Effect of progressive tool wear on the functional performance of micro milling process of injection molding tool

Davoudinejad, Ali; Li, Dongya; Zhang, Yang; Tosello, Guido

Published in:
Procedia CIRP

Link to article, DOI:
10.1016/j.procir.2020.02.031

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 87 (2020) 159–163

www.elsevier.com/locate/procedia

5th CIRP CSI 2020

Effect of progressive tool wear on the functional performance of micro milling process of injection molding tool

Ali Davoudinejad*, Dongya Li, Yang Zhang, Guido Tosello

Technical University of Denmark, Department of Mechanical Engineering, DK-2800 Kgs. Lyngby, Denmark

* Corresponding author. Tel.: +45-254897; fax: +0-000-000-0000. *E-mail address:* alidav@mek.dtu.dk

Abstract

In micro milling process, tool wear is one of the significant research area and tool behavior during machining is rather unpredictable. As tool wear progress, the cutting edge geometry change and leading to lower performance and failure of the machined surface integrity. This work investigate the influence of the progressive tool wear during micro end milling of a functional surface (micro ridges) on the injection molding tool with H13 tool steel material. In order to monitor the tool wear progress, five different TiAlN coated carbides micro end mills with 500 µm diameter were used to carry out the experiments in different cutting distances 64 cm to 320 cm. The chip formation, burr formation and surface quality in different tool wear conditions were evaluated. The burr form and size were affected by cutting edge wear and dissimilar results obtained at the end of cut. Moreover, the analysis of chip geometry in microscopic scale allows evaluating the chip morphology and cutting mechanisms in different tool wear conditions. The machined slots by the profile analysis and the surface quality of parts decreased as the tool wear growth. This work contribute to improved knowledge of cutting mechanisms with worn tools causing dissimilar material removal and surface integrity during machining process.

Keywords: Micomachining: Tool wear: Surface generation

1. Introduction

In micro milling process, tool wear is one of the significant research area and tool behavior during machining is rather unpredictable. As tool wear progresses, the cutting edge geometry changes leading to lower performance and failure of the machined surface integrity. In the process of manufacturing functional surfaces using micro-milling technology, tool wear has a direct impact on surface function. In many peer studies, tool wear is often associated with surface quality, burr formation, and chip formation.

W. Li, et al [1] investigated the effect of tool wear on the surface integrity in the milling of Inconel 718. At different level of tool flank wear, the surface integrity by different processing parameters were evaluated. M.A. Davies, et al [2] reported the influence of tool wear and chip formation mechanics in finish hard turning by cubic boron nitride tools on the surface topography. S Filiz et al [3] investigated the micro-machinability of copper 101 by studying the tool wear, cutting forces, surface roughness, and burr formation at different cutting condition to understand the wear mechanism of wear, and the relation to those characters. M. Rahman et al [4], C. Kim et al [5], and F. Ducobu et al [6][7] reported their work on the chip formation and tool wear during the micro machining of different materials. Moreover, A. Aramcharoen et al [8] and J. C. Miao et al [9] reported the mechanism of tool wear induced chip formation change due to the size effect and issues related to dynamics during micro milling.

In this paper, the surface function we studied is an anisotropic optical functionality [10]. This surface function is achieved by orthogonally textured micro ridges on the surface, which are processed by micro milling. The topography and the

10.1016/j.procir.2020.02.031

roughness of the working surfaces on the micro ridges were focused to investigate the surface functionality influenced by the tool wear propagation.

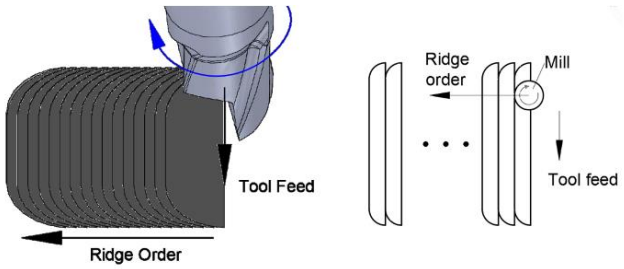
Nomenclature

f_z	Feed per tooth
a_e	Width of cut
a_p	Axial depth of cut
Sa	Average surface roughness
Sdq	Root Mean Square Surface Slope

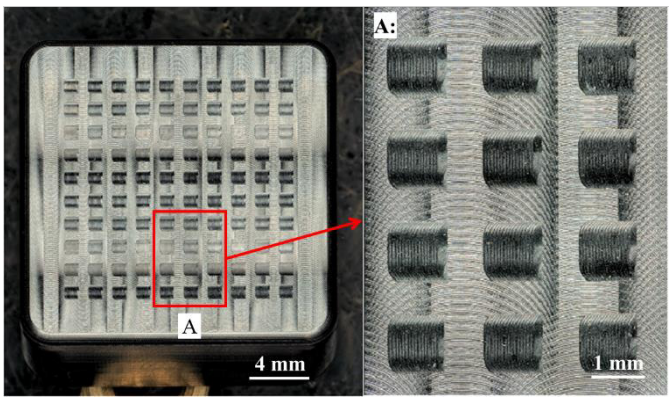
2. Experimental setup

A five-axis micro milling machine tool (MIKRON HSM 400U LP) was used for the experiments. The work piece was a functional surface for injection moulding (IM) process composed of micro ridges on the surface of Nitride hardened tool steel (Orvar Supreme from Uddeholm®, 48~50 HRC) suitable for IM replication. To quantify the cutting distance of the tools, the "module" was used as the basic element/unit. One module was 0.8 x 0.8 mm^2 including 16 micro ridges of 0.8 mm length.

(a) Five-axis CNC machine (b) Experimental setup



(c) Micro milling strategy



(d) Machined work piece and the micro ridges

Fig. 1. Machining setup, micro milling strategy and a machined work piece.

Fig. 1 shows the experimental setup, machining strategy, and machined work piece. The work piece was tilted by 5° during the machining, which made the "working surfaces" and the grooves perpendicular to the Z-axis of the CNC coordinate.

The machining strategy for the tool movement approach and direction (Fig. 1 (c)) was selected based on the previous study in order to minimize the burr formation during the machining process [10][11]. Five fresh tools were used to machine 50, 100, 150, 200 and 250 modules respectively. Each module was equivalent to a cutting distance of 12.8 mm. thus, each tool was used for cutting distance of 64 cm, 128 cm, 192 cm, 256 cm, and 320 cm, respectively. Prior the experiments the tools were checked and selected according to minimum deviation from nominal geometry. The specifications of the tools and the processing parameters are listed inTable 1. A down milling approach was used for machining the ridges.

Table 1. Micro end mill specification and cutting parameters.

Micro end mill nominal geometry	values
Diameter	0.5 mm
Material	µ grain carbide
Coating	TiAlN
Helix angle	25°
Number of flutes	2
Relief angle	8°
Rake angle	0°
Flute length	0.5 mm
Cutting edge radius	~3 µm
Milling parameters	**values**
Spindle speed	40000 rpm
Tool tilting	5°
Coolant	air
Feed rate	800 mm/min
Feed per tooth (f_z)	10 µm
Width of cut (a_e)	49.8 µm
Axial depth of cut (a_p)	24.4 µm
Cutting approach	Down milling

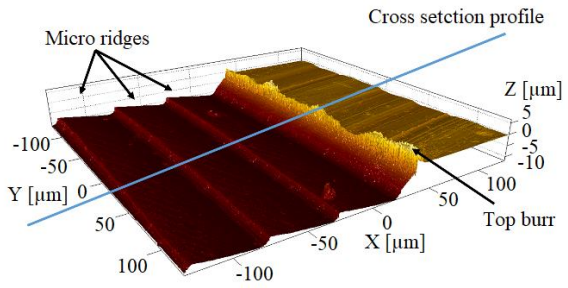
3. Evaluation of surface and tool

A confocal microscope (Olympus LEXT OLS4100) assisted by image processing software SPIP® was used to evaluate the geometry of the ridges and the surface roughness. Each module was inspected on the middle point of the top edge and on the module center in order to measure the burr formation and feature dimensions, respectively. A 20X magnification lens was used to acquire the surface machined by the last cut. The average profile of each measurement was obtained using SPIP® software.

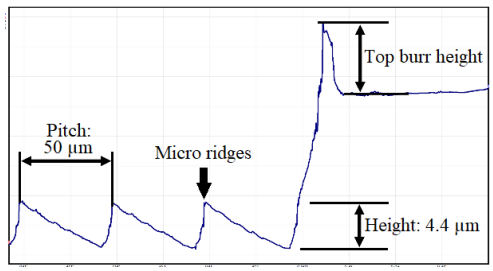
Fig. 2 explains the micro ridges and the top burr on the last cut in 3D view and the dimensional measurements on the cross section. The burr geometry in micro milling was defined in the previous works [12][13] and the top burr height characterized by peak point of the material left on the work piece surface as shown in the cross section Fig. 2 (b). Moreover, regarding the generated microchips in all the experiments, they were collected and observed by SEM for comparison with simulation results for future research. Both of the burr and chip

formation were used to reveal the effect of the tool wear on the surface topography.

The tool geometry was inspected by SEM and compared to understand the propagation of tool wear in the machining. The reduction in the radius of the micro end mill was used to characterize the wear. The tool wear was correlated with the surface quality including the feature geometry, burr formation and chip formation.



(a) Workpiece



(b) Cross section

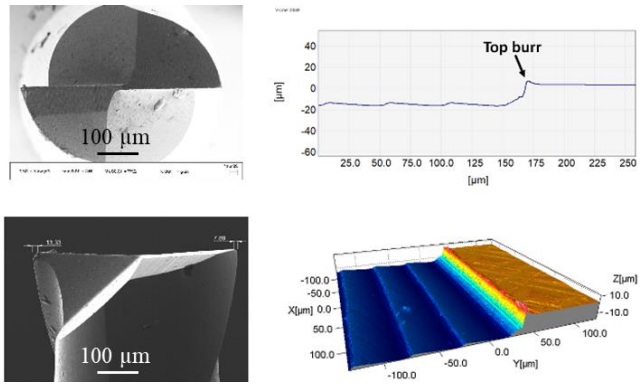
Fig. 2. (a) The geometrical definition of the ridges and (b) cross section of selected profile with top burr formation (higher aspect ratio applied for better visibility of the ridges).

4. Results and discussion

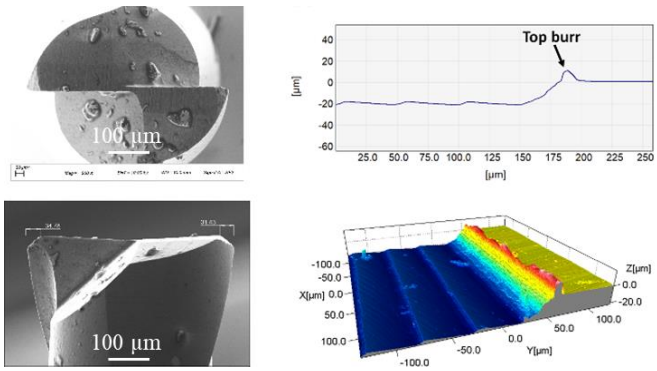
4.1. Burr formation

The experimental cross section of burr formations and the micro end mill used for the selected condition are presented in Fig. 3. In this section, top burr formation (the burrs generated in the top surface of the ridges, which reduced the surface functionality by covering the working surface) is considered. Tool wear affected the burr formation and dissimilar results obtained at the end of cut in the form and size of the burrs. It is clear that the burr formation was related to the tool wear growth. The burr height, tool wear and the cutting distance was plotted in Fig. 4 to understand the relationship quantitatively.

The top burr height was less than 5 µm in the first 128 cm's cutting, where the tooltips showed little wear of a reduction of 10 µm in radius after cutting a distance of 128 cm. The tool wear of the first tool and the subsequent burr formation was shown in Fig. 3 (a). As machining progressed, tool wear increased, resulting in a change in the formation of burrs: burrs slowly increased in height (> 10 µm locally and ~ 8 µm in average). Then, as shown in Fig. 3 (b), the burrs exceeded 10 µm in average generated by tool 4 with average wear of 33 µm in the radial direction after machining for 256 cm.



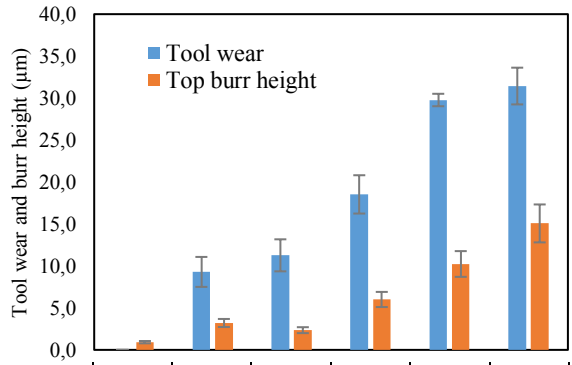
(a) Tool 1, module number = 50, cutting distance = 64 cm



(a) Tool 4, module number = 200, cutting distance = 256 cm

Fig. 3. Micro end mills and cross section of burr formations in (a) 64 cm and (b) 256 cm cutting distance.

Moreover, it can be seen from Fig. 4 that the tool wear and burr height have a positive correlation, but compared to ordinary micro-milling, this wear rate is too fast. This is due to the tilted sample in the machining of micro ridges. That made the two-flute tool kept cutting with the fragile tip of one of the blades, which exacerbated tool wear. As a result, the height of the burrs increased rapidly.



Cutting distance (cm)	1.28	64	128	192	266	320
Tool number	1	1	2	3	4	5
Module	1	50	100	150	200	250
ap [µm]	24.4	24.4	24.4	24.4	24.4	24.4
ae [µm]	49.8	49.8	49.8	49.8	49.8	49.8
fz [µm tooth/rev]	10	10	10	10	10	10

Fig. 4. Experimental burr height in different cutting distance.

4.2. Chip formation

The analysis of chip geometry in microscopic scale allows evaluating the chip morphology in different tool wear conditions. Fig. 5 shows the type of chips formed in the experiments with Tool 1 to 5 respectively.

The chips formed when the cutting distance was at 64 cm were continuous, curled and smooth, which indicated the cutting process was stable and the cutting edge was still sharp. With the progress of the micro milling, the tool wear grew and the cutting condition deteriorated. As a result, the chip form changed from continuous belt to lamellar shape, which can be explained with the wrinkles of the chips obtained from the tool 2, 3 and 4. The chips produced by the 5th tool with the cutting distance of 320 cm showed more frequent breaks and more disorder.

The mechanism of the chip formation change was believed to the size effect caused by the tool wear [8]. The wear resulted in the increase of the cutting edge radius, which turned the rake angle from 0 to negative. The cutting phenomenal changed from shearing-dominating to ploughing dominating. The chip form naturally changed from continuous to segmented and then discontinuous. Meanwhile, the chip thickness increased from around 20 µm to over 70 µm as the decrease of the chip length. That is another indication of the change of the cutting status.

Furthermore, the tool wear lowered the material removal as the engagement of the tool and the work piece was reduced.

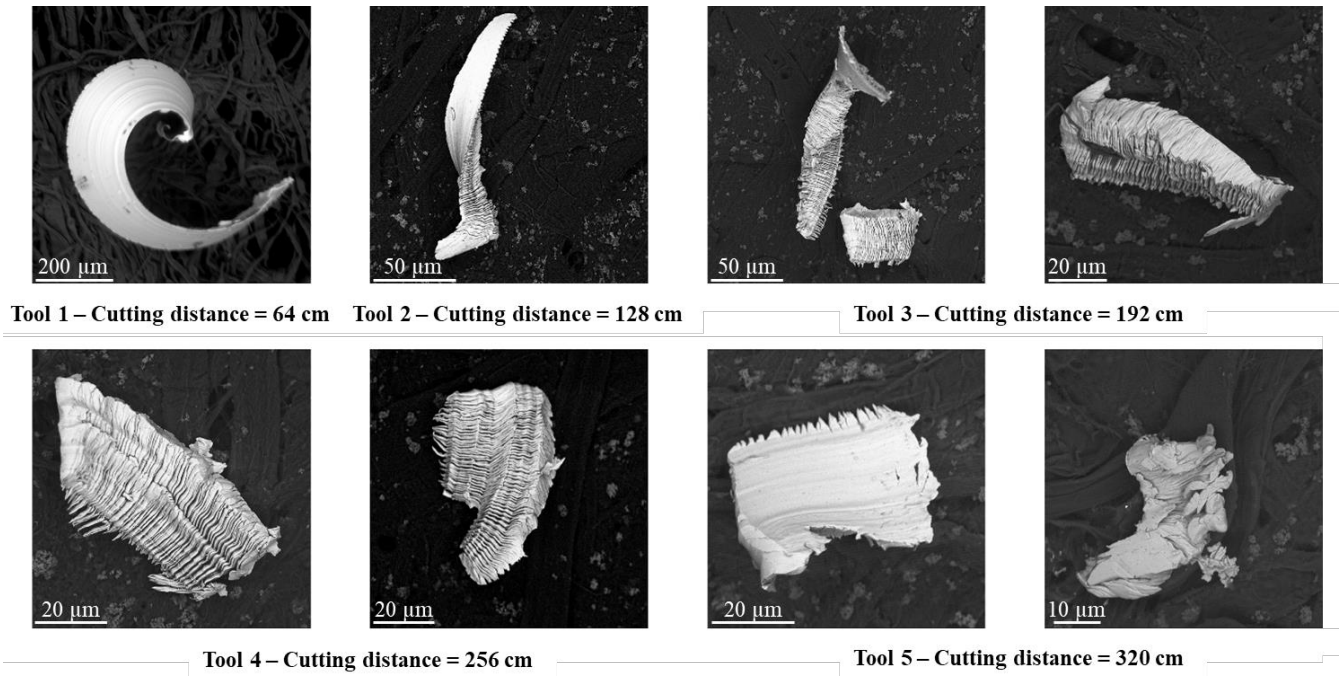


Fig. 5. Chip formation experimental results with different worn micro end mill in the same cutting condition.

4.3. Surface quality

Surface quality is highly associated with the surface functionality in this work. Therefore, the surface quality was defined as the quality of the microstructures: the accuracy of dimensions and surface roughness of the micro working surfaces.

Regarding the surface functionality, the surface roughness on the micro working surfaces influence the reflection for the surface functionality, *i.e.* contrast generation. Meanwhile, surface roughness could also reflect the cutting status and the tool wear. The surface roughness (Sa) was plotted versus the number of the machined module Fig. 6.

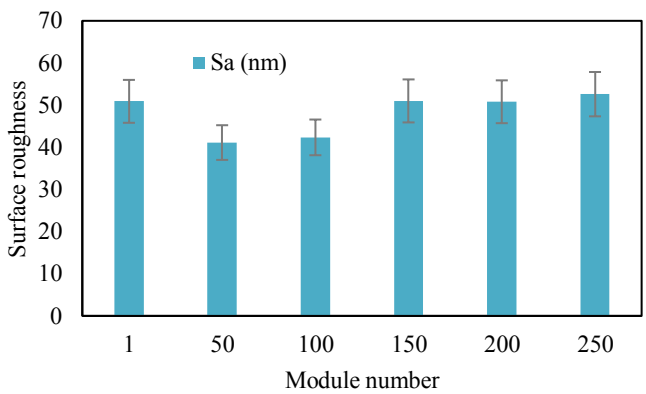


Fig. 6. Surface roughness experimental results of different modules machined with different worn micro end mill in the same cutting condition.

As shown in Fig. 6, machining in the beginning of the machining higher roughness achieved however, in the next

modules after the 50th (cutting distance = 64 cm). The surface roughness decreased. A possible explanation is that sharp scratches were left on the surface at the beginning of machining, which increased the surface roughness, as shown in Fig. 7. After the tool reached a certain amount of wear, the height of these tool marks were smoothly reduced by the rounder cutting edge. At the same stage, the tool wear was not too harsh to affect the machining process, thus the lower roughness reached. Though, continue machining, the tool wear increased and resulted in poor surface quality. Another explanation was the work hardening induced by the tool wear. As cutting edge radius increased during the machining of the first 64 cm, the cutting process changed from shearing to locally ploughing. Thus, as expected, the tool wear growth decreased the surface quality.

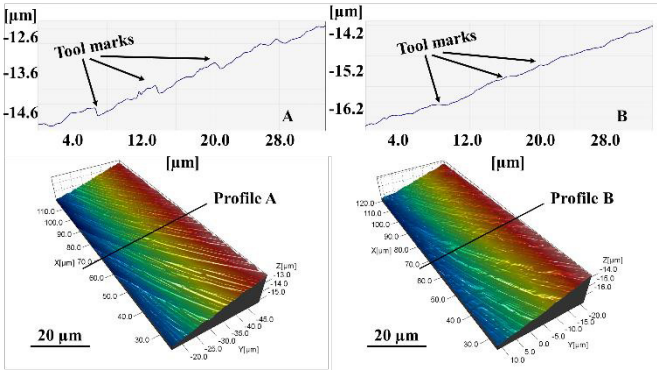


Fig. 7. Surface quality of module 1 (left) and module 50 (right) (higher aspect ratio applied for better visibility of the tool marks).

Other elements of surface integrity, such as hardness, residual stress and microstructure, were not considered in the current part of the study. However, some other factors such as burr formation and the surface roughness were discussed. The main aim of this work was to maximize the surface functionality. In the future study on the tooling by micro milling, surface integrity will be explored in a wider range in order to associate it with the injection molding process.

5. Conclusions

This paper studies the effect of tool wear on the surface quality of functional surfaces machined by micro milling. The burr formation, surface roughness and chip morphology at different stages of the process were investigated and correlated with tool wear propagation. The presented work could be concluded as follows:

The worn tool during the micro milling of micro ridges on the tool steel surface caused severe burr formation and reduced the quality of the functional surface. Tool wear at different stages was reflected by the burr formation and chip morphology. The mechanism of machining under different wear stages was understood. The machined surface was changed during the process based on the machining distance in different tool conditions.

Future work should also be devoted to understanding the effect of tool wear on the dimensions of the surface microstructures by conducting micro milling tests. In terms of surface functionality, the relationship with tool wear is also worth being quantified in order to obtain better surface functions.

Acknowledgements

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013) under REA grant agreement No. 609405 (COFUNDPostdocDTU).

References

[1] Li, W., et al. "Effect tool wear during end milling on the surface integrity and fatigue life of Inconel 718." *Procedia Cirp* 14 (2014): 546-551.

[2] Davies, Matthew A., Y. Chou, and Christopher J. Evans. "On chip morphology, tool wear and cutting mechanics in finish hard turning." CIRP annals 45.1 (1996): 77-82.

[3] Filiz, Sinan, et al. "An experimental investigation of micro-machinability of copper 101 using tungsten carbide micro-endmills." International Journal of Machine Tools and Manufacture 47.7-8 (2007): 1088-1100.

[4] Rahman, Mominur, A. Senthil Kumar, and J. R. S. Prakash. "Micro milling of pure copper." Journal of Materials Processing Technology 116.1 (2001): 39-43

[5] Kim, Chang-Ju, Matthew Bono, and Jun Ni. "Experimental analysis of chip formation in micro-milling." TECHNICAL PAPERS-SOCIETY OF MANUFACTURING ENGINEERS-ALL SERIES- (2002).

[6] Ducobu, F., E. Filippi, and E. Rivière-Lorphèvre. "Chip formation and minimum chip thickness in micro-milling." Proceedings of the 12th CIRP conference on modeling of machining operations. 2009.

[7] Ducobu, F., E. Filippi, and E. Riviere-Lorphevre. "Chip formation in micro-milling." Proceedings of the 8th national congress on theoretical and applied mechanics. 2009.

[8] Aramcharoen, A., and P. T. Mativenga. "Size effect and tool geometry in micromilling of tool steel." Precision Engineering 33.4 (2009): 402-407.

[9] Miao, J. C., et al. "Review of dynamic issues in micro-end-milling." The International Journal of Advanced Manufacturing Technology 31.9-10 (2007): 897-904.

[10] Li D, Davoudinejad A, Zhang Y, Tosello G. Evaluation of an improved micro milling strategy for the generation of tool steel micro features with optical functionality. World Congr. Micro Nano Manuf. (WCMNM2018), Portorož, Slov., 2018 World Congress on Micro and Nano Manufacturing (WCMNM2018), Portorož, Slovenia; 2018.

[11] Davoudinejad A, Li D, Zhang Y, Tosello G. Optimization of corner micro end milling by finite element modelling for machining thin features. Procedia CIRP 2019;82:362–7. doi:10.1016/J.PROCIR.2019.04.158.

[12] Lekkala R, Bajpai V, Singh RK, Joshi SS. Characterization and modeling of burr formation in micro-end milling. Precis Eng 2011;35:625–37. doi:10.1016/J.PRECISIONENG.2011.04.007.

[13] Davoudinejad A, Tosello G, Annoni M, Influence of the worn tool affected by built-up edge (BUE) on micro end-milling process performance: A 3D finite element modeling investigation. International Journal of Precision Engineering and Manufacturing. 2017, 1321–1332.