Study of the influence of cutting edge radius on micro-cutting of hardened steel using FE and SPH modeling

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Abstract

Micro machining allows the production of micro-components with complex geometries in various materials. However, it presents several scientific issues due to scale reduction compared to conventional machining. These issues, called size effects, have been the topic of worldwide researches. At this level, micromachining experiments raise difficulties and significant costs. So, which reliable method can we use instead of expansive experiment? This article presents two different numerical models of micro cutting of a hardened steel with different methods, a finite element one (Lagrangian) and a particle based one (SPH). The objective is to study the effect of tool edge radius on the micro cutting process through the evolution of cutting force, chip morphology and stress distribution in different areas. The results are compared with experimental data obtained in previous work. These results show that the two numerical methods are relevant for studying geometrical size effects because cutting force and stress distribution correlate with experimental data. However, some differences remain in the shape of the chip as well as in the implementation and result analyzing between the two approaches.

Keywords: Micro-machining, 41NiCrMo7 Steel, Finite element modeling, SPH modeling, Cutting edge radius, Cutting force, Chip morphology

1. Introduction

Cutting at microscopic scale differs from the conventional one, for example the cutting edge radius influence the cutting mechanism in terms of cutting force, chip morphology etc. This phenomenon is a well known size effect which has a huge impact on the produced surface quality and the tool life. Knowing that experimental studies are expensive and take a lot of time, researchers have widely studied the use of numerical simulation in understanding of the material removal in micro cutting. Most of numerical models have been developed within finite difference method, finite element method and meshless methods [1] .These methods were used by several works to study orthogonal micro cutting [2] . In the present study, an orthogonal micro cutting model of hardened steel 41NiCrMo7 at 54 HRC is provided by two different methods, finite element method and smooth particle hydrodynamics method, in order to analyze the capacity of these approaches to predict the size effect due to the ratio between tool edge radius and depth of cut. The evolution of cutting force, chip formation and stress distribution are predicted thanks to numerical models and are compared to experimental results.

2. Modeling methods

2.1. Global configuration

First, a 2D orthogonal micro cutting finite element model (FEM) based on the Lagrangian formulation is developed using ABAQUS software with an explicit dynamic integration scheme to analyze the cutting mechanism. The use of a Lagrangian formulation requires the use of a separation criterion between the machined part and the chip in finite element modeling. A second 3D SPH model is also developed to study the orthogonal cutting mechanism. This type of modeling uses a particular method: The workpiece is presented by a mesh of particles. Each particle will have an influence in a neighborhood. The influence depends on the distance between the particles described by a weighting function W. The advantage is that no remeshing is necessary and the damage occurs naturally when the particles leave the zones of influence. The main drawback is the management of free borders, where the particles have a neighborhood. As a result, state variables are not optimally evaluated.

The cutting tool used for the modeling purpose is considered as a rigid body and located by a reference point (RP) to acquire the cutting force value.

For realistic modeling, a cutting angle of γ = 8 °, a clearance angle of α = 6 ° and cutting edge radius of 1.5; 2; 5; 8; 10 (µm) are applied to the cutting tool. The cutting velocity V_c applied to the cutting tool corresponds to the experimental setup (V_c = 40 m/min) and a depth of cut h_c = 4 µm is used in the simulations.

The tool/part interaction is modeled with a surface contact ("surface to surface contact" in ABAQUS) with Coulomb friction law as defined in the bibliography [3] and the coefficient of friction attributed in this case is f = 0.63 [4].

A fine mesh is applied in the zone of strong deformations with quadratic first order elements with a reduced integration (see Fig. 1). The use of this type of element can lead to zero energy strain modes, called "Hourglass" modes that must be eliminated. It is commonly admitted in the literature that the artificial energy imposed on the elements to prevent Hourglass modes should not exceed 10% of the internal energy of the model [5].

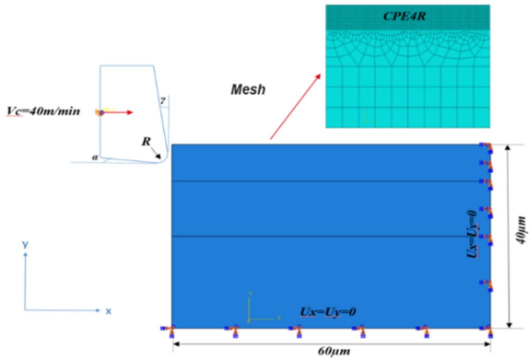


Fig. 1. FE model: geometry, boundary conditions and mesh

In this context, a comparative study between the different management methods of “Hourglass” available in the software led to the choice of the “Combined” one because it imposes the most significant artificial energy on the elements and it gives a greater radius of curvature of the chip compared to the other modes.

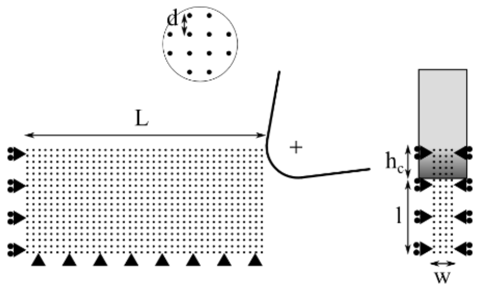


Fig. 2. SPH model: geometry, boundary conditions and mesh

Regarding the SPH modeling, a method of penalization is used to take into account the contact. When a slave element (particle of the workpiece) penetrates a master element by a certain distance along the normal to the contact, a contact force equivalent to a spring working only in tension is defined and tends to eject the penetrating element. Friction is also represented by a Coulomb model. The workpiece is subjected to boundary conditions in displacement on the lower free edge (fixed support) and on the left edge (zero displacement in X direction). The sides are also constrained in displacement (zero displacement in Z direction). The length L is 200 µm, the cutting width w is 5 µm and the height defined under the tool is 20 µm. The particle density is homogeneous and is characterized by a square mesh arrangement with a distance between particles of d = 1 µm (see Fig. 2).

2.2. Material properties and failure criterion

To simulate the cutting process with different tool geometry properly, it is necessary to introduce a material flow stress model to describe the material behavior. The more popular traditional Johnson-Cook material constitutive law with material damage criterion has been used for the proposed model. The Johnson-Cook model is described by the expression of average flow stress given by (see Eq.1).

$$\sigma = [A + B\,\varepsilon^n] \times \left[1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right] \times \left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)\right] \quad (1)$$

where ε is the equivalent plastic strain, $\dot{\varepsilon}$ and $\dot{\varepsilon}_0$ are the equivalent and reference plastic strain rates, T, T_{melt} and T_{room} are the material’s cutting zone, melting and room temperature, respectively, n is the strain hardening index, and m is the thermal softening index. Johnson-Cook Parameters A, B and C represent the yield strength, strain and strain rate sensitivity of the material. For reasons of data availability, simulations are carried out with a steel of the same type hardened to 41 HRC. Table 1 shows physical and mechanical properties of the steel hardened to 41 HRC and Table 2 shows the Johnson cook’s law parameters related to steel hardened at 41 HRC.

Table 1
Physical and mechanical properties of the steel hardened to 41 HRC [6]

Material	41NiCrMo7
Density	7,85 g/cm^3
Young Modulus	207 GPa
Poisson coefficient	0,2

Table 2
Johnson cook’s law parameters [7]

	A	B	C	n
41NiCrMo7	792	510	0,014	1,02

In order to simulate the chip formation, a failure criterion is used. It is described by the Johnson-Cook failure model. This model takes into account the influence of strain, strain rate, and temperature on material failure shown in Eq.2. In the presented work, temperature influence is neglected. Failure parameters of the Johnson-Cook model are shown in (see Table 3).

$$\varepsilon = [D_1 + D_2 \exp(-D_3\,\eta)] \times \left[D_4 + \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right] \times [1 + D5(\frac{T - T_{room}}{T_{melt} - T_{room}})] \quad (2)$$

Table 3
Failure parameters of the Johnson-Cook model [6]

D_1	D_2	D_3	D_4
0,05	3,44	-2,12	0,002

This damage criterion is not necessary in SPH modeling as the particles move apart during chip formation, they move away from the zones of influence during separation. The damage is then intrinsic to the SPH resolution. SPH modeling requires on the other hand an equation of state in a polynomial form (see Eq. 3) which define the pressure P as a function of the variation in volume μ of the system.

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \quad (3)$$

Only the parameter C_1 is non-zero and corresponds to the incompressibility modulus K of the material, this one being considered as isotropic. This modulus is related to the Young modulus E and to the Poisson's ratio *v* by the following equation (see Eq. 4):

$$K = \frac{E}{3(1-2\nu)} \tag{4}$$

3. Model validation through experimental results

The validation of the proposed numerical models is performed by correlation with experimental results. In this work, reference numerical simulations use the same cutting conditions and tool geometry as the elementary micro cutting machining tests [4].

For the FE model, the simulated distribution of stress during cutting is realistic. The different characteristic zones, in particular the shear zone, can be easily identified (see Table 4). From (see Fig. 3) we can notice that the amplitude of cutting forces resulting from the FE model are close to the values of cutting forces obtained experimentally: $F_{c\ (num)}$ = 12 N and $F_{f\ (num)}$ = -5 N against $F_{c\ (exp)}$ = 10 N and $F_{f\ (exp)}$ = -8 N for the same cutting depth h_c = 4 µm.

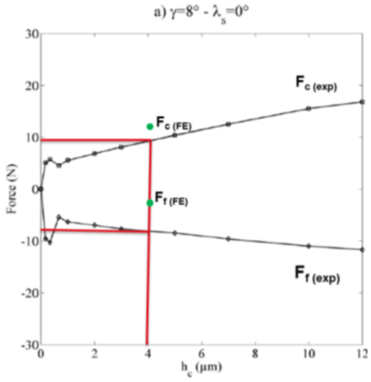


Fig. 3. The evolution of the cutting force along the X and Y directions: Experiments [5] and FE model for h_c = 4 µm

Regarding the SPH model, the cutting forces are underestimated: the cutting force (calculated for a thickness w of 318 µm) is of the order of 3.2 N, i.e. a ratio of 3 with the experimental results. On the other hand, we find the same ratio F_f/F_c close to 2 obtained by the FE method.

3.1. Study of the cutting edge radius influence

In order to study the influence of the h_c/r_β ratio on the cutting process, a cut angle ɣ = 8 ° is fixed. The cutting edge radius *rβ* and the cutting height *hc* are set at 2-5-8-10 µm and 2-4 µm respectively, as shown in Table 4. Observation of the Von Mises equivalent stress shows that whatever the cutting depth or the cutting edge radius, the maximum stress is in order of V_m = 1500 MPa in all cases.

On the other hand, the chip morphology and the stress field distribution are different depending on the case. Simulation results with a larger edge radius show that the shear zones merge to form a single zone. This explains the increase in cutting force along the Y direction for cases where the h_c/r_β ratio is less than one (see Fig. 4). As a result, the material is hardened and the stress rises in front of cutting edge, and by consequence, cutting forces rise as well.

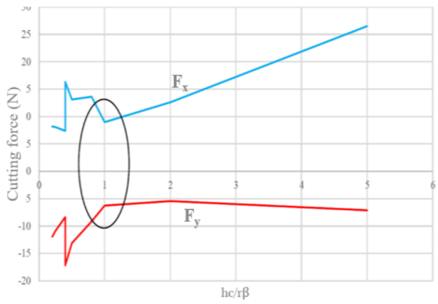
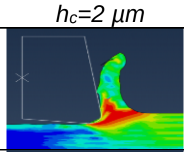
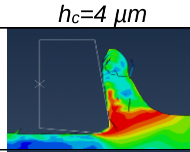
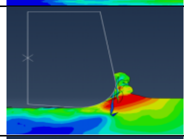
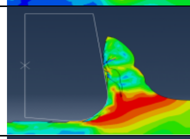
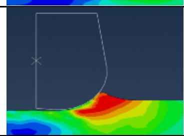
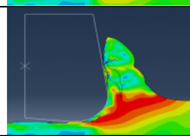
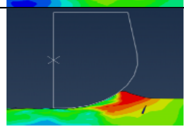
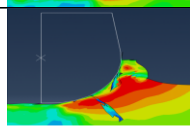


Fig. 4. Cutting force evolution with $\frac{h_c}{r_\beta}$ ration

Table 4
The influence of h_c and r_β on chip formation

	hc=2 µm	*hc=4 µm*
rβ=2 µm		
rβ=5 µm		
rβ=8 µm		
rβ=10 µm		

For the SPH method, the main parameters studied were the edge radius, the cutting depth and the cutting angle. Only three values of h_c (2, 11, 20 µm) and γ (-8°, 0° et 8°) were studied. The h_c parameter varied between 1 and 14 µm. As noticed in the FE method, the maximum Von Mises stress of 1320 MPa is reached in almost all cases. Figure 5 shows the evolution of cutting forces (in absolute value) in the different cases. Several points should be mentioned. Firstly, r_β has a large influence on the cutting forces. Secondly, when h_c is small comparing to r_β the cutting angle has no influence on the results. Finally, under a certain value of h_c, which depends on r_β, the cutting force component is lower than the feed force component (mainly when the cutting angle is no longer influencing).Figure 6 shows the relationship between F_f/F_c ratio and h_c/r_β ratio. It is clear that for a ratio h_c/r_β less than 0.8, the feed force *Ff* is greater than the cutting force *Fc*. Likewise, the cutting angle has no longer any influence on the forces for a ratio h_c/r_β less than 1. Concerning the stress distribution observed from SPH simulations, we can notice that the dimensionless parameter h_c/r_β provides results completely independent of the edge radius value. Figure 7 illustrates the geometry of the chip formation zone through the maximum of Von Mises stress as a function of h_c/r_β. We can see for low ratios of h_c/r_β, the zone starts at the lowest point of the tool and then takes a comma shape without following the radiated

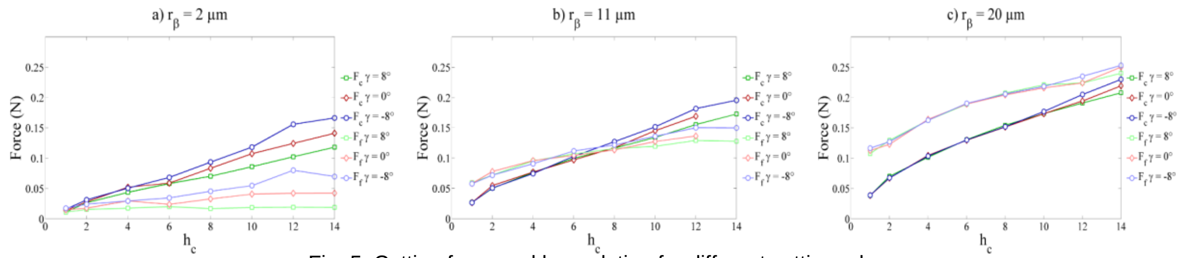


Fig. 5. Cutting force and h_c evolution for different cutting edges

part of the tool, suggesting the appearance of a dead zone. For the higher ratios, we obtain a band shape, which is common in the literature. It should be noticed that with the SPH model, the material flow near to the cutting edge is highly reduced with important values of r_β. It corresponds to experimental observations made from quick stop tests in micro-cutting where a sticking phenomena is clearly identified in this region of the chip for high values of edge radius [4]

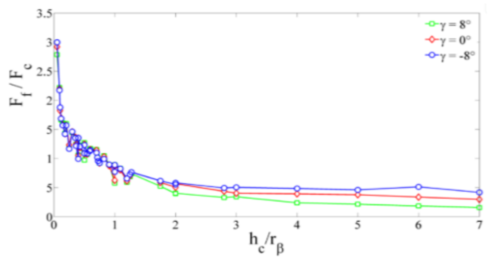


Fig. 6. Evolution of $\boldsymbol{F_f/F_c}$ with $\boldsymbol{h_c/r_\beta}$

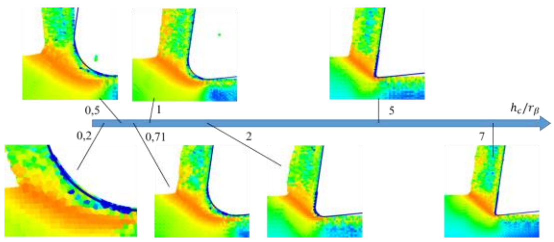


Fig. 7: Evolution of the geometry of the chip formation zone through the maximum of Von Mises stress as a function of $\boldsymbol{h_c/r_\beta}$.

4. Conclusions

This work describes the modeling of orthogonal micro cutting of hardened steel with two methods: finite element method and SPH method. The models show as outputs the distribution of Von Mises stress, cutting force and chip shape in order to study the influence of tool geometry especially the cutting edge radius on cutting process. Results show that in micro cutting maximum cutting force and Von Mises stress values are proportionally greater than in conventional machining. This is due to the reduction in the dimensions of the tool in regard of cutting depth.

With the FE model using a Lagrangian formulation, the cutting forces correspond well to the experimental results. A high sensitivity to the h_c/r_β ratio was observed from the stress field distribution and the chip morphology is consistent.

The SPH method shows the same tendencies concerning cutting force and stress evolution but presents more discrepancies with the experimental data, mainly on cutting force values and chip morphology. Nevertheless, the material flow seems to be more realistic around the cutting edge than in FE model. It is interesting in order to study sticking phenomenon influencing build up edges and tool wear.

The two methods show the capability to reproduce the h_c/r_β scale effect and allow studying the evolution of force and stress zones and even material flow, but not with the same relevance on each parameter. Thus, these numerical methods can be complementary to describe the phenomena not observable by experimentation. The next step of this study is to check the capability of a Combined Eulerian Lagrangian (CEL) approach to combine advantages inherent to each method by avoiding their drawbacks.

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