Chip Formation and Minimum Chip Thickness in Micro-milling

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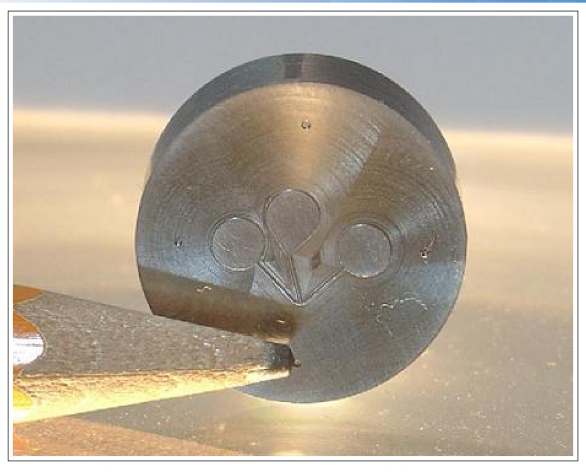

Fig. 1 – Micro-injection mould, Kernmicrotechnic

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 ⇒ ↗ of slipping forces + ploughing of machined surface ⇒ ↗ of cutting forces, burrs formation and surface roughness.
  - Strong dependency of minimum chip thickness to machined material and tool geometry.

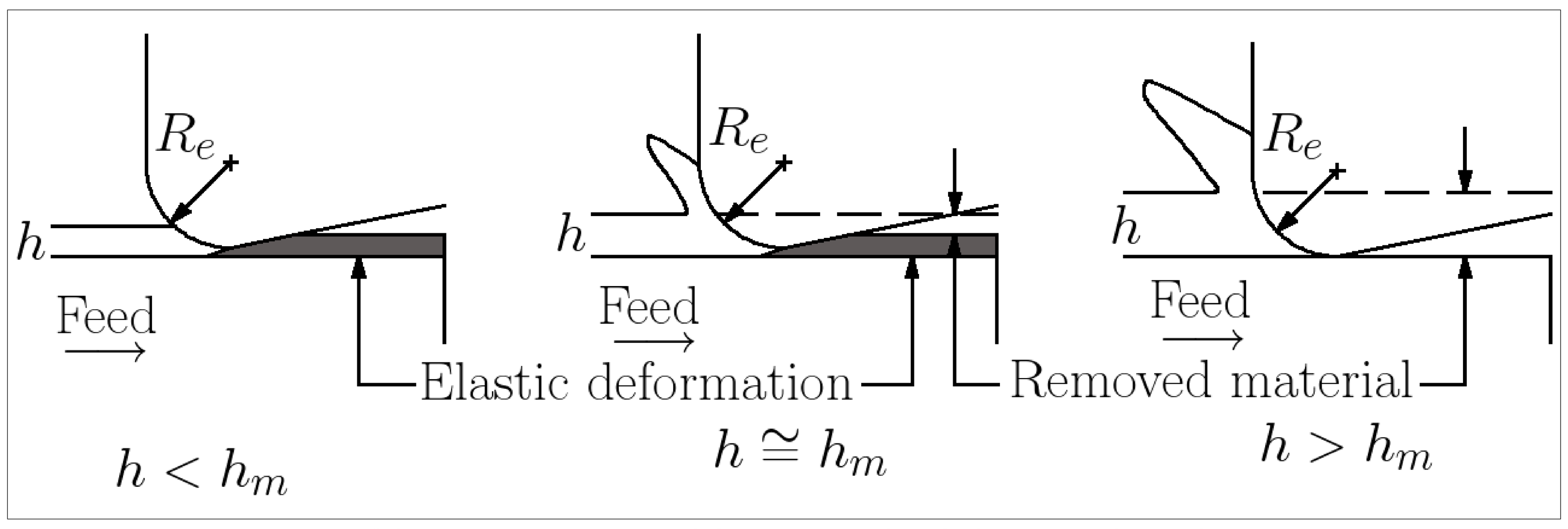

Fig. 2 – Schematic representation of the minimum chip thickness in orthogonal cutting (R_e, edge radius; h, depth of cut; h_m, minimum chip thickness), inspired of [1]

- 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).

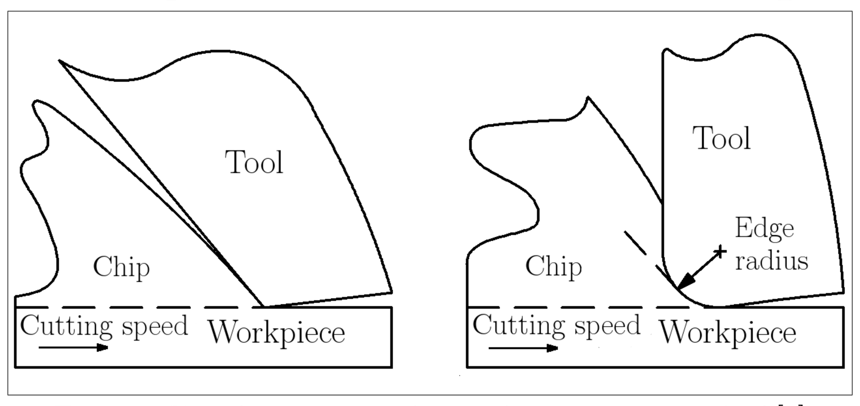

Fig. 3 – Chip formation, orthogonal cutting, inspired of [4]

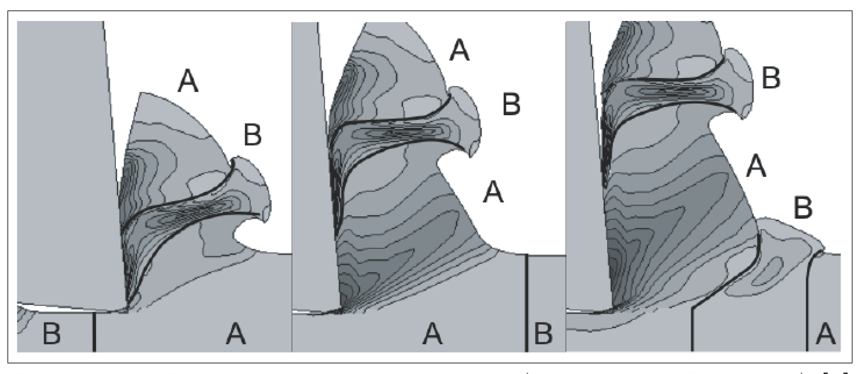

Fig. 4 – AISI 1045 steel chip formation (A: pearlite, B: ferrite) [3]

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 (Ti_6Al_4V) 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, tranformation of deformation to heat efficiency = 90%.

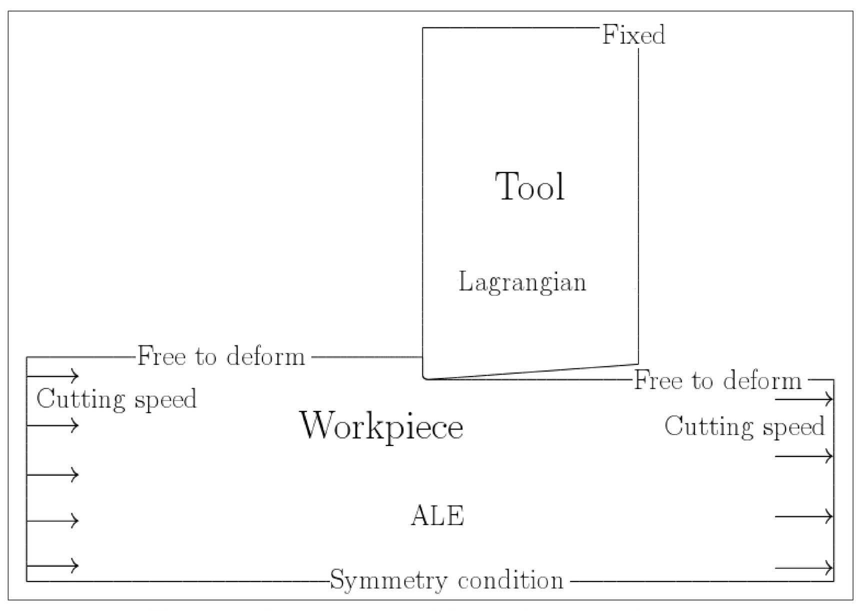

Fig. 5 – Geometry and boundary conditions

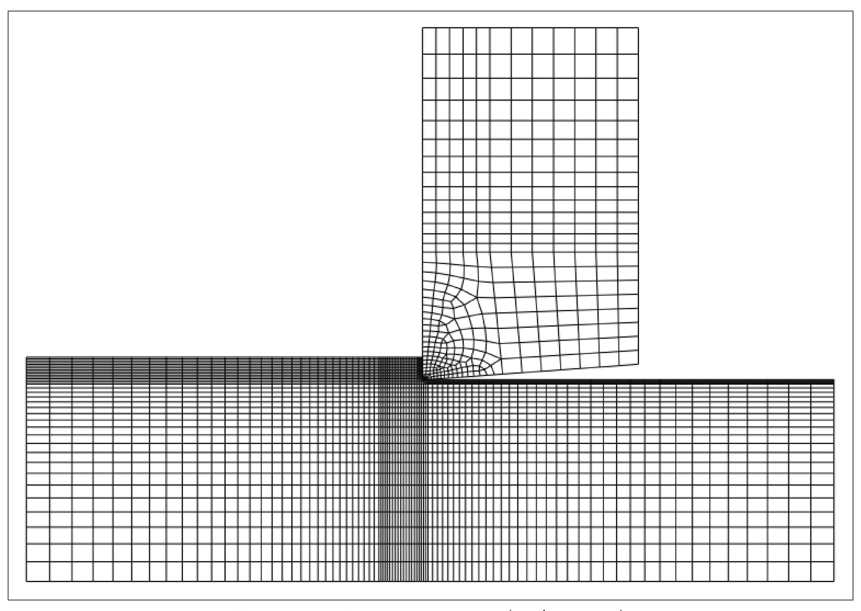

Fig. 6 – Initial mesh ($h/r = 5$)

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 these presented par Woon et al. [2].

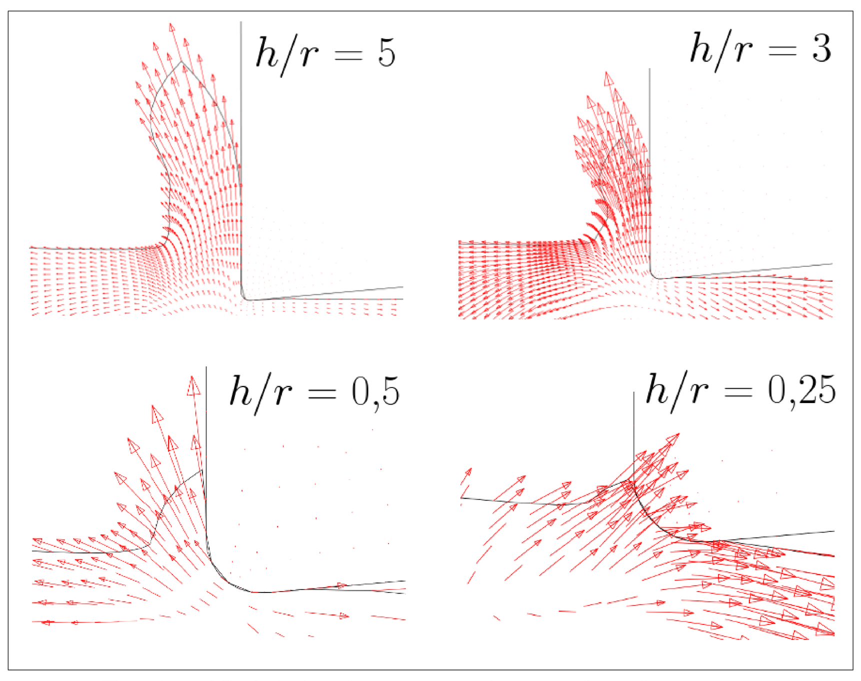

Fig. 7 – Nodal displacements during chip formation

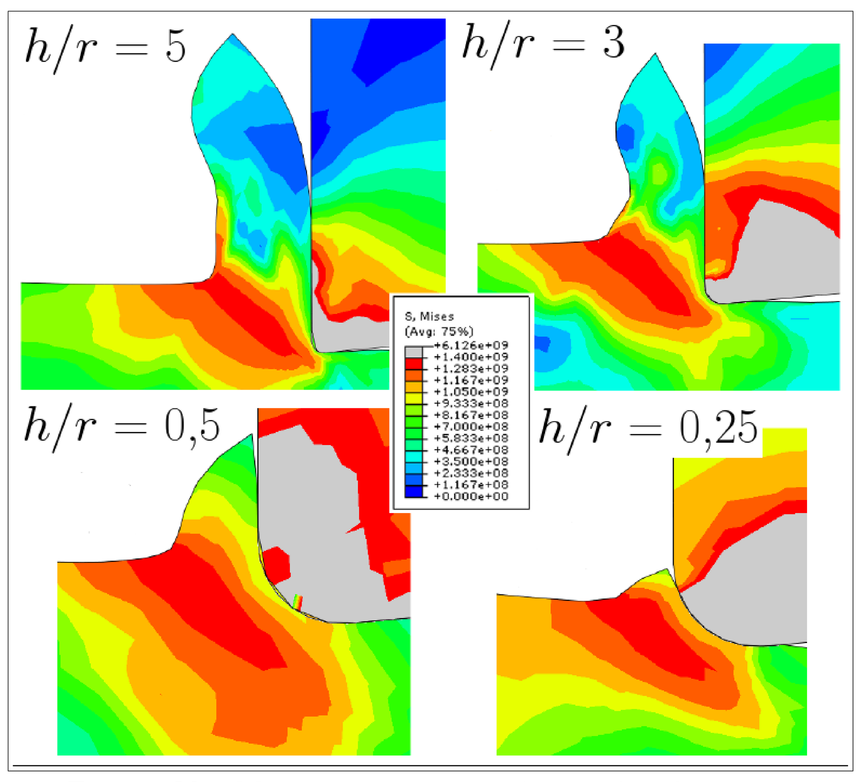

Fig. 8 – Von Mises stress contours during chip formation

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

[1] Chae, J., Park, S.S., Freiheit, T., 2006, Investigation of micro-cutting operations. IJMacTool, 45:313-332.
[2] Woon, K.S., Rahman, M., Fang, F.Z., Neo, K.S., Liu, K., 2007, Investigations of tool edge radius effect in micromachining: a fem approach. JMatProTec, 167:316-337.
[3] Simoneau, A., Ng, E., Elbastawi, M.A., 2006, Chip formation during microscale cutting of medium carbon steel. IJMacTool, 46:467-481.
[4] Dornfeld, D., Min, S., Takeuchi, Y., 2006, Recent advances in mechanical micromachining. Annals of the CIRP, 55:745-768.