FINITE ELEMENT MODELING AND ANALYSIS OF MICROCUTTING PROCESS WITH DEAD METAL CAP

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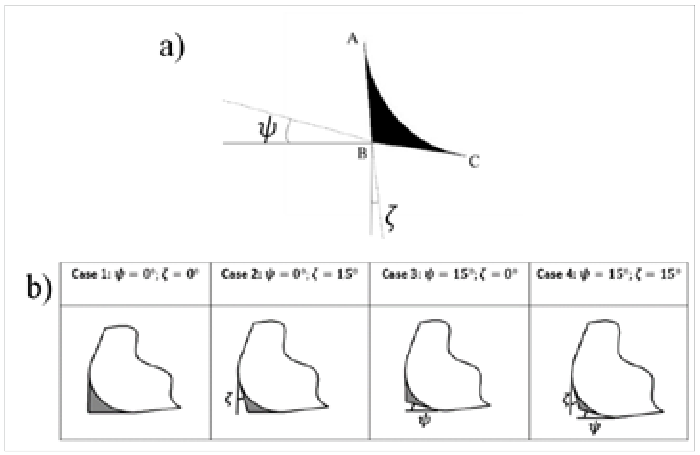
In the last decade production of small parts with acceptable relative accuracy has become a very important topic for industrial sector because of the application of these parts in electronics, aerospace and optics. There are many types of manufacturing process that can produce these miniaturized parts with required accuracy. Micro mechanical cutting is one of the frontiers of production technology and is well known for providing a 3D component with high-aspect-ratio microstructures.
However, despite significant development of machine tools to meet machining accuracy, the basic phenomena behind the fundamental mechanics of the process need to be further investigated. One of the phenomenon which has been stayed ambiguous is called stable Built-Up-Edge (BUE), also called Dead Metal Cap (DMC). In fact, there are numbers of research work for interpretation of cutting process with this piled up material at interface but the detailed description of the mechanics of the process with DMC has not been fully understood. Going to further details, the studies on this phenomenon can be classified into three main categories:

i) Experimental
ii) Analytical (mostly slip-line filed solution method)
iii) Numerical (Finite Element Method (FEM))

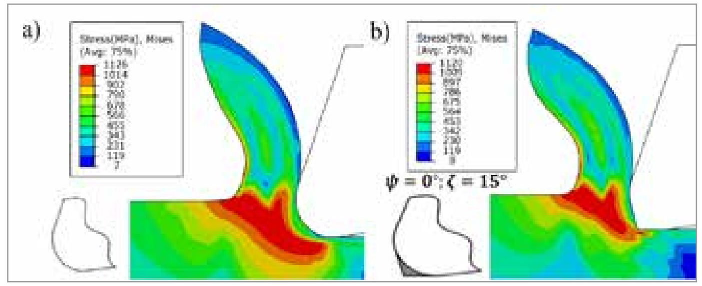
As expected, each of these techniques has its own drawbacks. For example, experimental studies are limited for analysis of machining with DMC because of the complexity in extracting/measuring the fundamental variables (workpiece deformation behavior, and temperature distribution, etc.) during the machining experiments because of the scale of cutting and technical challenges exist for high speed microcutting. Slip-line field solutions, as a representative of analytical models, are not proper techniques for detailed analysis of cutting process because of the assumptions behind the modeling development. For example, this modeling technique is based on mathematical formulation of the material plasticity then they cannot provide information on the elastic body of the tool which can play a big role in the micromachining operations. FEM, as the most popular numerical technique, in contrary to both experimental and analytical techniques, can provide information on fundamental thermo-mechanical variables such as temperature, plastic strain, and stress distribution, etc. However, the proper prediction performance of this modeling technique depends on the accuracy of input variables (mostly the contact properties, and material constitutive model).
In this thesis, the orthogonal



1. a) Sketch of the DMC b) DMC geometries

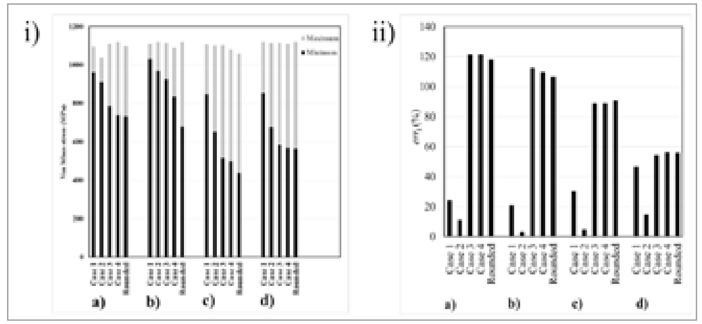
micromachining FE modeling approaches are used to overcome the drawbacks (not considering DMC stationary properties and proper geometry of DMC) of current FE models. In particular, the proposed approach consist in artificially introducing the piled up material on the surface of the modeled tool edge. With this modeling technique, it is possible to perform comprehensive investigation over geometry of DMC, going into further analysis on the mechanics of micromachining process. Extensive experimental campaigns support the development of the modeling techniques, and the validation of the simulated results.
Based on the experimental observations available in literature, the DMC is modelled with a sharp corner edge and smooth faces (Figure 1a). Geometry of the DMC is constrained in AC face by tool edge radius while it can be characterized by two angles *ψ* and *ζ* where they are drawn respectively to parallel and perpendicular directions to the workpiece free surface. The two faces of DMC (along AB and BC) are tangent to the tool edge radius to facilitate the material flow over rake and clearance faces. In this thesis, two magnitudes (0° and 15°) of clearance and rake angles of DMC are considered (Figure 1b) to investigate the sensitivity of the microcutting mechanics with respect to the geometry of DMC.

Arbitrary Lagrangian Eulerian (ALE) mesh distortion control along with adiabatic heating effects are used for 2D modeling of micro orthogonal cutting and



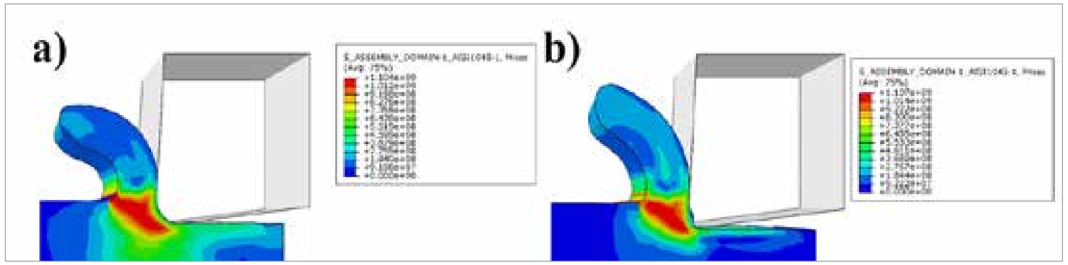
2. Stress distribution for different DMC geometries in the experimental conditions with v_c = 100 m/min, t_u = 9 µm: a) rounded tool edge; b) with DMC (ζ = 15°, ψ = 0°)

it is found that DMC is affecting the mechanics of the process significantly. In fact, it is shown that prediction of the process outputs depends on the DMC presence and its geometry. Indeed, DMC occupies the significant portion of tool-chip contact and as a consequence it affects the mechanics of the cutting process in micro scale. Figure 2 indicates the Von Mises stress distribution over chip formation zone and final chip geometry for rounded tool edge (a) and with DMC (*ζ* = 15°, *ψ* = 0°). The maximum and minimum of this quantity is determined along shear plane in workpiece and is shown for different cutting conditions and DMC geometry (Figure 3i). The outputs such as chip thickness, cutting and thrust force depend on DMC geometry. For example, the error between predicted thrust force and cutting force can be reduced by DMC consideration (Figure 3ii). Indeed, it is found that one single geometry (*ζ* = 15°, *ψ* = 0°) of the DMC is producing lowest error for most of cutting conditions.



3. i) Von Mises stress distribution along shear plane ii) Percentage error for thrust force prediction (err_r) in the experimental conditions with: a) v_c = 100 m/min, t_u = 6 µm; b) v_c = 300 m/min, t_u = 6 µm; c) v_c = 100 m/min, t_u = 9 µm; d) v_c = 300 m/min, t_u = 9 µm

In order to verify the results captured with 2D ALE approach and 9 µm tool edge radius, the second completely different simulation modeling (3D Coupled

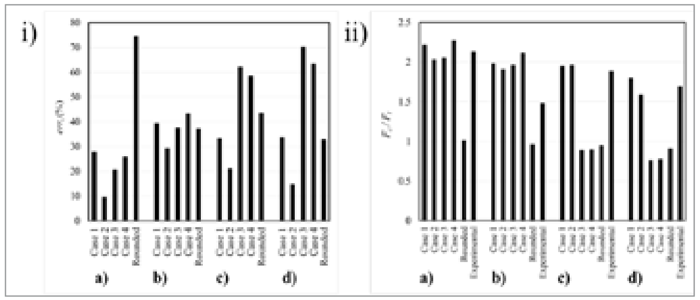


4. Von Mises stress (Pa) distribution for different DMC geometries in the experimental conditions with v_c = 300 m/min, t_u = 60µm: a) rounded tool edge; b) Case 2 (ζ = 15°,ψ = 0°)

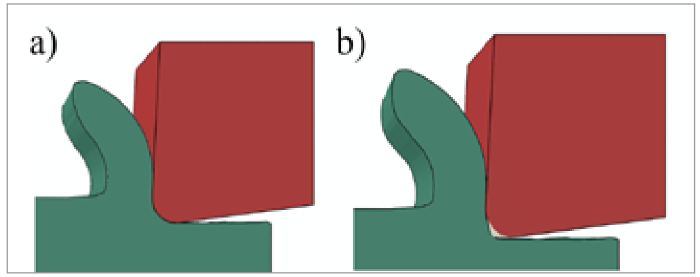
Eulerian Lagrangian (CEL), and edge radius of 60 µm) is designed and compared with experimental results (Figure 4 illustrates the chip formation with this modeling approach). From simulated results, it is found that the same geometry of DMC (ζ = 15°, ψ = 0°) is producing the lowest error for chip thickness, cutting and thrust force (Figure 5) in all of cutting conditions. It is found that if DMC clearance angle is set to 0° (ψ = 0°), the thrust force can be reduced significantly this particular DMC angle describes the experimental results better (Figure 5i). In addition, it is argued that the simulation with rounded edge tool tend to predict force ratio almost equal to 1 (F_c/F_t ≈1) while introduction of DMC into process modeling can break this rule and improve the prediction of this quantity (Figure 05ii).

To study in depth the micromachining process and put forward current understanding over mechanics of the process, fully thermo-mechanical properties of the process with CEL approach is considered (Figure 6). Indeed, with this approach it is possible to investigate the DMC deformation with different material designation and by doing so the proper parameters of Johnson-Cook flow stress model can be suggested. It is found that by reflecting the hardness on the initial yield stress of the material at room temperature coefficient of Johnson-Cook flow stress model (*A*) the DMC stays stable (Figure 6b) during the microcutting process and the errors (for chip thickness, cutting and thrust forces) between simulation and experimental results stay below 10%.

The temperature on the tool tip is also investigated and it is found that presence of DMC at the interface of chip and tool leads to lower thermal conduction through the tool edge. In facts, in micromachining simulation with rounded edge tool (Figure 6a), the temperature of the tool tip reached up to 297°C while with DMC (e.g. stable DMC case shown in Figure 6b) the temperature reached 208°C, where this difference indicates a big reduction of temperature at the tool tip in case of DMC consideration in the model. So the tool wear can be protected from higher degrees of temperature. Based on comprehensive investigation with FE models and experimental results, this study found that DMC has significant effects on process mechanics and it is suggested that for proper analysis of micromachining it would be better if the DMC is included in the modeling and interpretation of micromachining process. In fact, it is possible to conclude that DMC plays an important role in micro scale cutting since it occupies the great portion of contact between tool and chip, then it may not be desirable to ignore this phenomenon in interpretation of the process anymore. This is the important achievement of this thesis. In other words, with analysis and results offered in this thesis it is shown that the interpretation of micromachining mechanics cannot be perfectly achieved if DMC is ignored.



5. i) Percentage error for thrust force prediction (err_t) in the experimental conditions ii) Force ratio prediction in compare with the experimental conditions with: a) v_c = 100 m/min, t_u = 40 µm; b) v_c = 300 m/min, t_u = 40 µm; c) v_c = 100 m/min, t_u = 60 µm; d) v_c = 300 m/min, t_u = 60 µm



6. Chip formation with a) rounded tool edge; b) stable DMC

3D FINITE ELEMENT MODELING OF MICRO END-MILLING BY CONSIDERING TOOL RUN-OUT, TEMPERATURE DISTRIBUTION, CHIP AND BURR FORMATION

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Micro milling requires an accurate management of all the involved resources (machine tool, tool, fixtures, workpiece, etc.). Specific attention has to be paid compared to macro operations, due to the small scale and several difficulties can be faced both with physical experiments and simulations. Micro milling is a rather complicated process to simulate due to the involved complexities, such as geometrical, mechanical, tribological, thermal and chemical. There are many differences between manufacturing in macro and micro scale, which cannot be simply considered with downscaling approaches, due to the difficulties and challenges that need to be considered in micro machining.

Predictive models for machining operations have been significantly improved with numerous methods in the last few decades. Without successful models, expensive experimental testing will continue to dominate the practical process development. So far, not many 3D finite element models (3D FEM) have been presented by taking into account the exact geometry of a micro tool along with their experimental validation in micro milling. This study discusses the performance of a 3D FEM approach for the micro end-milling process on Al6082-T6 with TiAlN-X coated carbide micro end-mills. FE models shows some important advantages, i.e. they can easily deal with any kind of tool geometry and any side effects affecting chip formation such as thermal aspects and material properties changes.

A number of FE simulations were performed at different cutting conditions (full slot and up-milling contouring micro end-milling operations) to obtain realistic numerical predictions of chip flow, temperature distribution, cutting forces and burr formation. Two different approaches for modeling the cutting tool were applied in order to correctly model the exact geometry of the micro end-mill. According to the first modeling approach, the cutting tool was modeled in the FE software based on the measurements carried out on the tool geometrical features by an optical microscope (Alicona Infinite Focus ®), however, this method could not follow the exact geometry of the tool.

Then another approach was applied based on the 3D cloud of points acquired by the same microscope, which has been used to build a more realistic tool model for the simulation.

A 3D FE model, as the one used in this study, is able to consider the effects of the mill helix angle and cutting edge radius on the chip. Due to the small chip size in micro milling, extremely fine meshes and related remeshing techniques were used and consequently the computation time was increased. The Johnson–Cook material model was used as constitutive material model and the constants of the model were determined by an inverse method based on the experimental cutting forces acquired during the micro end-milling tests. The correct selection of these constants is a very important step to predict with a reasonable accuracy forces, temperature, chip morphology, etc. The FE model prediction capability was validated by comparing the numerical model results with experimental tests.

In each part of the model such as, inverse method for material modeling and tool geometry modeling approaches, different set of experiments were carried out to investigate the capability of the model in different cutting conditions. Chip formation and temperature distribution in the cutting area were in good agreement with the experimental results and correlations were observed in terms of burr dimension trends and force profile shapes and magnitude with the 3D tool geometry modeling approach.

Furthermore, the tooling geometrical effects on the micro end-milling performance were investigated and compared against physical experiments and another modeling technique.

The performance of the FEM prediction were compared with the performance of a state-of-art mechanistic model, capable of including minimum chip thickness aspects as well as effective rake angle effects.