Application of Smooth-Particle Hydrodynamics in Metal Machining

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Abstract. The finite element (FE) method has been extensively used to model complex cutting processes. However, due to large strains in a process zone, leading to increased element distortions, such simulations are confronted with numerical difficulties. Smooth-particle hydrodynamics (SPH) is a mesh-free computational method, which has been used to simulate multi-body problems. In this paper we present a 3D hybrid modelling approach for orthogonal micro-machining of a copper single crystal with the use of SPH and continuum FE. The model is implemented in a commercial FE software ABAQUS/Explicit. The study is used to gain insight into the effects of crystallographic anisotropy on the machining response of f.c.c. cubic metals.

1. Introduction
Machining of single-crystal metals is of interest due to a demand from various high-technology applications with single-crystal components due to their uniformity and reduced level of defects, important for manufacture of turbine blades and precision mirrors. Thus, there is a need for developing fundamental understanding of materials behaviour and material removal, since all crystalline materials are composed of grains and grain boundaries, which, to a large extent, define their mechanical properties. During mechanical micromachining of metals, a tool-workpiece interaction occurs entirely within either a single crystal or a few crystals of the workpiece material. Single-crystal copper is widely used in fabrication of precision instruments and civil communication devices due to its inherent favourable properties, such as excellent signal transportation and fatigue resistance [1, 2].

A number of finite element studies have confirmed that a machining response; including machining forces, chip shape and surface roughness, depends on the crystallographic orientation in f.c.c metals [3, 4]. These studies identified excessive element deformation as a fundamental problem for numerical modelling of the cutting processes. The problem with element distortion was overcome with the application of techniques such as adaptive meshing and an Arbitrary Lagrangian-Eulerian (ALE) scheme. Remeshing techniques have inherent limitations such as loss of data resolution and round-off errors from previous time-step increments. As a result, errors can accumulate in reported field variables [5, 6]. Hence, there is a need to develop numerical schemes to alleviate problems in numerical convergence in the modelling of high strain and strain-rate deformation regimes.

This has led to the development of element-free (or mesh-free) techniques in modelling high-deformation processes such as machining. Smooth particle hydrodynamics (SPH) is a mesh-free
computational method, which has been used to simulate N-body problems, including, i. a., complex fluid flows and large-strain solid-mechanics problems.

In this paper we demonstrate a multi-scale modelling approach in the simulation of a micro-machining process. The philosophy of this approach was to attain close-to atomistic details in the regions of interest with a continuum formulation for the rest of the workpiece volume so as to reduce computational demand. To gain a physical comprehension of the cutting process at the micro level, a material model based on crystal plasticity was implemented.

2. Multi-scale simulation model

A 3D workpiece with dimensions of 500 µm × 500 µm × 50 µm is selected as model. The workpiece was divided in two regions. A schematic of the tool and workpiece is shown in Fig. 1(a) and a 3D model is shown in Fig. 1(b). The right and bottom faces of the workpiece were fixed with regard to linear displacements and rotations. A tool with a cutting edge with a radius of 5 µm and $\theta = 45^\circ$ was used to cut a free surface of the workpiece. The workpiece was modelled as a deformable body and the tool as a rigid part. The region close to the cutting surface (150 µm × 150 µm × 50 µm) was simulated with resolution of 0.2 µm, while the remaining regions were modelled as a solid continuum. The geometry was meshed with eight-node brick elements (C3D8R) with reduced integration for a continuum FE region and PC3D for the SPH area, 668 particles were used for the SPH part. The Coulomb’s friction law with a friction co-efficient of 0.1 was used to model the frictional interaction between the tool and the workpiece surface material.

The crystal-plasticity model was implemented in a FE software package ABAQUS/Explicit using the user-defined material subroutine VUMAT [7]. Material parameters for single-crystal copper used in the FE simulations are listed in Table 1 [8].

3. Simulation results and discussion

All numerical experiments were carried out by indenting the workpiece to a depth of 50 µm. The indenter moved at a velocity of 50 mm/s. As expected, the workpiece material rearranged when the strain energy in the deformed lattice exceeded the binding energy of the workpiece particles. Consequently, that depth of penetration was observed to cause numerical convergence errors in a case of continuum finite element implementation. The stress distribution under different crystal orientation
Table 1. Material parameters of single-crystal copper [8]

| Elastic parameters | Parameters of slipping rate | Parameters of hardening |
|--------------------|-----------------------------|-------------------------|
| $C_{11}$ = 168.0 GPa | $\dot{\gamma}_0 = 0.001 \text{ s}^{-1}$ | $h_0 = 180 \text{ MPa}$ |
| $C_{12}$ = 121.4 GPa | $m = 0.05$ | $\tau_s = 148 \text{ MPa}$ |
| $C_{44}$ = 75.4 GPa | | $\tau_0 = 16 \text{ MPa}$ |

with regard to axes x and y is shown in the Fig. 2.

![Image](image.png)

Fig. 2 Plastic stress distribution for cutting process for different orientation setups: (a) (111)[110]; (b) (111)[1\bar{1}0]; (c) (111)[\bar{2}11]

The same plane (111) with three slip directions [1\bar{1}0], [110] and [\bar{2}11] was selected for our numerical simulations. The results demonstrate that different surface profiles and stress distributions were obtained in the micro-machining for various orientations. For instance, von Mises stress is nearly 25% higher in the case of (111)[1\bar{1}0] orientation setup compared to cases of (111)[110] and (111)[\bar{2}11].
To find a compromise between the conflicting requirements of accuracy and computational cost, a mesh-sensitivity analysis of the model was initially performed. The vertical path (A-B-C) was chosen to present the distribution of von Mises stress. Selecting the vertical path was linked to location of nodes in the workpiece to provide a shortest horizontal distance from the end of tool tip. There are only some changes in the stress along the path near point B (representing a boundary between SPH and FE domains). Hence, a mesh with a minimum element size of 0.2 µm at the region of machining was sufficient to characterize accurately the stress-distance behaviour during machining. The mesh-sensitivity analysis was performed for (111)[110] orientation setup of copper.

Fig. 3. Stress-distance distribution along path in workpiece material

4. Crystallographic orientation and cutting force
The primary indentation thrust forces along the direction of tool motion ($F_y$) at different crystal orientation are shown in Fig. 4. The value of $F_y$ was found to be lowest in the (111)[110] orientation setup followed by (111)[1$ar{1}$0] and (111) [2$ar{1}$1] combination. This indicated that the $F_y$ in the crystal orientation family (111) plane changed from [110] to [1$ar{1}$0] and [2$ar{1}$1] crystal orientation directions. This conclusion was consistent with the theory suggesting that a low tangential cutting force should be observed in the slip plane when oriented favourably to the deformation direction in the f.c.c. materials (i.e. (111)[110]).
Fig 4. Effect of crystallographic orientation on load-displacement response during indentation

5. Conclusion
In the present work a 3D hybrid finite-element model of micro-machining was developed to study deformation of a single crystal of copper. The present model allows for high deformations in the underlying material. It was observed that the influence of cutting direction in micro machining of single copper crystal significantly affects evolution of cutting forces.

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