Numerical Study of Micro-Milling Process Using Finite Element Method

Noor Aniza Norrdin*[,1], Juri Saedon[1] and Nurul Nadiah Azmi[1]

[1]School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia

Corresponding Author's Email: * nooraniza@uitm.edu.my

Article History: Received 07092024; Revised 05102024; Accepted 31102024;

ABSTRACT – The micro-milling process is a critical technique in manufacturing small-scale components with high precision and accuracy. Studies have been extensively conducted to investigate the effects of various process parameters on the performance of micro-milling process. Furthermore, simulation studies have been widely carried out to predict cutting forces, tool wear and tool deflection while at the same time reducing the cost of manufacturing. In this study, the effect of cutting parameters and the capabilities of the finite element method (FEM) to analyse the cutting force and tool wear during the micro-milling process is discussed using Abaqus software. The methodology of this study was justified. A three-dimensional model of micro-milling process was developed and two different cutting parameters were analysed using Abaqus software. The cutting parameters tested during the micro-milling process were between Vc= 100 m/min, f=4 µm, d=75 µm as the lowest and Vc= 100 m/min, f=4 µm, d=75 µm as the highest, which were analysed on the 20 mm material workpiece length of tool travel. Results demonstrated that as the cutting progressed, all cutting force components increased significantly due to the tool wear. This simulation study will provide insights into the optimisation of process parameters for improved productivity and part quality.

KEYWORDS: *Micro-milling, simulation, cutting force*

1.0 INTRODUCTION

Micro-milling is a critical manufacturing process for fabricating small-scale components with tight tolerances and high surface quality, such as those used in the electronics, aerospace and medical industries [1]. Compared to traditional macro-scale milling, micro-milling presents unique challenges due to the small feature sizes, high spindle speeds and complex tool-workpiece interactions. Experimental studies have been extensively conducted toinvestigate the effects of various process parameters on the performance of micro-milling, including cutting forces, tool wear, surface roughness and dimensional accuracy [2-4]. However,the studies can be time-consuming and expensive, especially when exploring a wide range of process conditions.

Numerical simulation using the finite element method (FEM) has emerged as a powerful tool to study the micro-milling process more cost-effectively and efficiently [5-6]. Finite element analysis can provide detailed insights into the stress, strain and temperature distributions during micro-milling, which are crucial for process optimization and development of predictive models. Several studies have explored the use of finite element modelling to analyse the micro-milling process, considering the effects of cutting parameters, tool geometry and workpiece material properties [7-9]. The primary source of machining mistakes in micro-milling, particularly with micro-tools having a high length-to-diameter ratio, is tool deflection [10]. Among the errors, tool deflection is the most severe impediment to precision machining [11]. Therefore, understanding the forces acting on the cutting tool design and estimating power requirements play an important role in the micro-milling process.

This paper presents a numerical study of the micro-milling process using the finite element method, which is Abaqus software. It investigates the effects of key cutting parameters, including cutting speed, feed rate and depth of cut, on the cutting forces in the workpiece material. The results can provide valuable insights into the tool wear of the cutting tool for the micro-milling process and can be used to optimise process parameters for improved productivity and part quality.

2.0 METHODOLOGY

2.1 Simulation Model

The finite element analysis of the micro-milling process was conducted using the Abaqus software package. Table 1 illustrates the material constant for the workpiece. The material for the cutting tool is defined using Young's Modulus, E = 200GPa and Possion's Ratio,v= 0.33.

Table 1: Johnson-Cook material constant for AISI D2 (Tang et al., 2011)

Material	A [MPa]	B [MPa]	n	C	m	Melt Temp. [K]
AISI D2	1766	904	0.312	0.12	3.38	1733

The model consists of a tool design with a two-flute end mill with 38 mm length and 0.5 mm diameter, which was modelled using CAD. The tool geometry parameters are given in Table 2 with a clear insight in Figure 1.

Table 2: Specification of cutting tool

Mill diameter (D1)	Shank diameter (D2)	Flute length (L1)	Overall length (L2)
0.5mm	3mm	1mm	38mm

Figure 1: Micro-cutting tool geometrical

The simulation considered the three-dimensional nature of the micro-milling process and incorporated the effects of tool geometry, cutting parameters and material properties. In the simulation, the milling tool rotates around the Z-axis and the workpiece feeds in the cutting direction at the same time, as shown in Figure 2(a). The workpiece moves in the direction X and is fixed in the direction Y. The tool and the workpiece are set as deformed bodies and rigid constraints are applied to the tool. The mesh type of the workpiece is defined as a hexahedral with eight-node coupled bricks and a first-order linear interpolation solid element, while the tool is defined as a tetrahedron with a node linear interpolation solid element, as shown in Figure 2(b). The simulation was carried out on the 20 mm material workpiece length of tool travel to investigate the cutting forces with the cutting tool in the new (initial cutting) and worn (final cutting) conditions. The cutting parameters used were Vc= 20 m/min, f=1 µm, d=15 µm as the low-level and Vc= 100 m/min, f=4 µm, d=75 µm as the high-level machining parameters representing Test I and Test 2, respectively.

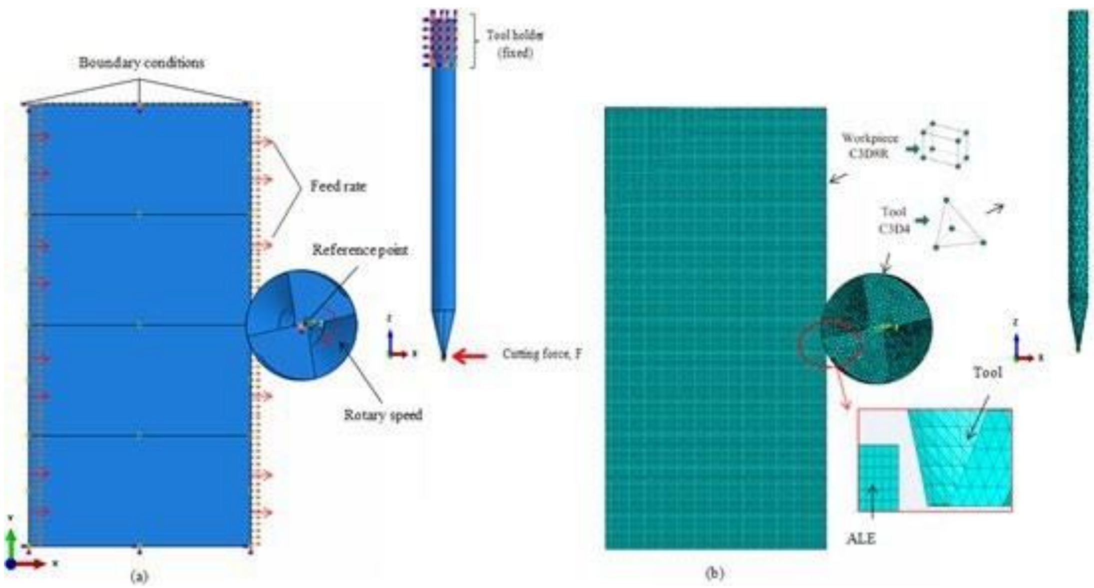

Figure 2: Top view of FEM setting (a) boundary conditions and (b) meshing of the workpiece and tool

The initial FE model was developed by referring to the existing model in the literature as the first step to get a validated model before the actual simulation analysis took place. The models were referred to by Chae et al. (2006) [12]. The simulation results obtained must be as precise as possible for the investigation of cutting force in micro-end milling operations, which can lead to model validation. After the initial model was validated, the different test cases with the same parameters used in the experimental literature approach of micro-end milling hardened AISI D2 cold work tool steel were used as in Saedon et al. work [3].

2.2 Validation Study

A validation study was conducted to compare the results with those of Saedon et al [3]. The parameters compared included the cutting force values from the simulation and the cutting force values from the experimental data by Saedon et al [3]. Table 3 shows the validation results between the referenced experimental results and presented simulation results with cutting parameters used; cutting speed, Vc of 50 m/min, axial depth of cut, d of 55 µm and feed rate, f of 2 µm/tooth.

Table 3: Relative error for cutting force values between and the present [3]

Force	Cutting force by Saedon et al. (N)	Cutting force (N)	Relative error
Fx	3.30	3.14	5%
Fy	3.25	3.19	2%
Fz	2.67	2.57	4%

3.0 RESULT AND DISCUSSION

3.1 Cutting force

The cutting force components, Fx, Fy and Fz obtained from the simulations of Test I are shown in Figure 3(a). All force components were seen to increase as the cutting progressed up to 20 mm cutting length as shown in Figure 3(b). Similar trends were also found for the Test II simulation case in Figure 4(a) for initial cutting and Figure 4(b) for final cutting.

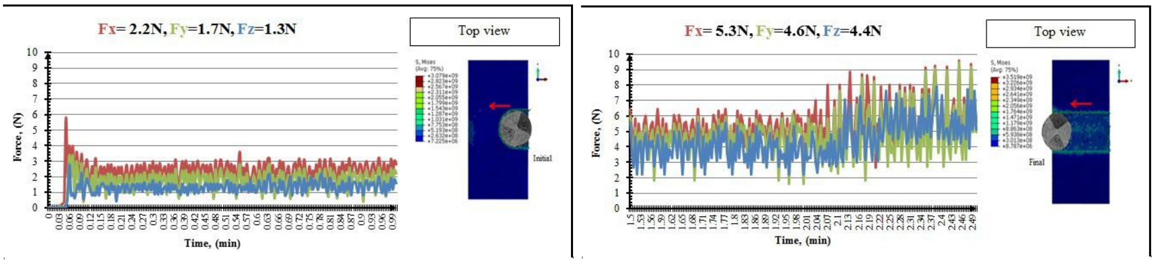

Figure 3: Cutting force in simulation (V_c= 20 m/min and f=1µm and d=15µm) for (a) initial cutting and (b) final cutting

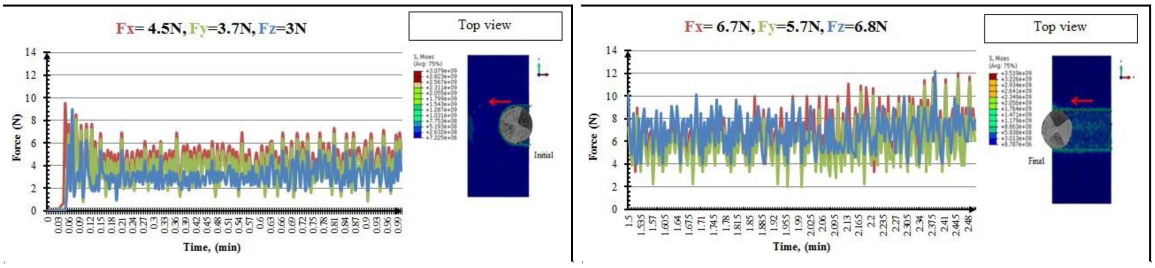

Figure 4: Cutting force in simulation (V_c= 100 m/min and f=4µm and d=75µm) for (a) initial cutting and (b) final cutting

Figure 5 displays the comparison in cutting forces between Test I conducted using low-level machining parameters and Test II carried out with high-level parameters. All forces increased significantly as the cutting proceeded. The feed force, Fx increased from 2.2 N to 5.3 N and 4.5 N to 6.7 N for Test I and Test II, respectively. The percentage increase was 58% and 33% approximately. For the normal force, Fy also improved from 1.7 N to 4.6 N for Test I and from 3.7 N to 5.7 N, giving the change of 63% and 35%. This was more observable in thrust force, Fz where a large increase was recorded for Test I from 1.3 N to 4.4 N with 70% of change while for Test II from 3 N to 6.8 N with 56% of change.

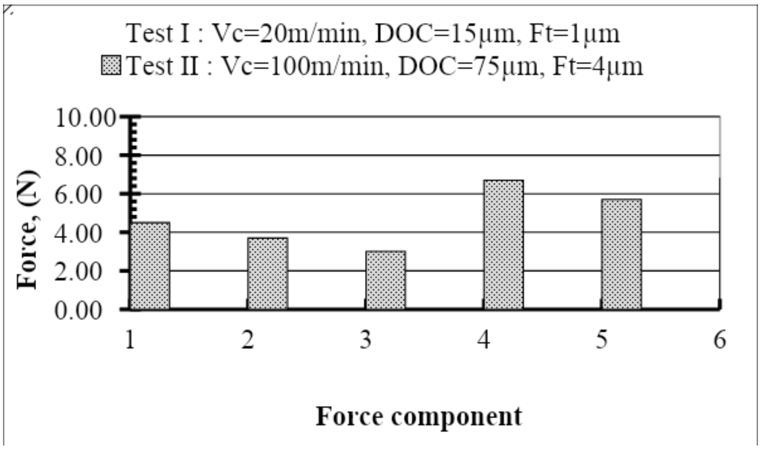

Figure 5: Predicted cutting forces generated in Test I and Test II during initial and final cutting.

The reason why the cutting forces increased as the cutting length proceeded is based on the fact that cutting force may be caused by further deformation energy required during the chip formation, thereby contributing to the size effects by modifying the chip formation at the tooltip. Fundamentally, as the cutting progressed, all force components increased significantly due to the tool wear that easily led to a tool deflection, tool breakage or damage to the workpiece or machined surface. Since a cutting tool greatly wears at the tooltip, it will be the first point to be categorized as wear criteria. This is because the tooltip is subject to the highest contact pressure compared to other parts of a cutting tool [13]. For micro-milling, it could be claimedthat the wear at the tooltip determines the tool deflection and tool life. Since the critical point of tool wear is at the tool tip, the tool wear effects are recommended.

3.2 Tool wear effect in Micro-milling

The cutting force components, Fx, Fy and Fz obtained from the simulations are shown in Figure 6. Investigations of the tool wear effect in micro-end milling were divided into three levels of cutting tool edge radius; re=3, 6 and 12 µm. The tools were divided into two categories where the new or unworn tool was represented by a tool edge radius of re=3 µm and the worn tool was represented by a tool edge radius of re=6 µm and re=12 µm. This indicates that as the tool continuously wears, the tool edge radius increases. The tests were conducted at the cutting speed, Vc of 100 m/min, depth of cut, d of 75 µm, and feed rate, f of 4 µm/tooth.

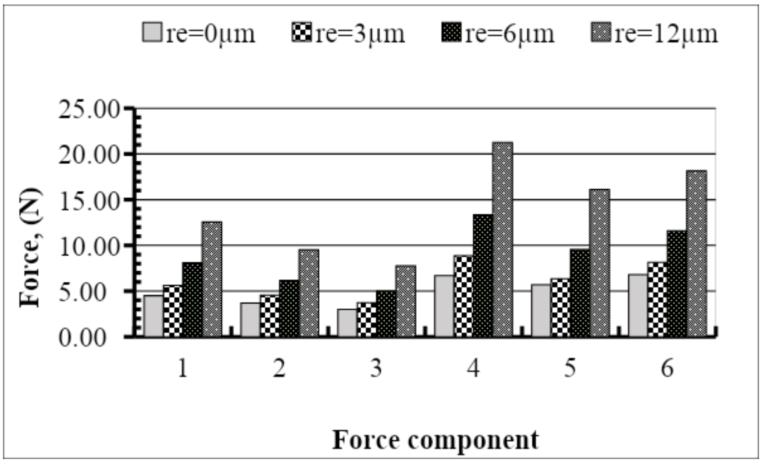

Figure 6: Predicted cutting forces in micro-end milling with four different edge radii.

All force components increased with the increase of tool edge radius. This indicates that cutting with a worn tool generates a higher cutting force compared to that with a fresh cutting tool (unworn tool). This might be due to the increasing rake angle provided by the larger edge radius. The more negative the rake angle through a wide and expanded plastic shear zone, the higher the energy and cutting forces obtained. The increase in cutting force can easily lead to tool deflection, tool breakage or damage to the workpiece or machined surface.

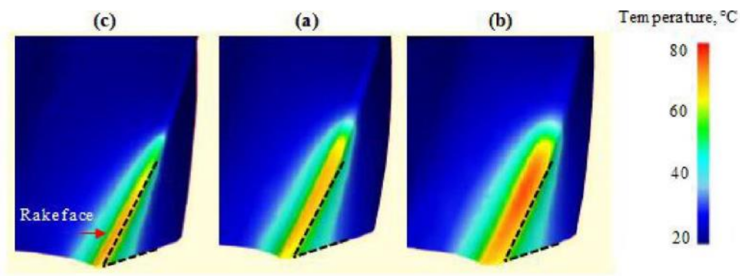

Figure 7: Temperature distribution for (a) 3µm, (b) 6µm and (c) 12µm

The temperature distribution is not located at the tooltip but stays above it, which can be detected near the rake face of the tool rather than the flank face of the tool (Figure 7). That is because the friction between the chip on rake face is greater than the friction cutting-tool workpiece. A large edge radius promotes higher temperature due to more deformation of material. It indicates the rising temperature along the cutting edge as the tool cuts through the workpiece, which may lead to the conclusion that the wear increases as the edge radius increases. Thepsonthi and Özel (2015) also argued that a large tool edge radius generated a higher cutting temperature compared to a small edge radius due to the larger shear zone resulting from the enlarged edge radius, which can decrease the shear angle [14].

4.0 CONCLUSION

The micro-milling process of 20 mm material workpiece length of tool travel has been carried out in simulation with cutting parameters between Vc= 100 m/min, f=4 µm, d=75 µm to Vc= 100 m/min, f=4 µm, d=75 µm. The results demonstrated that as the cutting progressed, all cutting force components increased. The feed force, Fx was a large increase compared to the thrust force, Fz and the normal force, Fy. The calculation observed was obtained by simulation in the Abaqus software. The wear development of the micro end mill can be described with the increasing tool edge radii. This change significantly affects cutting force generation. This can be attributed to the fact that the cutting forces increase alongside cutting length due to tool wear development. Therefore, the larger cutting edge attained due to tool wear significantly increased the cutting forces.

ACKNOWLEDGMENTS

The author would like to acknowledge Universiti Teknologi MARA, Cawangan Pulau Pinang for helpings in completing this research study. Appreciation also extends to all colleagues and others who have aided for this study on various occasions.

REFERENCES

[1] K. Sahai, A. Narayan, , & V. Yadava, "Micro-milling Processes: A Review." Lecture Notes in Mechanical Engineering, 403–411. https://doi.org/10.1007/978-981-15-8542-5_35, 2021.

[2] B. Z. Balázs, , & M. Takács, "Experimental investigation and optimisation of the micro milling process of hardened hot-work tool steel." International Journal of Advanced Manufacturing Technology, 106(11–12), 5289–5305. https://doi.org/10.1007/s00170-020-04991-x, 2020.

[3] J. B. Saedon, , S. L.Soo, D. K. Aspinwall, & A. Barnacle, "Micro-milling of hardened AISI D2 tool steel." Advanced Materials Research, 445, 62–67. https://doi.org/10.4028/www.scientific.net/AMR.445.62, 2012a.

[4] M. V. Vardhan, C. P. Mohanty, & B. Dhanraj, "Experimental Study on Parameters of P-20 Steel in CNC milling machine." Journal of Physics: Conference Series, 1495(1). https://doi.org/10.1088/1742-6596/1495/1/012027, 2020.

[5] M. Nur, A. Zulkifli, & H. Abdullah, "Simulation Approach of End Milling Process Based on Finite Element Method." Research Progress in Mechanical and Manufacturing Engineering, 2(2), 130–136. https://doi.org/10.30880/rpmme.2021.02.02.016, 2021.

[6] Y. Zhang, & X. Huang, "Simulation and research of aerospace material milling based on ABAQUS." Journal of Physics: Conference Series, 1653(1). https://doi.org/10.1088/1742-6596/1653/1/012070, 2020.

[7] M. H. Ali, B. A. Khidhir, , & B. Mohamed, "Finite element modeling for prediction of stress - strain at several feed rates and cutting speeds for titanium (Ti-6Al-4V) alloy." Advanced Materials Research, 587, 11–15. https://doi.org/10.4028/www.scientific.net/AMR.587.11, 2012.

[8] P. Li, & Z. Chang, "Numerical Modeling of the Effect of Cutting-Edge Radius on Cutting Force and Stress Concentration during Machining." Micromachines, 13(2). https://doi.org/10.3390/mi13020211, 2022.

[9] X. Nan, L. Xie, & W. Zhao, "On the application of 3D finite element modeling for small-diameter hole drilling of AISI 1045 steel." The International Journal of Advanced Manufacturing Technology, 84(9–12), 1927–1939. https://doi.org/10.1007/s00170-015-7782-y, 2016.

[10] A. Mamedov, K. S. Ehsan Layegh , & I. Lazoglu, "Machining forces and tool deflections in micro milling." Procedia CIRP, 8, 147–151. https://doi.org/10.1016/j.procir.2013.06.080, 2013.

[11] P. Rodríguez, , & J. E.Labarga, "Tool deflection model for micromilling processes." The International Journal of Advanced Manufacturing Technology, 76(1–4), 199–207. https://doi.org/10.1007/s00170-014-5890-8, 2015.

[12] J. Chae, S. S., Park, T. Freiheit, K. S., Woon, M. Rahman, F. Z.Fang, K. S. Neo, K. Liu, A., Simoneau, E. Ng, M. A., Elbastawi, D. Dornfeld, S., Min, , & Y. Takeuchi, "Investigations of tool edge radius effect in micromachining: a fem approach." In Annals of the CIRP (Vol. 45), 2006.

[13] F. Z. Fang, H., Wu, X. D., Liu, Y. C. Liu, , & S. T. Ng, "Tool geometry study in micromachining." Journal of Micromechanics and Microengineering, 13(5), 726–731. https://doi.org/10.1088/0960-1317/13/5/327, 2003.

[14] T. Thepsonthi, , & T. Özel, "3-D finite element process simulation of micro-end milling Ti-6Al-4V titanium alloy: Experimental validations on chip flow and tool wear." Journal of Materials Processing Technology, 221, 128–145. https://doi.org/10.1016/j.jmatprotec.2015.02.019, 2015.***Example :***

[1] E. P. Wigner, "Theory of traveling-wave optical laser," *Phys. Rev.,* vol. 134, pp. A635–A646, Dec., 1965.