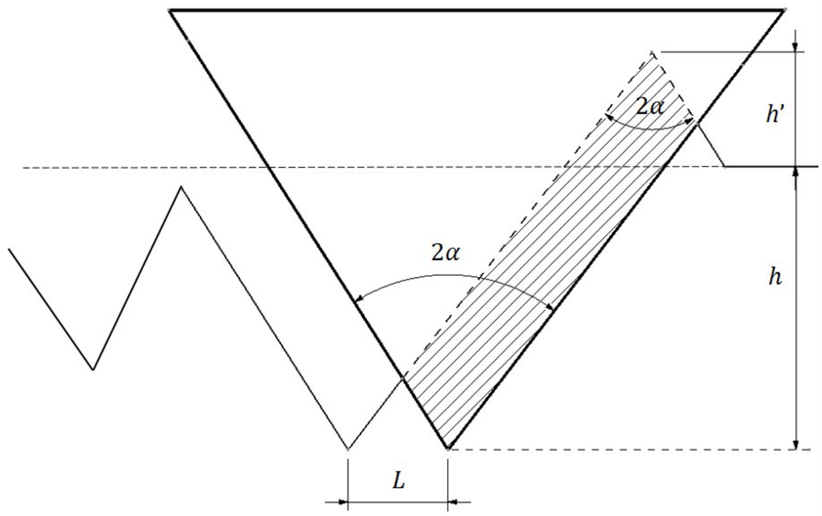

Figure 3. Geometry of a wear track produced in material already deformed by the production of an earlier track

Results and discussion

A set of 25 simulations were carried out according to different geometric parameters of Xie and Williams's model. For each FE simulation, a single parameter is varied in order to determine the evolution of the normal F_n, tangential F_t and lateral F_l forces generated by the indenter penetration in the workpiece. The values of the parameters were chosen to be consistent with Xie's experimental conditions. Table 1 presents the characteristics of the FE simulations. Subsequently, the numerical results of the overall friction coefficient are compared to the model (Eq.1 and Eq.2) for each parameter (*L, h, h', β and f*). The Fig. 4 (a) and (b) shows an example of the results of an FE simulation and the corresponding cutting forces.

Parameter	Values	Number of simulations	Simulation duration
L [µm]	10, 15, 20, 25, 30	5	69 hours
h [µm]	12, 16, 20, 24, 28	5	70,5 hours
h' [µm]	0, 2, 4, 6, 8	5	70,5 hours
β [°]	15°, 20°, 25.5°, 30°, 35°	5	69 hours
f	0, 0.2, 0.34, 0.48, 0.57	5	70,5 hours
		Total	349,5 hours

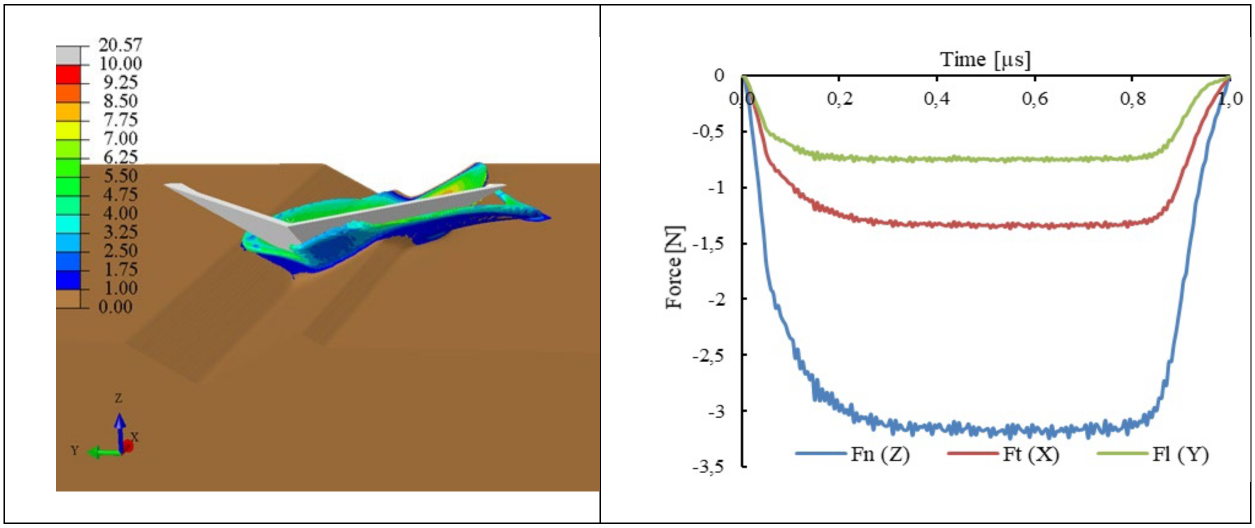

Figure 4. An example of an FE simulation where L=20µm, h=12µm, h'=6µm, β=20° and f=0.2: (a) The equivalent plastic strain in the workpiece (PEEQ). (b) The normal, tangential and lateral force generated by the indenter

Effect of the interfacial friction coefficient *f*: To analyze the influence of the local friction coefficient *f*, on the magnitude of the overall friction coefficient μ, *f* was varied between 0 and 0.57, while keeping the scratch depth, the attack angle, the pre-existing ridge height and the distance between adjacent scratches at 12µm, 25.5°, 6µm and 20µm, respectively, during the scratch test. The Fig. 5 shows the numerical and model results of the force ratio ($\mu = F_t/F_n$) as a function of the friction. It can be observed that the numerical force ratio increases as the interfacial friction coefficient increases. Clearly, the normal forces were not significantly affected by *f*. The interfacial friction had a more effect on the tangential forces. This was also confirmed by the work of Anderson et al [13]. Which also shows that the cutting tool is doing more ploughing or cutting as the interfacial friction increases. Except this is not the case for Xie and Williams's model, the empirical force ratio gradually decreases with the increase in friction.

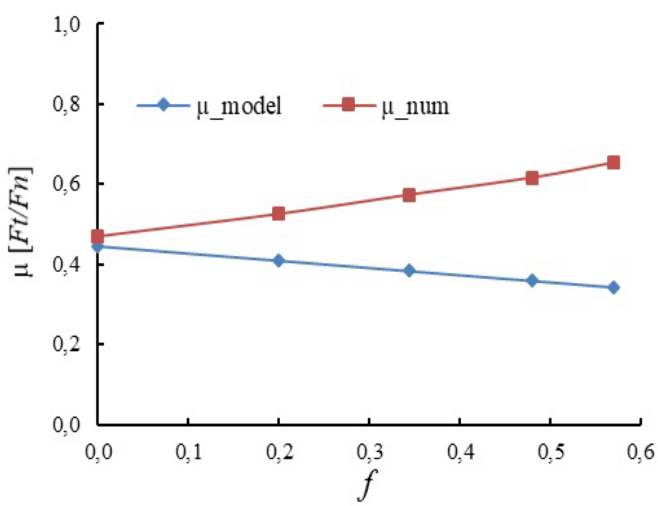

Figure 5. Variation of the force ratios with the interfacial friction coefficient

Effect of the attack angle of grit *β*: The results of the simulations are summarized in Fig. 6 (a). It is seen that the force ratios increase rapidly with β when the other parameters are fixed (*f*=0.2, *h*=12µm, *L*=20µm and *h'*=6µm). This can be explained by the increase in the value of forces generated by the indenter with a decrease in the attack angle, meaning that the normal force is much greater for β = 15° than those for larger β values, while the tangential force is not significantly affected by β. This is because for a given scratch depth, the contact area between the indenter and the workpiece increases rapidly with decrease in the attack angle, and hence, much larger normal forces are required to remove the material for a low angle β, as shown in Fig. 6 (b). This was confirmed by the Torrance and Badger's model [5] of the normal force on the grain (Eq.4). These numerical results also consistent with the experimental results of Subhash and Zhang [14].

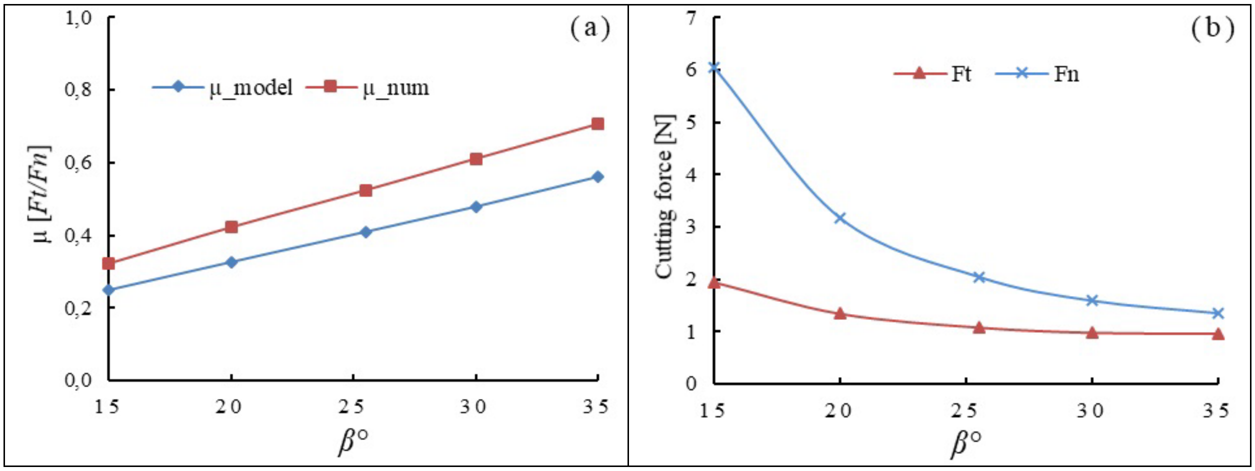

Figure 6. Variation of the force ratios (a), the normal and tangential forces generated by the indenter (b) with the attack angle of grit

Effect of the scratch depth *h*: As could be seen in Fig. 7, as the depth of cut increases, practically, there is no important effect on the evolution of the force ratios. All other parameters are considered as constant (β=25.5°, f=0.2, L=20µm and h'=6µm), and only the effect of scratch depth on the force ratios are investigated. These results are not surprising, it was expected that the increase in the scratch depth leads to a more severe material removal condition and consequently a proportional increase on the normal and tangential forces generated by the indenter, which gives a numerical force ratio does not depend on the variation of the scratch depth.

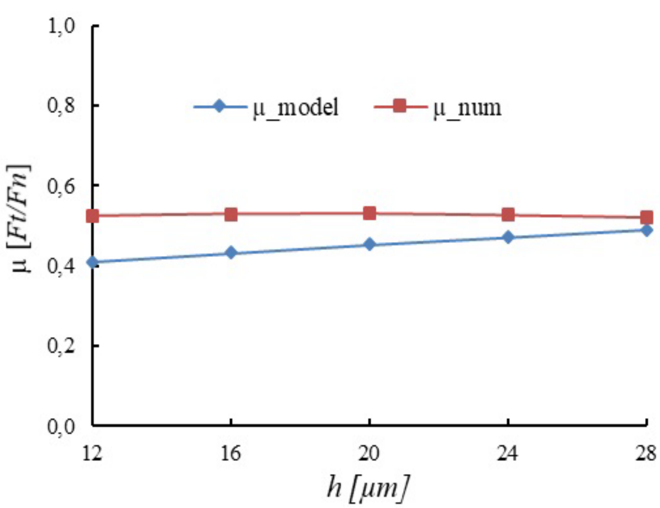

Figure 7. Variation of the force ratios with the scratch depth

Effect of *L* and *h'*: Fig. 8 (a) and (b) shows the variation of the force ratios with the distance between adjacent scratches (distance between the pre-existing scratch and the machined scratch) and the pre-existing ridge height, respectively, at the depth of 12µm, the Tresca's friction coefficient of 0.2 and the attack angle of 25.5°. It is obvious that the force ratios slightly change with *L* and *h'*. An increase in geometric parameters systematically increases the grain/material contact area, this can make the normal and tangential force increasing with the same rate but the force ratios has still the same values. In this case, the force ratio depends only on the modes of material deformation.

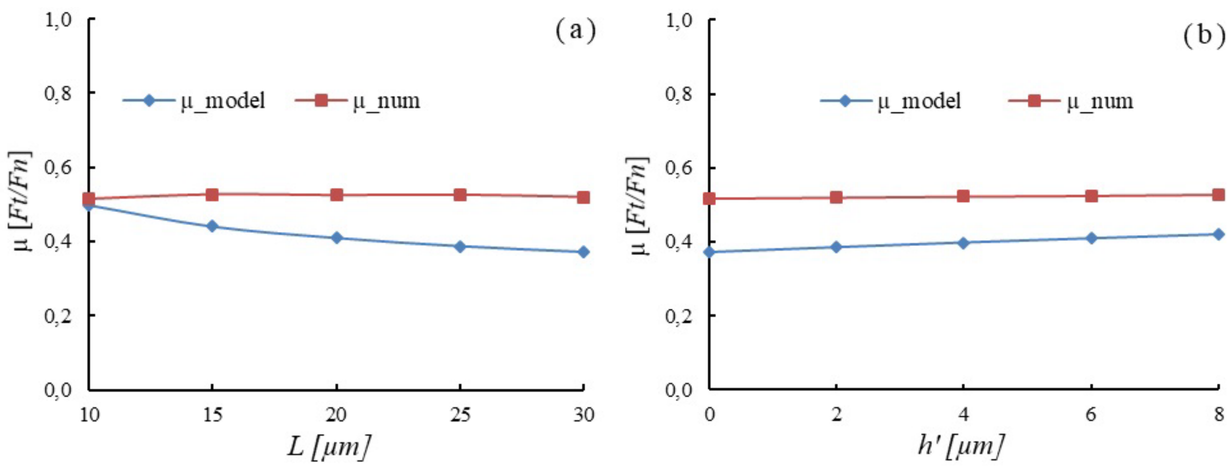

Figure 8. Variation of the force ratios with: (a) the distance between adjacent scratches, (b) the pre-existing ridge height (L=20μm)

Conclusion

A 3-D finite element analysis of abrasion process at grain scale, based on the CEL approach, was presented. The numerical results were compared with the model of Xie and Williams [7], which has been utilized in several works in the literature. The study was limited to the case of micro-cutting which corresponds to the configuration where the attack angle is larger enough. From the FE simulation of scratching with a pyramidal grain, it was found that the overall friction coefficient μ increases linearly with the interfacial friction coefficient *f* and the attack angle of grit *β*. It can be noted that the calculated values of μ as a function of the different parameters from the Xie and Williams's model agree well with FE model, except in the case of the variation of *μ* with *f*. In this case, the model of *μ*, given by Eq.1 and Eq.2, is half that obtained by FE simulation for high Tresca's friction coefficient and decreases rapidly with the increase of *f*, which is the opposite of the numerical results. This point will be clarified in future work by integrating the experimental results into our study.

The numerical and analytical results with a pyramidal indenter revealed that the overall friction coefficient *μ* cannot be completely decoupled into geometric variables. It was found to be independent from distance between adjacent scratches, pre-existing ridge height and the depth of cut. Therefore, the overall friction coefficient *μ* can be determined purely based on the geometry of the grain (i.e. the attack angle and the shape) and the interfacial friction of the contact.

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