Chip Formation and Minimum Chip Thickness in Micro-milling

F. Ducobu, E. Filippi, E. Rivière-Lorphèvre
Machine Design and Production Department (François.Ducobu@umons.ac.be)

In the current context of miniaturization, micro-machining processes are in full expansion. One of them is micro-milling. Micro-milling is a micro-manufacturing technology by removal of material making it possible to produce parts and features ranging from several mm to several μm. It requires a miniature tool (called a micro-mill) with a diameter between 100 μm and 500 μm. Although micro-milling is based on the same principle as macro-milling, the phenomena of micro-cutting are not a simple scaling-down of macro-cutting.

Chip formation

- Depth of cut and feed very small ⇒ no chip is formed below a certain value = minimum chip thickness (Fig. 2).
- Minimum chip thickness ⇒ no of slipping forces + ploughing of machined surface ⇒ no of cutting forces, burrs formation and surface roughness.
- Strong dependency of minimum chip thickness to machined material and tool geometry.

- Small depth of cut ⇒ highly negative rake angle (= macro-milling)
- ⇒ ploughing of machined surface + elastic spring back of the workpiece.
- Size effect = non-linear / of specific cutting energy when depth of cut ↓.
- Size effect = indicator to detect changes in cutting mechanism (from slipping to shearing)?
- Woon et al. [2]: 2D ALE orthogonal cutting finite element model, homogeneous workpiece material.
- Results: when depth of cut < a breaking value, chip formed by extrusion along edge radius of tool + confirmation that cutting edge of tool not sharp in micro-milling.

Influence of the machined material

- Depth of cut, tool or features dimensions to produce often < grains size of workpiece material ⇒ take into account its nature and micro-granular structure ⇒ not homogeneous and isotropic ≠ macro-machining.
- Lack of homogeneity of granular structure during machining ⇒ variations of cutting conditions (hardness in particular) ⇒ forces variations and vibrations + impossible to use averaged cutting coefficients ≠ macro-cutting.
- Simoneau et al. [3]: orthogonal cutting heterogeneous (AISI 1045 steel) finite element model, tool edge radius infinitely small.
- Results: softest material (ferrite) extruded between hardest grains (pearlite) ⇒ chip formation mechanism = quasi-shear extrusion chip (Fig. 4).

Finite element model development

Overview

2D plane strain thermo-mechanical orthogonal cutting model, finite element method (ABAQUS/Explicit v6.7):
- Area close to cutting edge of tool, cutting speed = 300 m/min.
- Workpiece material (Ti₆Al₇V) homogeneous, Johnson-Cook plasticity model.
- Workpiece mechanical formulation: Arbitrary Lagrangian Eulerian (ALE).
- Adaptive meshing and plastic flow of workpiece material ⇒ no chip separation criterion.

Tool material (tungsten carbide) linear elastic behaviour.
- Friction tool-chip: coulombic friction law + constant friction coefficient + all the dissipated heat due to friction converted into heat, 25% flow into chip.
- Initial temperature: 20°C, conduction only, transformation of deformation to heat efficiency = 90%.

Results

For a chosen machined material, minimum chip thickness = f(depth of cut (h) and tool edge radius (r)) ⇒ study of h/r ratio influence.
- 4 different cases via depth of cut variation: h/r = 5 (h = 100 μm), h/r = 3 (h = 60 μm), h/r = 0.5 (h = 10 μm) and h/r = 0.25 (h = 5 μm).
- Nodal displacements (Fig. 7) = Von Mises stress contours (Fig. 8)
  ⇒ Results globally similar to those presented par Woon et al. [2].

Conclusion

- Macro-milling ⇒ micro-milling = changes in cutting phenomenon
  ⇒ minimum chip thickness phenomenon.
- 2D plane strain orthogonal cutting model ⇒ chip formation and minimum chip thickness influence.
  ⇒ h/r value: great importance in micro-milling;
  ⇒ cutting tool considered not sharp.
  ⇒ chip formation mechanism evolves when h/r ratio ↓, becoming more different from macro-cutting chip formation.

Outlooks

- Analytically model minimum chip thickness.
- Experimentally evaluate minimum chip thickness.
  ⇒ get a comparison point with the presented model and validate it.

References