Modeling of Specific Cutting Energy in Micro-Cutting using SPH Simulation

Dattatraya Parle, Ramesh K. Singh, and Suhas S. Joshi*
Mechanical Engineering Department, Indian Institute of Technology Bombay, Mumbai-400076, India

Corresponding Author / E-mail: ssjoshi@me.iitb.ac.in  TEL: +91-22-25767527, FAX: +91-22-2572 6675

KEYWORDS: Micro-cutting, Specific cutting energy, SPH formulation

This work employs SPH method to simulate orthogonal micro-cutting process using LS-DYNA software. SPH is a meshless method suited for large deformation problems typically that occur in micro-cutting and overcomes limitations of other FE formulations. Process of micro-cutting modeling using SPH simulations have been benchmarked with experiments for cutting of AISI 1045. The purpose of this study is to investigate stress, strain, cutting forces and specific cutting energy in micro-cutting using SPH simulations under various parametric conditions. These results of micro-cutting process are in agreement with the fundamental machining behavior of ductile materials. Thus, this work demonstrates capability of SPH formulation in modeling of orthogonal micro-cutting with fairly accurate results overcoming limitations of other formulations, especially when the scale of the process is reduced to micro-cutting.

1. Introduction

Metal cutting is a complex process, in which several mechanisms are at work simultaneously, and they interact with each other. Further, the complexities in the simulation of machining process increase multi-fold due to a reduction of scale during micro-cutting. In spite of extensive research on micro-cutting, many facets of the material deformation during machining have not been completely understood or simulated. Search for effective analytical, experimental and numerical techniques still continues. Finite element method has been used as an alternative to the analytical and experimental approaches in metal cutting process since early 1970’s. Until the late 1990s, the majority of researchers used their own FEM codes. However, use of commercially available software packages has dramatically increased over the last ten years due to limitations on using customized FEM codes. Several researchers have successfully performed simulations using either general purpose commercial FEA softwares such as ANSYS, Abaqus, LS-DYNA, MSC.Marc or specialized numerical codes such as DEFORM, AdvantEdge, etc. [1]. Mackerle [2, 3] presented a bibliography of efforts related to numerical simulation of metal-cutting operations.

The FE simulation of micro-cutting requires explicit dynamic non-linear numerical formulation. Most of the past efforts in modeling of micro-cutting involve use of Lagrangian, Eulerian, Arbitrary Lagrangian–Eulerian (ALE) formulations.
Recently, researchers began investigating suitability of SPH formulations in metal cutting simulations. Use of SPH is a new topic for many researchers to investigate its applicability and very few studies are available in literature [4-10]. This work therefore, this work employs SPH method to simulate orthogonal micro-cutting process in the frame-work of LS-DYNA. The process of micro-cutting is modeled using SPH simulations and has been benchmarked with experiments for cutting on AISI 1045 steel. The purpose of this work is to understand micro-cutting process by studying stress, strain, cutting forces and specific cutting energy under various parametric conditions.

2. Micro-cutting simulations using SPH

2.1 Basics of SPH

SPH is a Lagrangian technique that was initially developed in the 1970’s as a means to simulate astrophysical phenomena [11, 12]. In SPH, a kernel approximation is used to calculate spatial derivatives within randomly distributed interpolation points. A function \( f(r) \) can be thus estimated by the relation:

\[
 f(r) = \int_{D} f(r') W(r-r', h) d\Omega', \quad (1)
\]

where,

\[
 W(r-r', h) d\Omega' = \text{kernel function which can be Gaussian, polynomial, spline, etc.}
\]

\( h = \text{smoothing length which defines a domain containing particles in interaction with particle } i \).

The value of a function at particle \( i \) is approximated using the values of the functions at all the particles that interact with particle \( i \). The continuous volume integrals are written as sums over discrete particles using Eq. 2:

\[
 f(r_i) = \sum_{j=1}^{N} \frac{m_j f(r_j) W(r - r', h)}{\rho_j} \quad (2)
\]

where,

\( m_j \) and \( \rho_j \) are the mass and density of each particle, respectively.

SPH is a meshless method, which does not require a computational grid to perform simulations. Rather, SPH operates by representing the material as a group of Lagrangian particles. These particles interact with one another based on a smoothing length and a statistical kernel function. Essentially, the smoothing length provides an individual particle search radius to find neighboring particles, while the kernel function is used to provide how strongly or weakly the particles interact. Using SPH, a user no longer needs to be wary of mesh (size, smoothing and tangling), adaptive re-meshing or a chip separation criterion, which is essential in other formulations during micro-cutting.

In present work, uncut chip thickness used is in the range of 5-25 \( \mu \)m and at a lower uncut chip thickness, these issues become very critical, hence, SPH has been used in this work. This work therefore presents SPH-based simulations to investigate the parametric effects in micro-cutting process. The simulations are validated using micro-cutting experiments.

2.2 Micro-cutting model set-up using SPH

In this work, orthogonal cutting and a corresponding 2D geometrical model are considered. The geometry of workpiece is 1 x 0.5 mm rectangle with 0.2 mm cutting width. SPH particles are created in the workpiece. The workpiece contains total 3,09,630 SPH particles. Tool is meshed with solid elements. The workpiece particles are constrained in all directions at the bottom edge. A cutting speed is applied in x-direction to the tool. Node to surface contact is defined between the workpiece and the tool. However, sticking phenomenon along chip-tool interface is not considered in the friction model. Fig. 1 shows a scheme of simulation for orthogonal micro-cutting.

Mass, distance and smoothening length of particles are defined for workpiece SPH particles. The total mass of all particles should be equal to the mass of the workpiece calculated analytically. Smoothing length is another important parameter in numerical modeling using SPH particles. The typical parameters required in SPH formulations are shown in Fig. 2. To keep enough particles neighboring a particle, variable smoothing length is the best option i.e. smoothing lengths vary during the calculation process.

![Fig. 1 Scheme of simulation for micro-cutting a. Tool-workpiece geometry b. Enlarged workpiece showing SPH particles](image)

![Fig. 2 Important input parameters for SPH particles](image)

In this work, a total 27 SPH based micro-cutting simulations were performed on medium carbon steel (AISI 1045) using a full-factorial design. Table 1 shows the levels and factors which were used in the micro-cutting simulations. Three levels of rake angle, feed and cutting speed were selected.
The cutting tool is modeled as a rigid-body whereas workpiece is modeled as an elasto-plastic body. Table 2 shows overall tool and work material properties used in the simulation of orthogonal micro-cutting. Elasto-plastic behavior of workpiece is modeled using Johnson-Cook (J-C) [13] constitutive material model and is given by Eq. 3.

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

(3)

In SPH formulation, kinematics of material separation is inherently captured. Hence, a separate chip formation criterion is not required as in Lagrangian and Eulerian formulations. The material damage is incorporated at SPH nodes through a loss of cohesion as neighboring SPH particles are separated from each other. When the distance between the particles is more than a critical distance, the material is assumed to have failed.

### Table 2 Work and tool material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>AISI 1045</th>
<th>Tungsten carbide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7800 kg/m³</td>
<td>15800 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>200000 MPa</td>
<td>680000 MPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>0.24</td>
</tr>
<tr>
<td>Model</td>
<td>Johnson-Cook</td>
<td>Rigid Isotropic</td>
</tr>
<tr>
<td>A (MPa)</td>
<td>553.10</td>
<td>600.80</td>
</tr>
<tr>
<td>B (MPa)</td>
<td>600.80</td>
<td>553.10</td>
</tr>
<tr>
<td>C</td>
<td>0.234</td>
<td>0.234</td>
</tr>
<tr>
<td>m</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>n</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### 3. Results and Discussion

This section presents various results obtained using SPH simulations of micro-cutting and experimental validation of cutting forces.

#### 3.1 SPH Simulation results

In the post-processing of FE simulation, fundamental machining results such as stress and strain have been studied. Fig. 3 shows a typical von-Mises (VM) stress contour plot obtained by the SPH simulation. The maximum von-Mises stress in the shear zone is 1324 MPa for a typical case shown in Fig. 3. Similarly, a typical strain plot obtained using SPH simulation is shown in Fig. 4. For given cutting conditions, machining strain is found to be 2.145.
3.2 Benchmarking of micro-cutting simulations using experiments

The validation of SPH simulation involves a comparison of cutting force obtained from simulation with those obtained from the experimental results. The micro-cutting experiments were performed on a three-axis multipurpose miniature machine tool developed by Mikrotools (see Fig. 5). The inserts is made of Tungsten Carbide with three cutting edges and mounted in an insert holder. Workpiece (see Fig. 6) was prepared using wire-EDM and mounted on a force measuring dynamometer (Kistler Minidyne 9256C2) using a workpiece holder. Orthogonal micro-cutting experiments were monitored using CCD-based OMM camera which travels with the tool. Limited experiments were performed to benchmark FEA simulations. Table 3 shows various cutting parameters used during experiments.

Fig. 7 shows a typical plot of cutting force vs. time obtained from SPH simulations and the experiments. Average cutting force obtained by the experiment in the steady state region is 15.94 N. Similarly, the average cutting force in the steady-state region during SPH simulations is 13.98 N. Error in SPH simulation and experimental average cutting force is 9.22% for given cutting condition. Both plots show an initial unsteady region followed by a steady-state region.

3.3 Chip morphology

Continuous chips are observed during micro-cutting experiments as well as corresponding SPH simulations under various cutting conditions. Table 4 shows comparative chips obtained under three different cutting conditions. Chips are observed using CCD camera during micro-cutting experiments.

Table 3 Cutting conditions for micro-cutting experiments

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Rake Angle (Deg)</th>
<th>Feed (µm)</th>
<th>Cutting Speed (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. 1</td>
<td>0</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>Exp. 2</td>
<td>5</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>Exp. 3</td>
<td>10</td>
<td>25</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4 Chip obtained using experimental and SPH simulation

<table>
<thead>
<tr>
<th>Case</th>
<th>Experiments</th>
<th>SPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. 1</td>
<td><img src="image" alt="Exp. 1" /></td>
<td><img src="image" alt="Exp. 1" /></td>
</tr>
<tr>
<td><img src="image" alt="Exp. 1" /></td>
<td><img src="image" alt="Exp. 1" /></td>
<td><img src="image" alt="Exp. 1" /></td>
</tr>
<tr>
<td>Exp. 2</td>
<td><img src="image" alt="Exp. 2" /></td>
<td><img src="image" alt="Exp. 2" /></td>
</tr>
<tr>
<td><img src="image" alt="Exp. 2" /></td>
<td><img src="image" alt="Exp. 2" /></td>
<td><img src="image" alt="Exp. 2" /></td>
</tr>
<tr>
<td>Exp. 3</td>
<td><img src="image" alt="Exp. 3" /></td>
<td><img src="image" alt="Exp. 3" /></td>
</tr>
<tr>
<td><img src="image" alt="Exp. 3" /></td>
<td><img src="image" alt="Exp. 3" /></td>
<td><img src="image" alt="Exp. 3" /></td>
</tr>
</tbody>
</table>
3.4 Cutting forces

A variation of cutting forces with the machining parameters like cutting speed, rake angle and feed is illustrated in Fig. 8. It is observed that cutting forces increase with an increase in feed (see Fig. 8), whereas the forces decrease with an increase in rake angle (see Fig. 9) and cutting speed (see Fig. 10). Results of cutting forces are in agreement with the fundamental machining behavior of ductile materials [15].

It is also observed that the effect of cutting speed is minimum at lower feed and increases as feed increases. Fig. 9 also shows that experimental and simulated forces are in close agreement.

3.5 Specific cutting energy

Figs. 11 and 12 show that the specific cutting energy increases with a decrease in feed. This increasing trend in the specific cutting energy at lower feed is also termed as the size effect [15]. Specific cutting energy is given by Eq. 4. In this equation, cutting force obtained through SPH simulations is used for calculating specific cutting energy during microcutting.

\[ u = \frac{F_c}{b \times f} \]

In further analysis, the effect of cutting speed and rake angle are investigated on the specific cutting energy. The specific cutting energy is observed to decrease with an increase in the cutting speed (see Fig. 11). This could be due to a decrease in cutting forces at higher speeds. A decreasing trend in specific cutting energy is observed with an increase in rake angle (see Fig. 12). This could be explained by the decrease in the cutting forces due to reduced ploughing at higher rake angles.
4. Conclusions

Some of the main conclusions of this study are as follows:

- Orthogonal micro-cutting of medium carbon steel has been modeled and simulated using SPH based framework within LS-DYNA software.
- SPH simulation overcomes the challenges faced during Lagrangian based simulations when feed decreases to 5 micrometer.
- Simulation results were benchmarked using specific micro-cutting experiments.
- The predicted values of cutting forces match well with the experimental data. The results also show trends that are in agreement with the fundamental machining behavior of ductile materials.
- It is observed that cutting forces increase with an increase in feed, whereas the forces decrease with an increase in rake angle and cutting speed.
- Specific cutting energy (also called as size effect) increases nonlinearly as feed decreases. The specific cutting energy is observed to decrease with an increase in the cutting speed due to a decrease in cutting forces at higher speeds.
- A decreasing trend in specific cutting energy is observed with an increase in rake angle. This is due to the decrease in the cutting forces due to reduced ploughing at higher rake angles.

REFERENCES