REVIEW ON FEM NUMERICAL SIMULATION OF MICROMACHINING PROCESSES

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Abstract. *In micromachining processes, the microtool cannot be assumed as perfectly sharp, in opposition to traditional machining in macro scale. This phenomenon happens because the cutting-edge radius of the microtool has the same size scale as the minimum chip thickness or even the microstructure of the workpiece material. This problem is known as size effect and it is detrimental for the understanding of the cut in micro scale. It is desirable for the industry to optimize the micromachining process by predicting output variables and possible problems caused by the size effect, in order to reduce costs. By knowing the mechanical properties of the workpiece, it is possible to use the Finite Element Method (FEM) to determine different output parameters. Thus, this article proposes a literature overview about the use of numerical simulations in micromachining processes. The following output parameters in micromachining were analyzed: chip formation and minimum chip thickness; cutting temperature; cutting forces; and burr formation. In most of the studies chosen for the present review, the Johnson-Cook plasticity model was used to characterize the mechanical behavior of the workpiece material since it has proved to be consistent with experimental data for some materials. It was possible to observe that the minimum uncut chip thickness is an important parameter in micromilling that is not yet completely predictable or understood, because it depends on several non-linearities that cannot always be taken into account in numerical simulations. On the other hand, the measurement of cutting forces tend to match experimental data more often. None of the analyzed studies focused in simulating the effect of cutting fluid application in micromachining, although the lubrication condition plays crucial role in determining the surface quality of micromachined surfaces. Finally, in the studies analyzed, it was possible to observe that microtool wear is not usually predicted through FEM, since tools are generally modelled as rigid bodies in numerical simulations. In general, according to the present review work, there are still many challenges in predicting output parameters in micromachining because there are several non-linearities that are aggravated by size effect.*

Keywords: *Micromachining; Finite Element Method; Numerical Simulation; Size Effect.*

1. INTRODUCTION

Micromachining is a term that has been used more and more often in the last few years to refer to the fabrication of very small features and pieces. The recent trend of miniaturization of mechanical components has stimulated the development of machining processes that allow the fabrication of ultra-precision machine parts. Micro-components require high levels of geometrical quality and are usually manufactured using traditional cutting tools that are capable of removing micro or nano chips (Jain et al., 2012). One of the most used micromachining processes is micro milling. According to Ng et al. (2006), micro milling is characterized by the depth of cut, which should range from a few nanometers to some micrometers. According to Aramcharoen et al. (2009), on the other hand, a milling process is considered micro milling when the value of feed per tooth is comparable to the cutting-edge radius of the microtool. So, there is not yet a consensus on what exactly defines micro milling, however the most widely accepted definition is based on the geometry of the cutting tool. Camara et al. (2012) define micro milling as any milling process in which the diameter of the microtool is between 1 µm to 1000 µm.

An important aspect of micromachining operations is that the dimension of cutting-edge radius of the microtool is similar to that of the minimum chip thickness, so that the physical principles usually applicable in traditional machining in macro scale cannot be used in machining in micro scale (Câmara et al., 2012). Micromachining processes are usually associated with several complications. For example, the cutting forces must be as small as possible to avoid breakage of the tool, the rigidity of the machine tool must be high enough to minimize precision errors and the finishing process requires more precision. Besides, the performance of microtools is highly influenced by small vibration and excessive forces, which may be damaging to the tool life and the tolerance control of the machined parts (Chae et al., 2006).

In traditional machining, that is to say, machining in macro scale, the cutting-edge of the tool is considered perfectly sharp, because its radius has negligible size. On the other hand, in micromachining operations, the cutting-edge radius

cannot be neglected since it has the same size scale as the minimum chip thickness and, sometimes, even the size of the grains in the microstructure of the workpiece material. This phenomenon is called size effect and is detrimental to the mechanism of cutting in micro scale (Chae et al., 2006). Figure 1 represents the comparison between a) machining in macro scale and b) machining in micro scale. It can be seen that, when the tool is perfectly sharp, the chip flows along the flank face of the tool with a positive rake angle α. In micromachining, on the other hand, the radius of the cutting-edge, r_e, is comparable to the uncut chip thickness, h, so that a large amount of the workpiece material in only deformed plastically and a small amount of it is removed in the form of chips, with a negative rake angle. This creates an increase in the specific cutting energy of the cut, because the rate of energy per unit of volume of removed material is greater than in traditional machining (Chae et al., 2006). Besides, depending on the relation between the cutting-edge radius and the uncut chip thickness, it is possible that the workpiece material is only deformed by the tool and no material is effectively sheared. This means that there is a minimum uncut chip thickness below which there is no chip formation at all, which causes bad quality on the surface, does not generate the desired geometry and drastically intensifies the wear of the cutting tool (Dib et al., 2018).
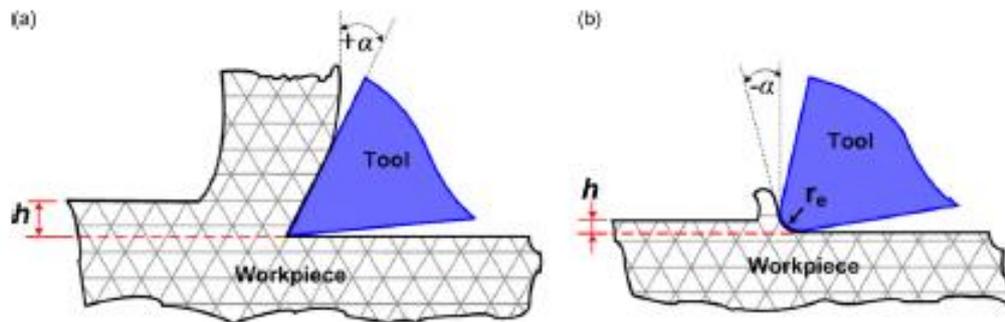

Figure 1: Effect of the size of the cutting-edge radius of the tool in traditional machining (a) and micromachining (b) (Aramcharoen and Mativenga, 2009).

Regarding surface quality, micromachined components have high tendency to present burrs, which are ridges of plastically deformed material that were not effectively removed as chips, characterized by the plowing effect caused by the rounded cutting-edge. Burrs in micromachining tend to be relatively big in comparison to the geometry of the cut and can eventually get four times as high as the minimum chip thickness, resulting in poor surface quality (Dib et al., 2018). Other common problem in micromachining is the dynamical response of the microtool, which is very sensitive to the spindle speed and can cause radial throw, causing the trajectory of the tool to deviate from the idealized geometry (Nahata et al., 2018). Besides, the plowing caused by the size effect in micromachining may lead to excessive forces in the region of interface between the tool and the workpiece, which may cause chip adherence and tool breakage (Schueler et al., 2010).

Therefore, machining in micro scale still presents many aspects that are not yet completely understood, especially in what refers to the mechanisms of burr and chip formation and their influence in surface quality of the final product and tool life. Considering all the challenges associated with micromachining, this work proposes a bibliography review on the most important aspects to be considered in finite element method simulations. The research was carried out using keywords such as *micromachining, numerical simulation, finite element method, cutting forces* and *cutting temperature.*

2. SIMULATION OF MICROMACHINING THROUGH FEM

The finite element method (FEM) can be used for simulating orthogonal cutting. Through the orthogonal cut, it is possible to represent in two dimensions any machining process that uses a cutting tool with a defined geometry, such as milling and turning. It is a simplification of the problem that consists in depicting the tool moving towards the workpiece to analyze chip formation. Depending on the geometry of the instances, material properties and machining parameters, different responses can be observed and compared to experimental results (Jinsheng et al., 2008).

In FEM simulations, a popular way of simulating chip formation is to assign a fracture criterium to the elements that compose the workpiece material (Rao and Vijayaraghavan, 2013). When a material is submitted to plastic deformation, such as in machining, it is necessary to determine its isotropic hardening curve in order to characterize its mechanical behavior in a FEM simulation. There are numerous constitutive models that can be used to mathematically describe the elastoplastic behavior of a material, however, one of the most commonly used is the Johnson-Cook (JC) constitutive model. This model describes the dependency of plastic flow stress on equivalent plastic strain, normalized equivalent plastic strain rate and homologous temperature. Besides, it is assumed that damage accumulates linearly in each element according to the rate between the increment in plastic strain and the equivalent strain at fracture.

2.1. Chip formation and minimum chip thickness

Several authors have used FEM simulations to determine the minimum uncut chip thickness and its influence in chip formation for different materials. It is known that the size of the cutting-edge radius of the tool is essential to determine size effect in micromachining, by changing the material flow pattern around the tip of the tool and expanding energy dissipation due to increased area of contact between the tool and the chip. Liu and Melkote (2007) simulated micro-cutting of Al5083-H116 alloy, using different values of chip thickness. The authors concluded that tool edge radius and the temperature drop in the secondary deformation zone can cause non-linearities in the chip formation simulation.

Lai et al. (2008) developed a FEM model to simulate the micro-orthogonal cutting of OFHC copper using a microtool with cutting-edge radius 2 µm and rake angle 10º. By using different values of chip thickness (h), the authors observed different responses in chip formation and Mises stress distribution, as observed in Fig. 2. The authors concluded that the minimum chip thickness is 0.25 times the cutting-edge radius of the tool. Besides, the specific shear energy increases greatly when the chip thickness is smaller than the minimum value, due to the plowing phenomenon.
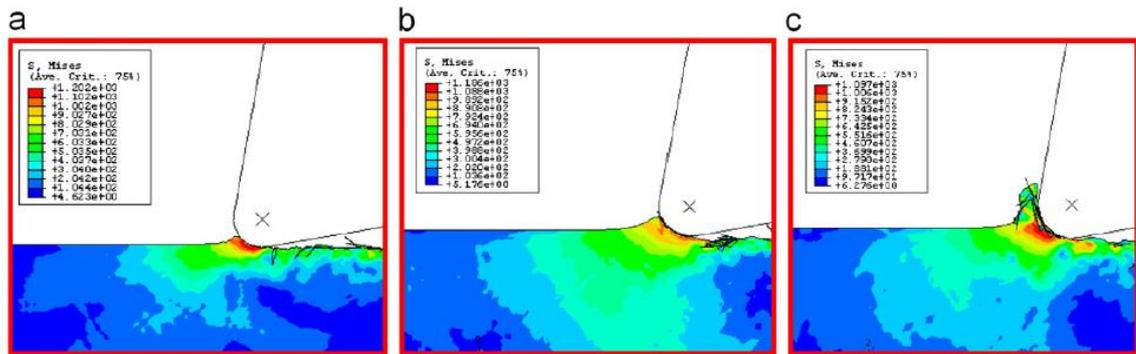

Figure 2: Chip formation in micromachining simulation of OFHC copper: a) h = 0.2 µm, b) h = 0.4 µm, c) h = 0.6 µm (Lai et al., 2008).

Chen et al. (2019) investigated segmented chip formation in orthogonal cutting of Ti-6Al-4V alloy using different constitutive models, concluding that ductile failure models can characterize the flow softening behavior during segmented chip formation. Thepsonthi and Özel (2016) also observed the formation of segmented chip, in comparison to continuous chip, when modelling micromachining of Ti-6Al-4V, depending on whether the constitutive model that describes the workpiece material is viscoplastic or elasto-viscoplastic, as observed in Fig. 3. These authors concluded that using a viscoplastic material assumption can reduce simulation time up to eight times that of a simulation with elasto-viscoplastic assumption. According to these authors, when using the viscoplastic assumption, it is considered that the elastic deformation is negligible in comparison with the plastic deformation. This assumption is generally valid for traditional machining; however, the degree of elastic deformation may become relevant in micromachining due to size effect. Therefore, a more sophisticated elasto-viscoplastic assumption may be necessary to obtain more precise results, despite the expense of significantly increasing computational time.
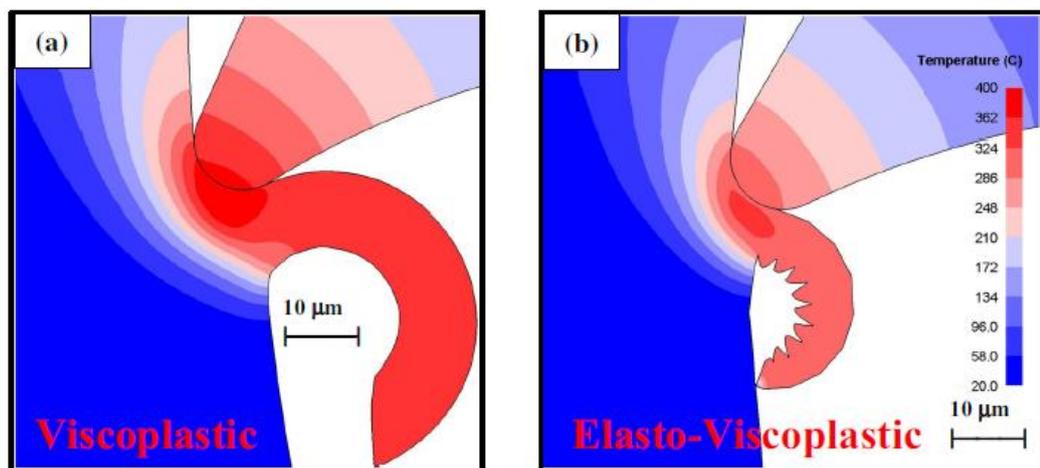

Figure 3: Formation of a) continuous chip and b) segmented chip according to material constitutive assumption (Thepsonthi and Özel, 2016).

In another work, Attanasio et al. (2019) conducted an experimental investigation of micro milling of CuZn37 brass, as well as FEM simulations to investigate the effects of cutting speed and feed rate on forces, chip flow, and shapes. By

comparing predicted and measured results, the authors concluded that the size of the tool run-out deviation does not result in direct connection to the cutting speed. The authors also noted that the qualitative comparison of predicted chip flow and chip shapes and the measured chip shapes led to reasonably good results. As observed in Fig. 4, the authors' simulation was able to predict some chip segmentation as well (Attanasio et al., 2019).
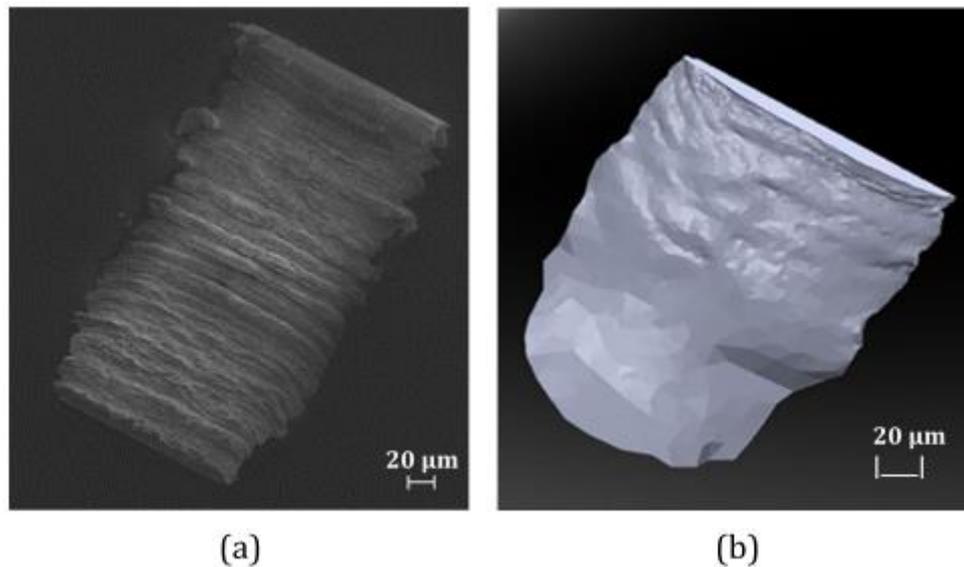

Figure 4: Comparison between (a) a SEM image of a chip and (b) a part of the simulated chip obtained by FEM (Attanasio et al., 2019).

2.2. Cutting temperature

Measuring cutting temperature experimentally is difficult due to the inherent nature of cutting process in micro scale. In FEM simulations, since the simulation time is usually small, it is common to implement in the material properties a heat transfer coefficient that is higher than usual. Otherwise, it may not generate sufficient temperature rise in the analyzed part (Thepsonthi and Özel, 2016).

In the region of interface between the tool and the workpiece, the shear zone is expected to be the area where the temperature is maximal, as observed by Ducobu, Rivière-Lorphèvre and Filippi (2017). According to these authors, who simulated machining of Ti-6Al-4V alloy, the cutting temperature is directly linked to cutting forces and the level of flow stress. According to Thepsonthi and Özel (2016), the viscoplastic FEM model predicts a 15-20 % higher temperature compared to elasto-viscoplastic FEM model, because some energy is converted to heat instead of being stored as strain energy.

De Oliveira et al. (2021) conducted an experimental and numerical study of micro milling of Inconel 718, which is a low machinability alloy, using an explicit dynamic, thermos-mechanically coupled FEM model specialized in metal cutting processes. The authors concluded that there are three main chip types in micromachining Inconel 718, which are helicoidal, ribbon and spheroidal chips. According to the authors, the high specific cuttingenergy in the micro-cutting process can lead to extremely high rates of oxidation in very small volumes of Inconel 718, which may become a spheroidal chip with dendritic microstructure. It was possible to observe in the 3D simulation that the helicoidal chip was successfully formed in the main cutting-edge, with ribbon chips being formed in the minor cutting-edge. The authors characterize the presence of spheroidal chips as an indicator of high specific cutting energy and the necessity of improvements in cutting parameters. Although the spheroidal chip could not be clearly observed in the numerical simulation, it was possible to observe the formation of small volumes of Inconel 718 with elevated temperature, which is presumably the initial stage of its formation, as observed in Fig. 5.
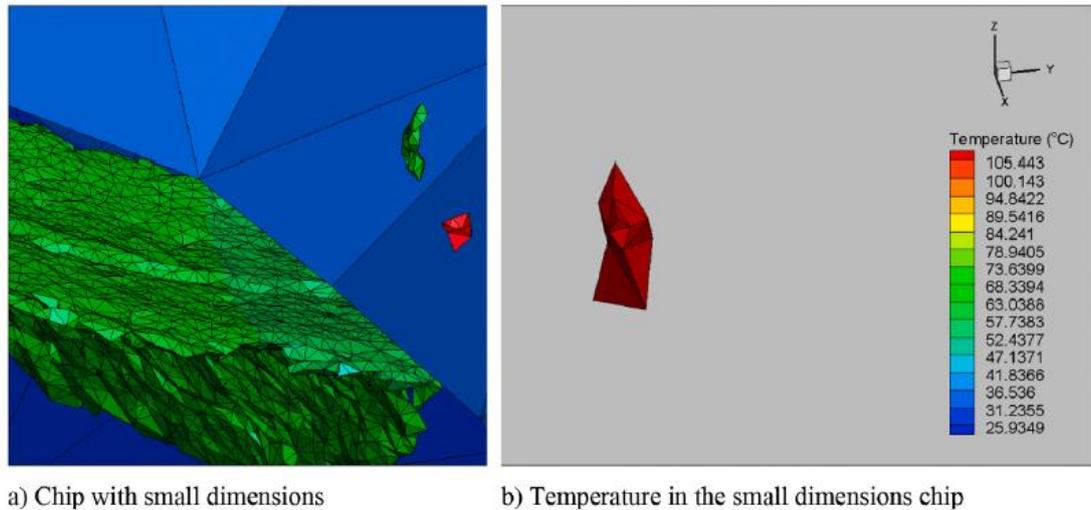
a) Chip with small dimensions   b) Temperature in the small dimensions chip

Figure 5: Presumable formation of spheroidal chip: a) chip with small dimensions and b) elevated temperature in the small chip (de Oliveira et al., 2021).

2.3. Cutting forces

The cutting force is a fundamental parameter in micromachining operations and can be an important variable to optimize cutting conditions. Prediction of cutting forces is of great significance for controlling of any machining processes. Chen et al. (2019), in their study, concluded that different plastic constitutive models result in similar results in terms of cutting forces in simulation of Ti-6Al-4V cutting. The authors compared the Johnson-Cook model (JC), modified Johnson-Cook model (JCM) and Khan Huang Liang model (KHL), obtaining a maximum error of 8% in comparison with the experimental results.

In micro milling, the dimensions of the machined feature are dominated by tool deflection, which is associated with forces in the X and Y directions. Therefore, the component of the cutting force in the Z direction (axial direction) is negligible since it has no significant effect on regenerative chatter. Jing et al. (2020) developed a model for predicting cutting forces in micro-end milling, using FEM to calculate force coefficients as a function of uncut chip thickness. The authors concluded that the effect of elastic recovery rate (Pe) on predicted cutting force is more obvious for lower feed per tooth. Besides, the root mean square (RMS) values of cutting force increases with increasing feed per tooth, as observed in Fig. 6.
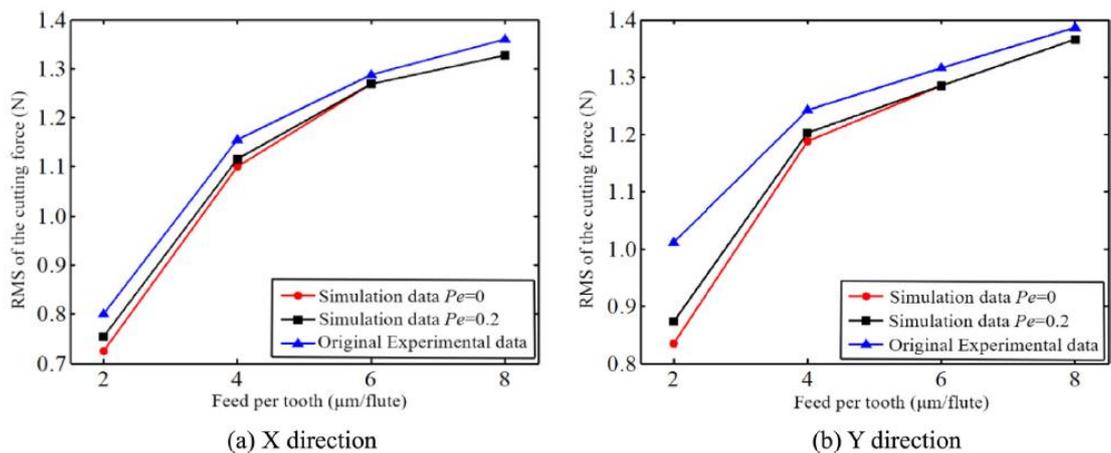

(a) X direction   (b) Y direction

Figure 6: Root mean square values of cutting forces in micro-end milling simulation, considering the elastic recovery rate (Pe) (Jing et al., 2020).

Yuan et al. (2018) developed a mechanistic cutting force model for micro end-milling, as well as an algorithm to determine instantaneous uncut chip thickness. In this work, the authors consider a combination of the run-out effect, the minimum chip thickness, the elastic recovery of the material, the trajectory of the cutting tool flute and the variation of the exit and entry angles of the tool run-out. A FEM simulation of the orthogonal cutting process was established to determine cutting force coefficients, which were identified as nonlinear functions of the uncut chip thickness, the edge radii, and the cutting velocities. The authors found out that the predicted and experimental cutting forces showed similar variation patterns and closely matched amplitude levels, with a difference of less than 7% (Yuan et al., 2018).

In their work, Thepsonthi and Özel (2016) conducted a sophisticated analysis of cutting forces in simulation of micro milling. The authors modelled a micro-end mill with two flutes, made of tungsten carbide in a cobalt matrix, coated with a 2 µm layer of boron nitride. The authors proposed an analytical model to predict tool wear rate as a function of temperature, normal stress and sliding velocity. Considering the maximum forces, the authors observed that the viscoplastic model is enough to predict force at a deviation of only 1% from the elasto-viscoplastic model, as observed in Fig. 7.
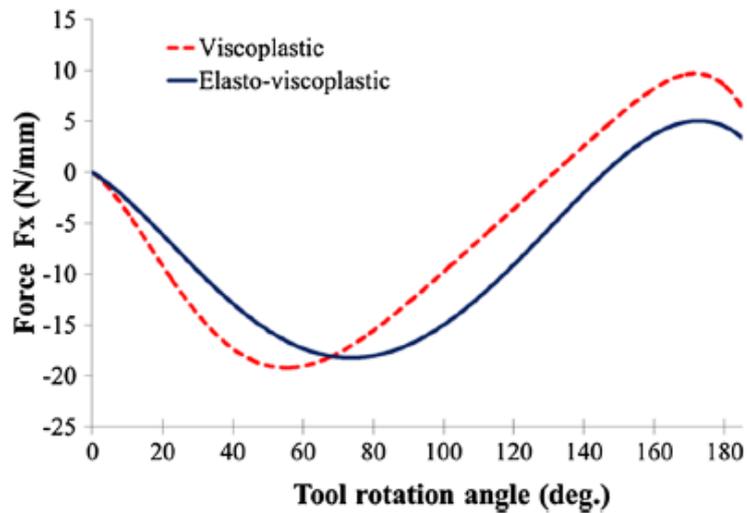

Figure 7: Cutting forces in micro-end milling simulation using viscoplastic and elasto-viscoplastic models.

In order to investigate the influence of interface on machinability of interfacial phases of SiCp/Al, Zhang et al. (2022) developed a two-dimensional three-phase finite element model of composites including interfacial phase, Al matrix phase with a reinforced phase of SiC particles based on a cohesive model. The authors analyzed the plasticity and failure behavior, as well as particle breakage and surface morphology, of the SiCp/Al composite matrix under micro milling conditions. The experimental workpiece was a SiCp/Al composite with 20% volume fraction. With the advance of the tool, the authors noticed that the Al matrix is extruded by the cutting tool, causing the material to be pushed to the upper part of the particles of SiC in such a way that the some of the broken SiC particles form pits on the machined surface after being pulled out of the Al matrix. The numerical model was able to predict cutting forces which were close to the results obtained experimentally, as observed in Fig. 8. The authors concluded that the cohesive model can accurately describe the mechanical properties of interfacial phases of composites.
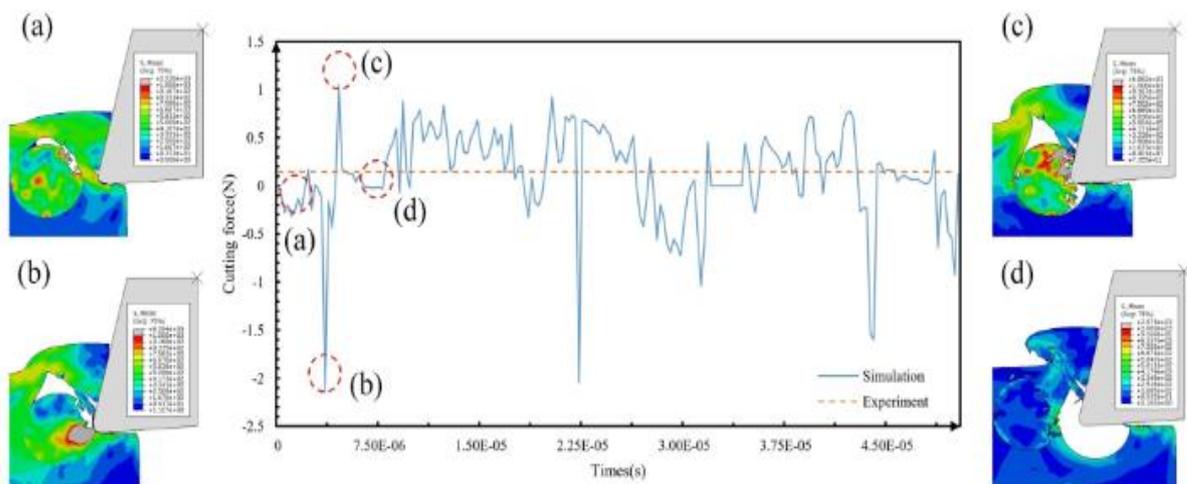

Figure 8: Comparison of cutting forces measured numerically and experimentally in SiCp/Al composite. The red dashed circles represent the numerical data (Zhang et al., 2022).

2.4. Burr formation

The presence of high burrs is a common problem in micromachining, especially in low machinability alloys (Silva et al., 2021). In micro milling of Inconel 718, for example, it is common to use minimum quantity lubrication (MQL) to improve cutting performance, because the absence of lubrication tends to cause large burrs and very low tool life (Aslantas and Çiçek, 2018). So, it is important to predict burr formation by means of numerical simulations in order to avoid the deterioration of the tool and the surface quality of the machined part. Özel et al. (2017) conducted an experimental and numerical investigation of micro-end milling using 3D FEM simulations. The authors measured the burr heights resulted from the simulations, concluding that burrs become higher with higher values of tool edge radius, as observed in Fig. 9.
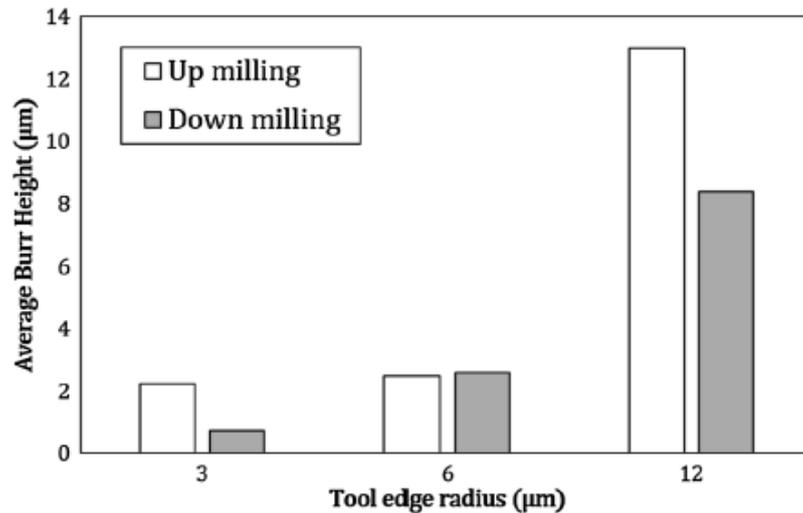

Figure 9: Effect of tool edge roundness on burr height in FEM simulation of micro milling (Özel et al., 2017).

In their work, Thepsonthi and Özel (2015) conducted a comparison of 2D and 3D viscoplastic FEM simulations, which indicated that 2D FEM simulation models may be adequate for force analyses and tool wear predictions, with less computational cost. However, the authors observed that there is a distinct advantage of 3D FEM simulation over 2D FEM simulation for better prediction of chip and burr formation, because the 3D model considers the tool helix angle, the edge radius, and the corner radius. In the 2D viscoplastic FEM model, chip flow is limited to the plane strain deformations in the XY plane, resulting in an excessive chip accumulation in front of the tool. By using the 3D FEM simulation, a more realistic behavior of the chip flow and curling was obtained, enabling to predict the behavior of the chip flow and curling, as observed in Fig. 10. According to the authors, knowing the behavior and the direction of chip flow and curling may allow the designer of the tool to avoid chip clogging and minimizing burr formation. It is known that burr formation is heavily associated to some cutting conditions and locations.
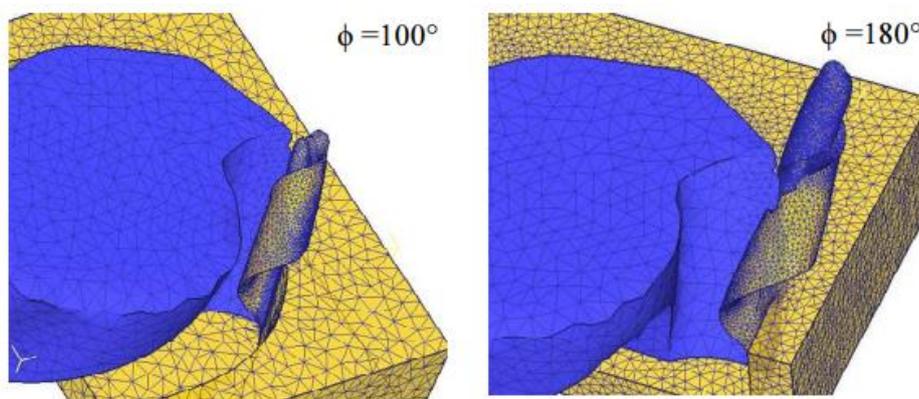

Figure 10: Predicted chip formation in 3D FEM simulation of micro milling for different values of shear angle φ (Thepsonthi and Özel, 2015).

Most research works about burr formation in micro milling focus on milling of conventional rectangular or circular micro slots, nevertheless, Deng et al. (2022) developed a technique to fabricate Ω-shaped reentrant microchannels. The authors investigated the effects of cutting parameters on side burr size by means of experiments and finite element simulation. The authors used tungsten carbide micro ball end mills with two flutes and a diameter of 0.8 mm to manufacture circular cavities in prefabricated micro slots in samples of pure copper. The burr area was used to characterize the burr size due to the difficulty in measuring burr height in the circular shaped cavities. In the FEM simulation of the

process, the authors considered the workpiece as a plastic material, described by the Johnson-Cook model. The tool was considered a rigid body and both instances were discretized by tetrahedral meshes. By comparing the morphologies of the reentrant micro channels obtained by the simulation and the experiment, the authors noticed that the side burrs were formed only on the down milling side, as observed in Fig. 11. The authors found the minimum uncut chip thickness to be around 0.25 of the micro ball end mill radius.
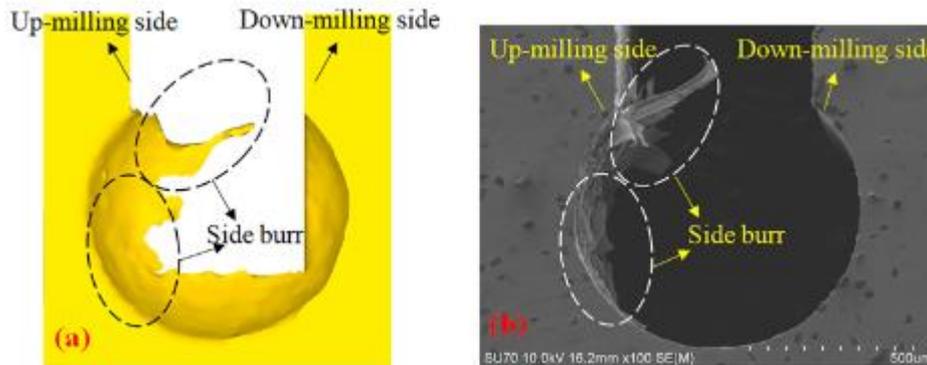

Figure 11: Burr formation in Ω-shaped reentrant microchannels obtained by (a) simulation and (b) experiment (Deng et al., 2022)

Since burr formation is expected to depend on the stress state and microstructure of the undeformed workpiece material, it can be hindered by cold working, which leads to grain refinement and the appearance of residual stresses on the material surface. In that regard, Yadav et al (2022) proposed a robust numerical modelling and experimental verification of burr size control in micro milling of Ti-6Al-4V by introducing compressive residual stresses on the surface of the workpiece. The authors found that the presence of residual stress suppresses the burr generation by up to 63% in terms of width and height. The simulation was performed on Abaqus using a recrystallization and strain gradient flow model accompanied by a user-defined friction algorithm. The critical uncut chip thickness was found to be 24% of the cutting-edge radius and more burrs were seen on the down-milling side rather than on the up-milling side, which is uncommon in micromilling.

3. CONCLUSIONS

In this contribution, a bibliography review was done in order to analyze the main works of FEM simulations to the understanding of micromachining processes. The following conclusions and tendencies can be drawn:

- The principal constitutive model used to describe the mechanical behavior of the workpiece material in FEM simulations of micromachining is the Johnson-Cook model, which has proved to generate numerical results that match experimental results.
- In most FEM simulations of machining, the problem is simplified with a 2D modelling of orthogonal cutting, which can represent any traditional machining process and is enough to provide fairly precise results for the most important output parameters.
- Works about numerical simulations of micromachining are normally focused in determining minimum chip thickness for different machining parameters. However, there is still a lack of studies about the influence of the workpiece material in the value of the minimum chip thickness.
- Not many authors focus on the computational cost and mesh optimization in machining simulations, probably because several assumptions are normally used to simplify the problem. However, simplifications in the constitutive model can lead to inaccurate results depending on the size effect in micromachining.
- The effect of lubrication with cutting fluids was not studied in any of the analyzed works. This aspect is not commonly simulated through FEM, although it is common to use cutting fluids in micromachining experiments.
- Cutting forces in micro milling can be easily predicted using FEM simulations, which is an important parameter to predict tool life.
- The effect of roundness of the cutting-edge of the tool can be analyzed in orthogonal cut simulations by changing the radius of the cutting-edge. This phenomenon, which is caused by the rapid tool wear in micromachining, has proved to cause higher cutting forces, worse chip formation and worse surface quality.
- The cutting tool in most simulations of micromachining is represented as a rigid body, because the workpiece material is the zone of interest. Therefore, it is not common to directly simulate tool wear in micromachining, although analytical models can be used to predict it from FEM data.

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