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INFLUENCE OF THE TOOL PATH STRATEGY ON THE PROCESS VIBRATIONS DURING MILLING OF COMPOSITE MATERIAL

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Abstract: *Besides the tools and the machining equipment, the optimal design of the machining technology is of central importance in the field of machining. This is especially the case in machining thin-walled profiles made of fiber-reinforced composites. Vibrations during machining represent an important factor for the tool stability and tool life. The object of the study is thus an experimental investigation of pocket milling with solid carbide tools with different tool path strategies. The resulting vibration patterns and machining forces are analyzed. As a result of the study, an objective comparison of the different technologies based on key performance indicators is presented.*

Key words: *Optimization, Machining, Vibration, Composite, Cutting tool path.*

1. INTRODUCTION

Thin-walled profiles made of thermoplastic composite material are typically used as a key part of frames with complex design for modern windows. Various profile designs can be easily produced by the continuous extrusion. The thin-walled profiles have typical wall thickness of about 2 mm. The thermoplastic matrix is strengthen with the short glass fibers. Some specific design features (e.g., various holes, pockets and slots) have to be machined into the profile. Due to production setup flexibility, the profiles are clamped with relatively compliant fixtures enabling collision-free movement of multiple working spindle with cutting tools. High speed spindles with small diameter end mills (diameter of 4 to 8 mm) are used for milling of these details. Thus, the final process force should be minimized to avoid undesirable deformations of the fixture system or the cutting tool. Concurrently, time per part have to shorten to increase the overall production productivity and also to minimize the overall power consumption related to the produced part [1].

The machining processes have to ensure the requested dimensional accuracy of the part, the surface quality and concurrently productivity of the process. The overall results of the machining can be significantly influenced by the proper selection of the cutting tool, cutting conditions and tool path strategy. This selection have to be done with respect to the workpiece geometry and its material and also with respect to the stiffness of the whole machining system.

In machining of thin-walled thermoplastic composites with the high precision and surface quality, the cutting edge geometry, cutting conditions and engagement conditions are important for sufficient results. Masek [2] presented key influence of cutting tool engagement parameters on the cutting force size and the burr size during edge trimming of C/PPS composite (polyfenylensulfid matrix with carbon fibers). The machined edge of the workpiece might be damaged also with tear-out fibers [3]. Teicher [4] proposed method for complex characterization of the surface roughness of milled reinforced plastic structures based on the Rt and Rmax parameters which can consider delamination and fiber tear-out effects along the total evaluation length.

The compression double-helix design with very positive rake angle of about 20° was presented as beneficial cutting tool design for edge trimming of composite plates with the minimized burr creation [3]. The very positive cutting edge geometry with sufficient space for chip evacuation is the typical reference tool for productive high quality milling of thermoplastic composites [5]. The higher cutting speed increases the machining productivity and also surface quality. The cutting speed is limited with the process temperature and risk of matrix melting and chip sticking on the tool [2, 6].

Tool path planning strategy is the key factor for machining of the thin-walled parts influencing the tool and workpiece force load and also the level of vibration, including risk of chatter occurrence. Choi [7] presented method for numerical control (NC) tool path generation for pocket milling with respect to the contour shape and the tool load characterized with the tool engagement arc length. Tool path strategies for milling of pockets with various complexity were compared by Romero [8]. The workpiece material was an Aluminum alloy. The contour-parallel strategy is mentioned as optimal approach to achieve lower machining times, better contour roughness and acceptable (medium high) cutting force level. Smith [9] presented the tool path generation strategy for machining of thin-walled Aluminum parts. The study shows importance of the workpiece support through unmachined workpiece material.

The tool path definition for machining of thin-walled parts has been investigated especially for aluminum alloy workpieces. Besides that, there is also existing knowledge regarding the cutting tool geometry and cutting condition selection for milling of composites with thermoplastic matrix. This paper compares various tool path strategies for pocket milling of thin-walled G/PA66 GF (polyamide 66 matrix with glass fibers) composite profile with respect to criterions of machining time, cutting force size and vibration levels. The presented findings base on the experiment results using one type of the tool and one setting of the cutting condition.

The paper is organized as follows: The experimental setup and all boundary conditions are described in the section 2. Data processing and evaluation is presented in the section 3. The results are discussed in section 4 with a conclusion in section 5.

2. EXPERIMENT SETUP

2.1 Workpiece geometry and material

The thin-walled profile made of combined plastic composite and Aluminum profiles was used for the experiments. The profile structure and its main dimensions is presented on Fig. 1. The composite had a PA66 matrix with 25 % volumetric share of short glass fibers.

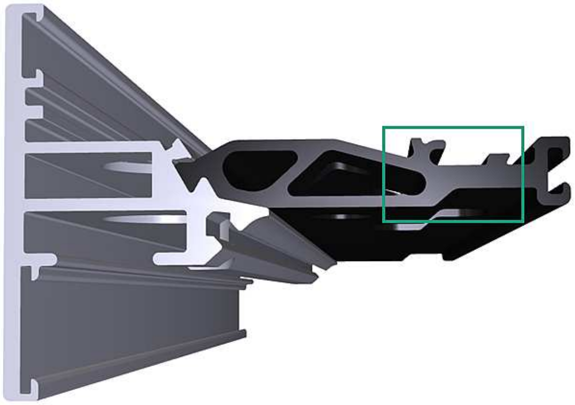


Fig. 1. A photo and a cross section sketch of the thin walled profile composed of Aluminum alloy and G/PA66 composite parts used for experiments. The area of the pocket machining through the composite profile is highlighted with a color rectangle.

Mechanical properties of the composite are given in Table 1.

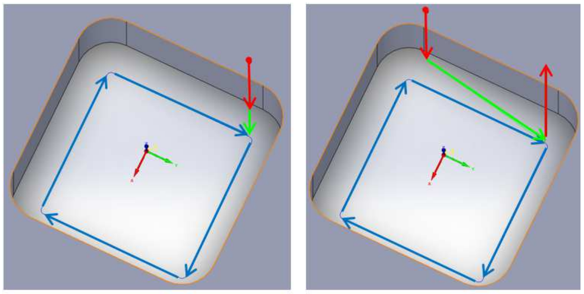
Table 1

Selected material properties of the G/PA66 GF25 composite

Property	Values & Unit
Mass density ρ (ISO 1183)	1.32 g/cm³
Tensile strength Rm (ISO 527)	170/120 MPa
Specific heat c_p	1.50 J/(g·K)
Continuous use temperature ϑ_u	130 °C

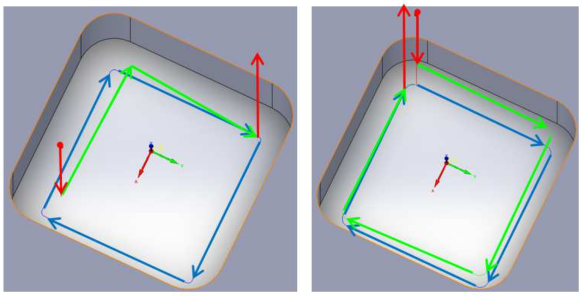
2.2 Testing geometry and tool path strategies

The test geometry was a square pocket with outer dimensions of 25 x 25 mm and a corner radius of 4 mm. The standard strategy used typically in the industry for cutting of these pockets is based on the axial plunging in the center of the pocket and then milling of the pocket contour. The main reason for such tool path strategy development was to enable plunging of the tool out of the contour to avoid contour surface errors caused by the workpiece deformation during the initial plunging operation. On the other hand, this strategy also has some disadvantages. There is risk of the tool breakage during the plunging operation. It is also not optimal from the view of the machining time. This strategy denoted as “S” was used as a reference for subsequent comparison.



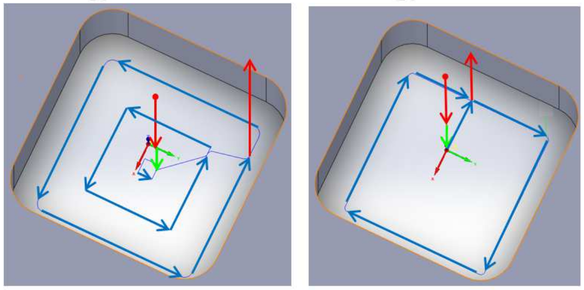
Strategy A

Strategy B



Strategy C

Strategy D



Strategy E

Strategy S

Fig. 2. Schema of the tool path for the reference strategy “S” and five other alternative strategies. The red arrows mark the tool rapid movements into the workpiece and out of the cut. The green arrows mark the plunging operation with variable Z coordinate of the tool center point. The blue arrows indicates contouring operation with constant Z level of the tool.

Further five alternative tool paths, including contour-parallel strategy with various ramping setting, were proposed for comparison within this case study:

- Strategy A: Vertical plunge followed with a full contour milling with constant Z level.
- Strategy B: Ramping along one side followed with a full contour milling with constant Z level.
- Strategy C: Ramping along two sides followed with a full contour milling with constant Z level.
- Strategy D: Ramping along four sides followed with a full contour milling with constant Z level.
- Strategy E: Vertical plunge followed with stepped contouring with constant Z level.

The tool path strategies are schematically presented on the Fig. 2. Please note, that there are radius segments of the tool path in the pocket corners. The linear interpolation G00 and G01 commands and the circular interpolation G02/G03 commands were used for the NC code creation.

2.3 Overall experiment setup

The experiments were conducted on the three axis vertical machining center HAAS MiniMill. The spindle has maximum revolution of 6,000 rpm and maximum power of 5.6 kW.

A special one-tooth uncoated solid carbide end mill with a polished surface ensuring smooth chip evacuation without chip sticking on the tool was used.

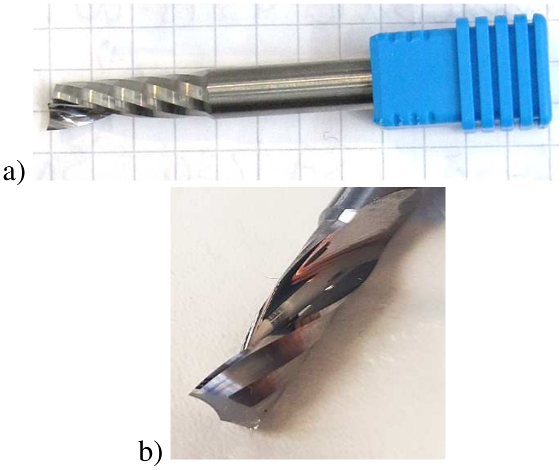


Fig. 3. Uncoated polished solid carbide end mill used for machining experiments: a) overall view (the mat grid is 5 mm); b) front view with detail of the tooth and helix.

The tool was produced as a custom-specific prototype for machining of thermoplastic-based materials. The tool with diameter of 6 mm had the rake angle of 11° and helix angle of 20°.

There was a constant cutting condition setting used for all experiments: cutting speed of 109 m/min, feed per tooth of 0.24 mm.

The overall setup of the experiment is presented on the Fig. 4. The workpiece was clamped using a dedicated fixture. The fixture was mounted on the KISTLER 9257B dynamometer placed on the machine tool table and connected via Kistler 5017 charge amplifier and a DAQ Goldammer USB basic for the process force measurement.

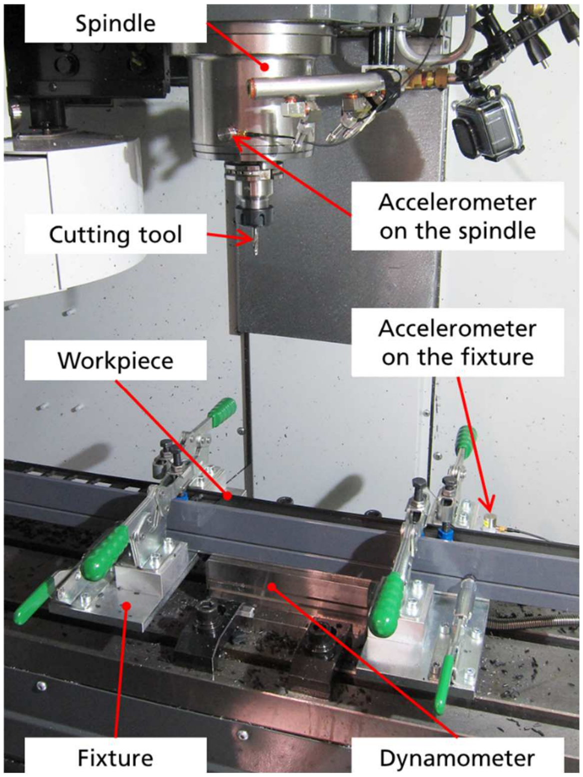


Fig. 4. The overall setup of the experiment.

Also, two accelerometers for the process vibration monitoring were installed and connected with an analyzing unit (Machine Tool FFT Analyzer, NT Engineering Japan). One unidirectional accelerometer was placed on the spindle for vibration measurement in Y-direction. This is an example of universal sensor position that can be used for all operations. There is disadvantage of noise from the spindle drive and bearings that must be filtered from the acquired signal. The other unidirectional accelerometer was placed on the fixture for vibration measurement in Z-direction, see Fig. 5. This is the example dedicated sensor placement. As an advantage, the accelerometer on the fixture collects the workpiece vibration directly without other influences. This experimental installation can be used in laboratory only; it is not a universal solution for industrial use due to risk of sensor damage in the real machining environment.

Fig. 5. Detail of placement of two accelerometers: on the spindle in Y-direction (left - red) and on the fixture in Z-direction (right - blue).

3. DATA PROCESSING AND EVALUATION

For every mentioned machining strategy, there was machined series of four pockets with one repeating. I.e., eight pockets for every strategy were machined in total. The measured vibration and force signals were not synchronized together. Segmentation of the signal to extract the single pocket record was the key issue of the signal postprocessing.

3.1 Vibration signal processing

The vibration signals were filtered and processed as described below.

The recorded vibration raw data were filtered using band pass filter <5; 2000> Hz to avoid the signal DC component and also to remove high-frequency vibrations related mainly to the non-important structural vibrations of the system. The filtered signal time-domain was processed using short time Fourier transformation (STFT) with the time step of 0.1 s. The STFT spectra were analyzed and frequency with highest amplitude in the frequency domain has been identified. The spectral signal on this identified frequency with dominant amplitude was used as an auxiliary signal for the segmentation of the acquired signal (see signal processing example on Fig. 6).

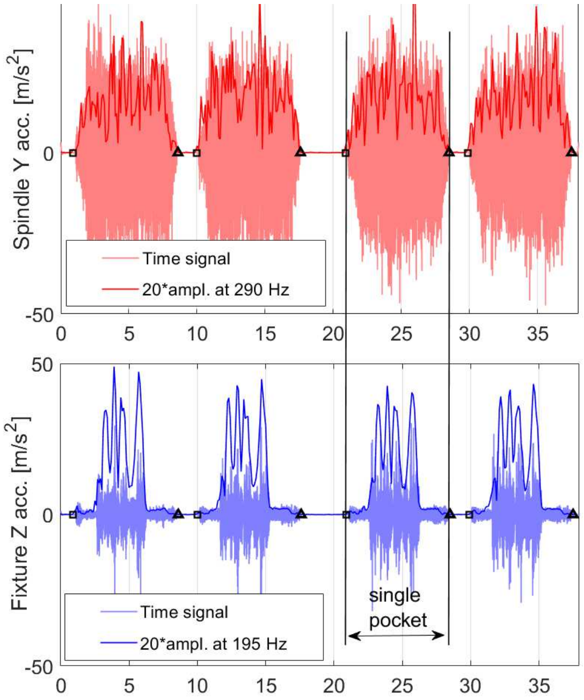


Fig. 6. Example of the acquired vibration signal (light color) as a series of four-pocket milling. The dark color is a single-frequency spectral component used for the signal segmentation. The black squares mean process start, the black triangles mean process end.

The results of the vibration signal processing for both the used sensors are presented for every single cut on the Fig. 7. It can be seen, the detected total process duration time may vary ±0.1 s due to inaccuracies in the process start and end identification which is acceptable. The pocket milling time differs up to 1 s between the tool path strategy A and the tool path strategy C as a consequence of the various tool path length.

The calculated vibration signal RMS has a lower deviation for the signals acquired on the fixture. The higher deviation of the spindle vibration signal is a consequence of the additional vibration content caused by the spindle. Higher overall RMS values of the spindle signal comparing to the fixture vibration signal RMS supports this hypothesis.

To be able to compare the vibration level with respect to the pocket machining time for specific strategy toward to the reference strategy S, the overall performance factor has been calculated as a key performance indicator for every strategy using mean values of the acceleration RMS and mean value of the machining time:

$$OPF_{vibr} = \frac{\left(\frac{\overline{a_s}}{\overline{a_i}}+\frac{\overline{t_s}}{\overline{t_i}}\right)}{2} \quad (1)$$

where a means vibration level, t means machining time. Values of the acceleration RMS and the machining time for the reference strategy are marked with subscript s, values for the evaluated strategy are marked with subscript i. The calculated results are presented in Fig. 8. The higher value means better overall result in this case. The strategy A has the best overall performance factor based on the fixture accelerometer data. The strategy D has the best overall performance factor based on the spindle accelerometer data. The results for strategies B, D, and E are consistent for both accelerometer positions. The results for strategy A and C are different comparing signals acquired on the spindle and on the fixture. The reason for this might be different dynamic compliance (frequency response function – FRF) between the machining place and the sensor position and the varying cutting force direction along the specific tool path.

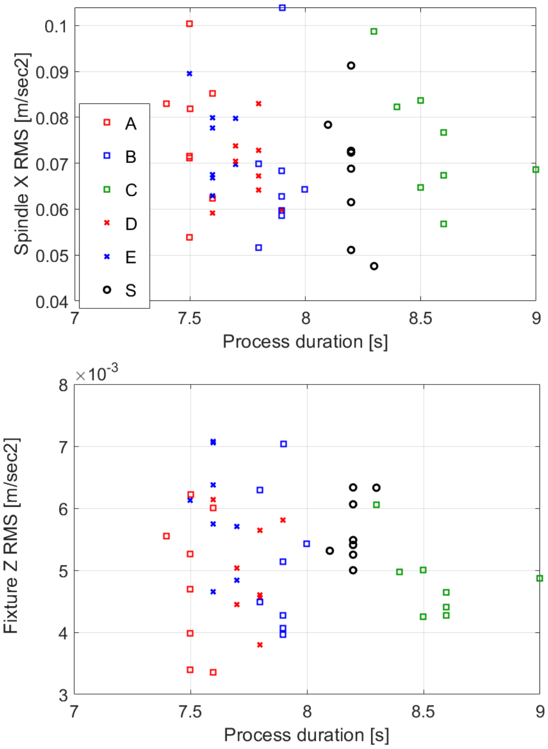


Fig. 7. Results of the vibration signal processing for various tool path strategies.

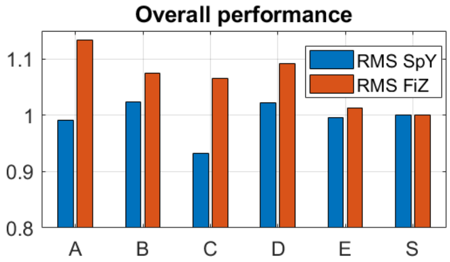


Fig. 8. Comparison of the overall performance factor based on the measured process vibration level and pocket machining time. Higher value means better result.

3.2 Cutting force comparison

The signal drift of the recorded force raw data was compensated firstly. The signal was acquired with sampling frequency of 1000 Hz. RMS of the partial time domain signal with duration of 0.1 s has been calculated. This enabled avoidance of local peaks. This partial RMS signal was used as an auxiliary data for the segmentation of the acquired signals (see Fig. 9).

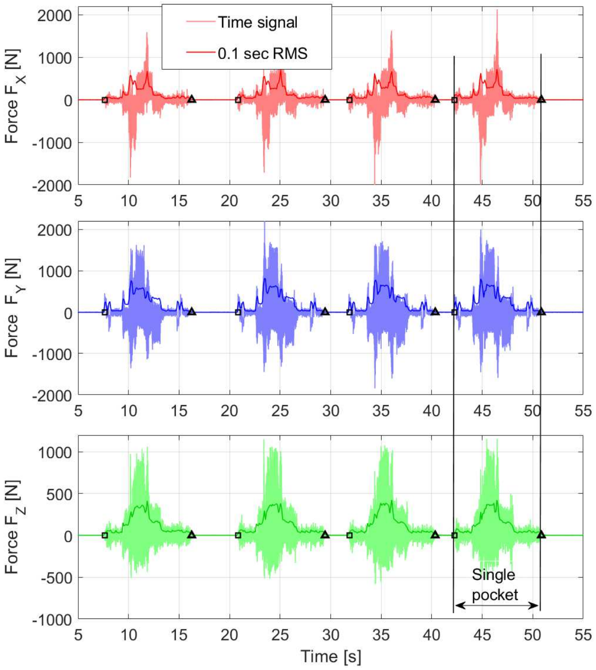


Fig. 9. Example of the acquired vibration signal (light colors). The dark color is the RMS value calculated from 0.1 s time-domain signal. The black squares mean process start, the black triangles mean process end.

The active cutting force and the total cutting force were calculated using the measured F_X, F_Y and F_Z measured signals:

$$F_{active} = \sqrt{F_X^2 + F_Y^2} \tag{2}$$

$$F_{total} = \sqrt{F_X^2 + F_Y^2 + F_Z^2} \tag{3}$$

The active cutting force characterizes the workpiece in-plane loading that have to be taken with the clamping system. The total cutting forces presents the overall force loading of the process acting in XYZ directions.

The mean values of the calculated active and total forces are presented for every single cut in Fig. 10. As in the previous case, the estimated total process duration time may vary ±0.1 s due to inaccuracies in the process start and end identification. The machining time identified for every strategy using the force signal is the same as the process duration identified using the vibration signal. I.e., signal segmentation is consistent for both signal types. The calculated mean force values have quite low deviation and the results are clearly clustered, see Fig. 10.

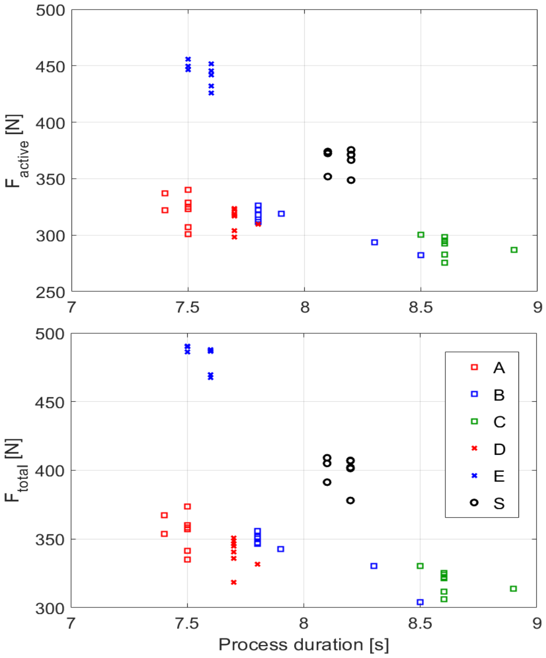


Fig. 10. Results of the measured force processing for various tool path strategies.

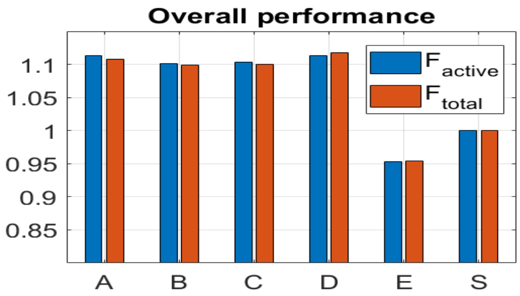


Fig. 11. Comparison of the overall performance factor based on the measured cutting forces and pocket machining time. Higher value means better result.

The workpiece force loading with respect to the pocket machining time for specific strategy toward to the reference strategy S was compared with the overall performance factor calculated again for every strategy using mean values of the cutting forces and mean value of the machining time:

$$OPF_{force} = \frac{\left(\frac{\overline{F_s}}{\overline{F_i}} + \frac{\overline{t_s}}{\overline{t_i}}\right)}{2} \tag{4}$$

where F means specific force level, t means machining time. Values of the mean force values and the machining time for the reference strategy are marked with subscript s, values for the evaluated strategy are marked with subscript i. The calculated results are presented in Fig. 11. The higher value means better overall result in this case. The results are similar for active and total cutting force. Only the strategy E had worse results compared to the reference strategy S. The strategies A, B, C, D provided better results than the reference strategy. The strategy D has the best overall results. The strategy A was only very slightly worse than the strategy D.

4. RESULT DISCUSSION

Shortening of operation time is the crucial need for improving of the productivity of the machining operation. The lower cutting forces and low forced vibrations are also necessary for high quality of the machined surfaces and edges. This request becomes more important in case of machining of thin-walled composite profiles.

The presented study compares six various tool path strategies for pocket milling in the G/PA66 composite profile. The cutting tool and cutting conditions were the same in all tested cases to ensure equal conditions for the strategy comparison. The main request was minimizing the operation time, vibration level and cutting forces.

The analysis provides mainly comparison between standard strategy S and alternative machining strategies. The initial strategy S had the machining time of one pocket about 8.2 s. The vibration RMS (Root Mean Square) value measured on the spindle was about 0.067 m/s^2. The average value of the active cutting force was about 366 N. These initial average values of the reference strategy S can be compared with results of other strategies, see Fig. 12. These diagrams show averaged results of all experiment runs presented in detail on Fig. 7 for vibration results and on Fig. 10 for cutting force results.

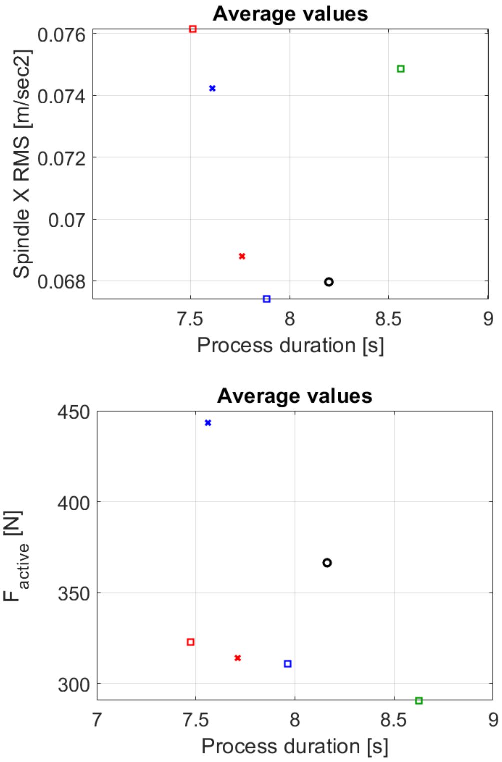


Fig. 12. Overview of averaged values of vibration and force signals for all strategies.

The machining time for every specific strategy is defined with the total tool path length. The shortest machining time was 7.5 s for strategy A which means 92% of the time needed for the reference strategy S. The longest machining time was 8.6 s which is 105% of the machining time of the reference technology. The difference of the tool path length depends on the ramping strategy. However, the difference of a few percent is not critical in machining of such a relatively small feature as a 25x25 mm pocket.

Three contour-parallel strategies with ramping along one, two or four sides were tested (strategies B, C, D). The strategy D was evaluated as the best technology from the vibration and also from the cutting force point of view. It means, the disadvantage of the long ramping path is compensated with the smooth cut minimizing the workpiece force load and also minimizing the vibration level. This knowledge can be generalized: It is beneficial to have longer ramping path because the increasing of the machining time is relative low but the cutting forces are significantly lower.

We can see that also from the other side. The spiral strategy E had the worse results because the tool path is long and the tool has constant engagement. This produces higher cutting forces and also vibrations.

The strategy A had the shortest machining time and still acceptable level of vibration and force load. The reason might be optimal selection of the pocket starting point in the lowest profile thickness followed with continuous increasing of the tool engagement.

The cutting forces cannot be measured directly easily on the machine during the manufacturing on the real shop floor. Process vibration monitoring might be an alternative technical solution. As presented in this paper, it is important to find optimal position of the accelerometer.

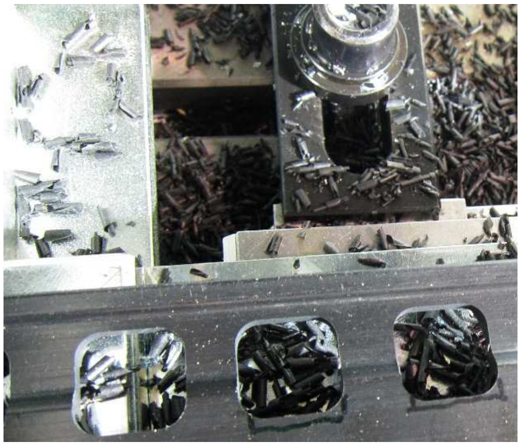


Fig. 13. Detail of the machining setup with created well-segmented chips.

An important result for concluding the whole experiment result evaluation is information about chip formation and the machined contour quality evaluation. The machined composite material created mostly short well-segmented chips, see Fig. 13, which is possible to evacuate easily. The reason for that is tough material matrix and relatively small feed per tooth value. The chip surface has been checked. No material melting has been found. This means, the cutting temperature remain under the melting temperature of the matrix material, which indicates safe process (melted material is sticky and can cause the tool breakage [2]).

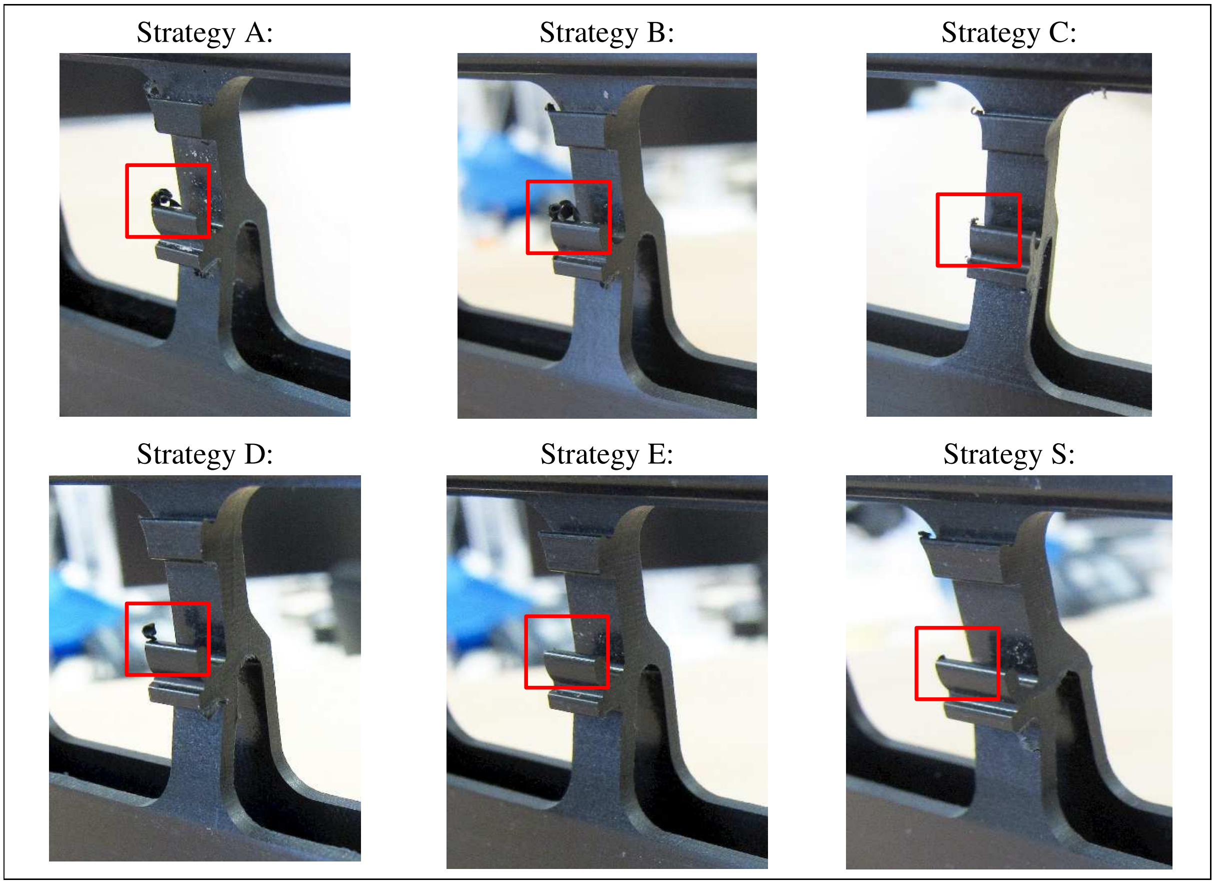
Long chips may also occur accidentally, especially in case of Z-plunge feed of the tool used for strategies A and S, see the Fig. 14. This kind of chips is already dangerous because it may lead into tool breakage.

Fig. 14. Detail of accidentally created long chip remaining on the tool after finishing the pocket machining with the strategy S.

The pocket contour should be clear without any uncut burr. Since the complex profile shape has been machined, some differences of the burr size were visible between strategies. Examples of the burr caused by uncut material are on the Fig. 14 for different strategies. As can be seen, the burr has different size and shape for all strategies. However, systematic burr size evaluation is not easy because it needs 3D scanning of the workpiece geometry to be able to quantify the shape and burr size automatically to get the statistically significant results. Development of automatic method for that is planned as a future work.

5. CONCLUSION

Six tool path strategies for pocket milling of thin-walled G/PA66 composite profiles has been compared. The contour-parallel strategy using ramping engagement along four sides of the pocket (in this case, notated as strategy D) had the best results from the vibration and the cutting forces point of view. The reason is a smooth cut with lower cutting forces and forced vibrations with only relatively small increasing of the machining time.



Strategy A:

Strategy B:

Strategy C:

Strategy D:

Strategy E:

Strategy S:

Fig. 15. Details of the typical burr shapes remained on the composite profile rod.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] Denkena, B., Abele, E., Brecher, C., Dittrich, M.-A., Kara, S., Mori, M. *Energy efficient machine tools.* CIRP Annals, 2020, vol. 69, no. 2, pp. 646-667. https://doi.org/10.1016/j.cirp.2020.05.008

[2] Masek, P., Zeman, P., Kolar, P., Holesovsky, F. *Edge trimming of C/PPS plates*. The International Journal of Advanced Manufacturing Technology, 2019, vol. 101, pp. 157–170. https://doi.org/10.1007/s00170-018-2857-1

[3] Masek, P., Zeman, P., Kolar, P. *Develop-ment of a cutting tool for composites with thermoplastic matrix*. MM Science Journal, 2013, October issue, pp. 422 – 427. https://doi.org/10.17973/MMSJ.2013_10_201312

[4] Teicher, U., Rosenbaum, T., Nestler, A., Brosius, A. *Characterization of the surface roughness of milled carbon fiber reinforced plastic structures*. Procedia CIRP, 2017, vol.

66, pp. 199-203. https://doi.org/10.1016/j.procir.2017.03.282

[5] Sheikh-Ahmad, J. Y., *Machining of polymer composites*. New York: Springer Science + Business Media, 2009. e-ISBN 978-0-387-68619-6.

[6] Saglam, H., Yaldiz, S., Unsacar, F. *The effect of tool geometry and cutting speed on main cutting force and tool tip temperature*. Materials & Design, 2007, vol. 28, no. 1, pp. 101-111. https://doi.org/10.1016/j.matdes.2005.05.015

[7] Choy, H.S., Chan, K.W. *A corner-looping based tool path for pocket milling*. Computer-Aided Design, 2003, vol. 35, no. 2, pp. 155-166. https://doi.org/10.1016/S0010-4485(02)00049-0

[8] Romero, P.E., Dorado, R., Díaz, F.A., Rubio, E.M. *Influence of Pocket Geometry and Tool Path Strategy in Pocket Milling of UNS A96063 Alloy*. Procedia Engineering, 2013, vol. 63, pp. 523-531. https://doi.org/10.1016/j.proeng.2013.08.194

[9] Smith, S., Dvorak, D. *Tool path strategies for high speed milling aluminum work-pieces with thin webs*. Mechatronics, 1998, vol. 8, no. 4, pp. 291-300. https://doi.org/10.1016/S0957-4158(97)00058-5

INFLUENȚA STRATEGIEI DE STABILIRE A TRAIECTORIEI SCULEI ASUPRA PROCESULUI VIBRATOR LA FREZAREA MATERIALELOR COMPOZITE

Pe lângă sculele și echipamentele de prelucrare, proiectarea optimă a tehnologiei de prelucrare este de o importanță deosebită în domeniul fabricației. Acesta este și cazul special al prelucrării profilelor cu pereți subțiri fabricate din materiale compozite armate cu fibre. Vibrațiile din timpul procesului de prelucrare reprezintă un factor important pentru stabilitatea procesului și durabilitatea sculei. Obiectul studiului prezent îl constituie o investigație experimentală a frezării unui locaș/buzunar, cu freze din carbură metalică, și în conformitate cu diferite strategii ale de stabilire a traiectoriei sculei. Au fost analizate tipurile de vibrații generate în timpul prelucrării și forțele de așchiere. În urma studiului, este prezentată o comparație obiectivă a diferitelor tehnologii pe baza indicatorilor cheie de performanță.

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