ADAPTIVE PATH CONTROL IN TANGENTIAL MICROMACHINING: A FEASIBILITY STUDY WITH USP LASER

ADAM CERMAK[1], MARTIN NOVAK[1], PETR MASEK[1], PAVEL ZEMAN[1]

[1]Department of Production Machines and Equipment (RCMT), Faculty of Mechanical Engineering, Czech Technical University in Prague, Technicka Street 4, 16000 Prague, Czech Republic

DOI: 10.17973/MMSJ.2025_10_2025082

e-mail to corresponding author: a.cermak@rcmt.cvut.cz

Tangential laser micromachining with ultra-short pulses offers high precision and is increasingly used for forceless machining of hard materials, especially in medical, watchmaking, and microtool applications. However, existing machining strategies often fail to maintain effective cutting conditions across varying workpiece dimensions. This preliminary study introduces an adaptive path control (*APC*) approach aimed at optimizing the angle of incidence (*AOI*) during the process. A closed-loop system was implemented to adjust the laser path based on in-machine measurements of the workpiece diameter during the machining process. Results show that adaptive control can significantly enhance material removal rate (*MRR*) up to 2.5 mm³/ min, when having the constant cutting conditions during entire process. The study confirms the feasibility of using *APC* laser strategy to improve process performance and provides a basis for future development of intelligent micromachining systems.

KEYWORDS

Tangential machining, USP laser, Adaptive control, Angle of incidence

1 INTRODUCTION

Tangential laser micromachining is becoming increasingly important in modern manufacturing due to its ability to process hard and brittle materials using the force-free interaction of the laser beam with the material of workpiece (Raciukaitis, 2021; Franz et al., 2023) which is especially beneficial in the production of all rotary shapes, e.g., biomedical components (Filiz et al., 2008), precision watch parts (Laser turning: Watch axis, 2023) and microtools (Hajri et al., 2018; Chen et al., 2021; Häfner et al., 2020).

Despite growing industrial applications, tangential micromachining remains relatively unexplored field. Several studies have proposed various scanning strategies using ultrashort pulse (*USP*) lasers in tangential configurations (Zettl et al., 2021a), where the position of the laser beam can be adjusted to a tangential position relative to the workpiece (Zettl et al., 2021a) with angle of incidence (*AOI*) close to zero (Syrovatka et al., 2021) or to a so-called quasi-tangential position with non-zero value of *AOI* (Zettl et al., 2023; Zettl et al., 2021b; Zettl et al., 2020).

In order to take advantage of effective conditions, especially during roughing operations, it is necessary to achieve a certain contact angle range, which was described in the study (Zettl et al., 2021a). This study presented the influence of *AOI* on the amount of material removal, where the maximum ablation removal ranged from 40 to 50 deg of *AOI*.

The fully tangential and fixed quasi-tangential strategies described in the above literature do not allow any process control that would lead to increased micromachining productivity. From the perspective of process control, various methods of feedback control can be found in several relevant studies. Zuric et al. (Zuric & Brenner, 2022) presented lateral monitoring of secondary process emissions for real-time defect detection. Another of his study (Zuric et al., 2019) research developed a multisensor system using emission characteristics for microstructuring control. Mezzapesa et al. (Mezzapesa et al., 2013) demonstrated the possibility of measuring ablation rate using optical interferometry. Ruutiainen (Ruutiainen, 2016) proposed adaptive control of ultra-fast laser scribing with online spectrometry. Based on these articles, the growing importance and effectiveness of advanced real-time monitoring and control for the precise, efficient use of ultrashort pulse lasers in micromachining and material structuring is evident.

A novel strategy which focuses on the adjusted position of laser beam against to workpiece set by operator to achieve non-zero *AOI* values during the process of micromachining was proposed in this study. Despite the inability to control the *AOI* with standard approaches, the increase of *MRR* has been achieved compared to the strategies with fixed beam described in previous studies. The enhanced *MRR* values achieved using this strategy validate the assumption that precise control of the *AOI* leads to highly efficient and progressive ablation performance.

The objective of this study is to propose an adaptive path control (*APC*) that enables ideal *AOI* control during the tangential micromachining process, which can be used to maximize MRR compared to currently available methods.

The proposed solution enables continuous measurement of the current workpiece diameter during the machining cycle. The obtained values are then used to recalculate the paths so that optimal process conditions (e.g. *AOI*, cutting depth a_p) are maintained. To implement this approach, it was necessary to design an adaptive control cycle that includes precisely defined boundary conditions for reliable diameter detection. Based on a correctly defined recognition interface (*RI*) algorithm, various *AOI* settings were then tested, the effect of the *AOI* on process parameters is further analyzed.

2 MATERIALS AND METHODS

2.1 Material

The ground rod made from solid carbide with ultra-fine-grain size (TSF44) produced by Ceratizit Group was selected for the experiment due to its high performance in demanding micro-machining applications. This type of carbide material contains up to 12% of Co binder, which is beneficial for precision cutting tool applications, another mechanical properties are shown in Table 1. For this study, a ground bar with a diameter of 3 mm and a tolerance of IT5 was used.

Grade	Co [wt %]	Density [g/cm³]	Hardness [HRA]	TRS [MPa]	E [Gpa]	Poisson's ratio [-]
TSF44	12,0	14.10	92,7	4600	547	0,218

Table 1 Material characteristics

2.2 Experimental Setup

For the purposes of the experiment, a laser micromachining system equipped with an ultra-short pulsed (*USP*) laser source

Carbide from Lightconversion was used. This source is tunable in the pulse length range from 270 fs to 10 ps and generates a maximum average power of 40 W in the repetition frequency range of 100-1000 kHz. At the same time, it allows pulses to be generated in GHz mode using burst mode. This beam is further circularly polarized by λ/4 phase plate (*QWP*) and the power output is adjusted by using a motorized attenuator and expanded using a Beam Expander before entering the galvo scanner. The laser beam is further guided by a galvo scanner intelliScan 14SE by Scanlab. After the scanner, the beam is focused using a telecentric F-theta lens with a focal length of 160 mm. For accurate alignment of reference points and recognition interface during experiments, a camera system by IDS was used. The entire experiment was performed by 5 axis kinematics by Standa. Cylindrical samples were clamped into precision-ground collets to ensure minimal radial runout.

2.3 Design of Adaptive Path Control

The objective of this article was to propose an adaptive path control *APC* process depicted in Figure 1 based on user-defined boundary conditions, where it would be possible to maintain constant process conditions in terms of the position of the laser beam relative to the workpiece according to *AOI* or constant cutting depth a_p. Within this strategy, workpiece positioning (rotation and translation in the axis direction) is performed by multi-axis kinematics, where one rotary and one linear axis are used. The movement of the laser beam is currently limited to a simple wobble by galvo-scanner, which is defined in the shape of an ellipse (Figure 1c).

In order to make the adaptive cycle (Figure 1a) feasible, it was required to design it with a focus on the accuracy of the data obtained from the measurements. Furthermore, it was necessary to master the possibility of processing this data directly in the control system for reuse during cycle revalidation, which is also a conditional step for updating the workpiece dimensions. For this purpose, workpiece measurement was programmed into the laser micromachining process directly between each lasered path. It was essential to obtain the dimensions without the necessity to unclamp the workpiece (i.e., in a single clamping) between each laser machining path. For this purpose, the measurement was performed using an integrated camera system and control system equipped with algorithms for a recognition interface (*RI*). The adaptive cycle was designed on the basis of the initial value of the workpiece D_0. After machining with the first laser path, the workpiece is measured for the first time to the diameter D_i (where i = 1). After measurement, the path is recalculated, and the laser beam moves to a new path according to the user-defined boundary conditions. When measuring new diameters, the *ddz* parameter (Figure 1b) was always adjusted to define the new distance in the Z-axis direction to ensure correct focusing conditions for each path.

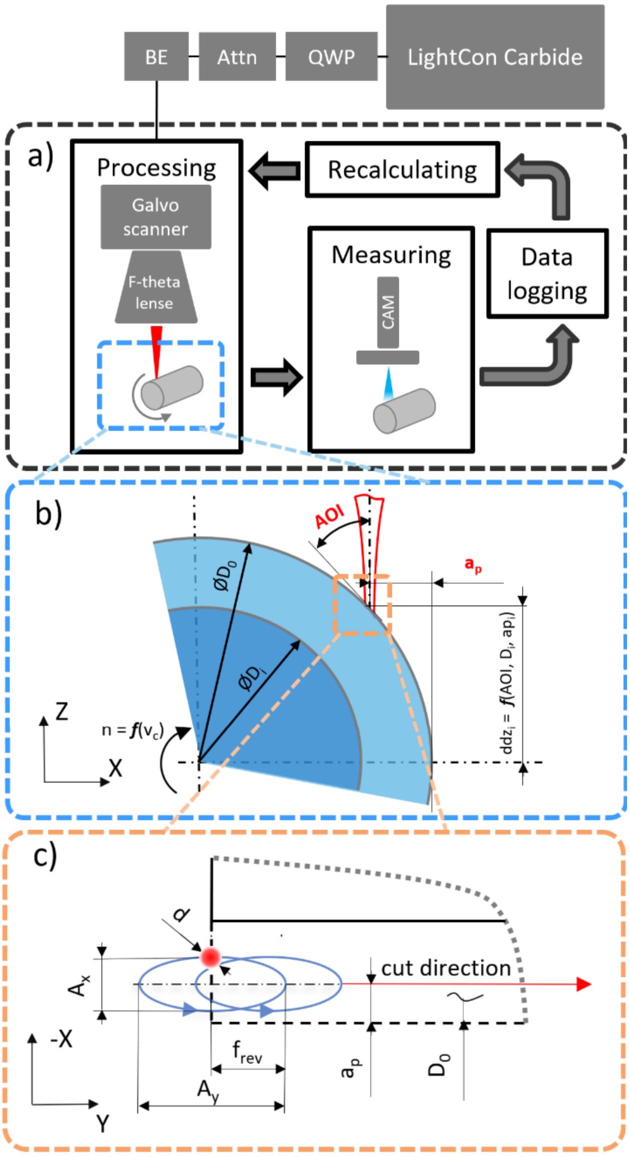

Figure 1 Scheme of adaptive control cycle in laser tangential micromachining: (a) adaptive cycle, (b) details of possible boundary conditions, (c) detail of laser processing

2.4 Camera Setting and Data Logging

In order to achieve high-quality measurements, parameters were set for the recognition interface using an industrial monochrome camera UI-5250CP-M-GL (IDS GmbH) equipped with a high-resolution telecentric lens that provides a pixel size of approximately 1.33 µm. The optimal settings included an exposure time in the range of 10–22 µs, which ensured sufficient image illumination without overexposure and with minimal noise. At the same time, it was necessary to maintain precise focus of the optics (defocus = 0 mm) to avoid systematic measurement errors caused by defocusing. These conditions were verified and confirmed in 10 repetitions, providing consistent results within the tolerance of a $6^{-0,004}$ mm diameter calibration rod, where dimension was obtained with measurement uncertainty of ±0.41 µm. The combination of correctly selected optics, appropriate exposure time, and precise focus proved essential to achieving reliable and reproducible results, when logging the data.

Based on the camera and appropriately set *RI*, data on the transitions between the right and left sides of the workpiece are obtained between the individual paths based on transmissive measurement. These recorded data primarily contain data on straight lines for calculating diameters. Secondarily, depending on the user's boundary conditions, the subsequent coordinate values of the laser beam relative to the workpiece are calculated in the X (new value for d_i) and Z (*ddz*) coordinates (according to Figure 1b). Duration of processing is also recorded for MRR evaluation.

2.5 Design of Experiment

The aim of the experiment was to verify *APC* under various cutting conditions when changing the *AOI* angle in the range of 10–50 degrees, in 10-degree increments. For the purposes of this experiment, constant process parameters of the laser system were set at 1030 nm, 270 fs without a burst-mode option, where pulse energy of 200 µJ and repetition rate of 200 kHz were applied. The wobble setting was also unchanged. The major and minor axes of the ellipse were 0.4 mm and 0.15 mm, respectively, with a frequency of 500 Hz. Camera optics with better resolution was used.

As part of the adjustment of cutting conditions, it was necessary to determine the applicable ranges for the main movement: cutting speed v_c (m.min^{-1}) and feed per revolution f_{rev} (mm.rev^{-1}), which are performed by the workpiece. The cutting speed v_c is the circumferential speed of the rotating workpiece relative to the stationary laser beam, which is defined by initial workpiece diameter D_0 and speed of rotation n (rev^{-1}). The feed per revolution f_{rev} is defined as the displacement of the workpiece relative to the laser beam per 1 revolution of the workpiece. The conditions tested are summarized in Table 2.

AOI [deg]	10, 20, 30, 40, 50
Cutting speed [m/min]	2.5, 3.0, 3.5
Feed per rev. [mm/rev]	0.002, 0.006, 0.010, 0.014, 0.018

Table 2 Overview of tested process parameters

Each sample in the experiment was machined with 8 paths from a diameter of D_0 = 3 mm to a diameter of D_i (where i = 8), where the length of turning was set to 2.3 mm. As part of the evaluation, the MRR parameter was examined, which presents the difference in volumes D_0 - D_8 over time. For the purpose of evaluating the MRR parameter, the duration of each path was also recorded, which includes the time required for the adaptive control method (measurement and recalculation). The data obtained was also used to evaluate the removal parameter between consecutive paths MRR_i.

3 RESULTS AND DISCUSSION

In the pre-experimental phase, the cutting speed v_c was adjusted within the range of 2.5-4.0 m/min in increments of 0.5 m/min. However, the highest v_c values showed a negligible increase in MRR compared to 3.5 m/min. In this case, the rotary axis had already reached its maximum speed, which prevented the desired cutting speed from being achieved. For this reason, the vc range was adjusted to 2.5–3.5 m/min. In the case of feed per revolution, the range of values was increased during the pre-experiment to a final range of 0.002–0.018 mm/rev, with a step of 0.004 mm/rev.

A non-parametrical statistical analysis was applied to the measured data to reveal the significance of control factor v_c, f_{rev} and *AOI* on the *MRR* value in each path. It was not possible to use the standard parametric ANOVA test because the measured data were not normally distributed. The Kruskal-Wallis test was used instead. On the level of significance 0.05 the Zero hypothesis about the equality of medians for the f_{rev} and *AOI* was rejected. These two control factor are statistically significant for increasing MRR (see Table 3). The control factor f_{rev} and *AOI* had an increasing effect on the *MRR* (Figure 2). The *AOI* had a greater effect on the *MRR* than the f_{rev}. The control factor v_c did not increase the *MRR*.

Descriptive Statistics					Test	
Variable		N	Median	Z-Value	H-Value	P-Value
v_c [m/min]	2.5	198	1.18	-0.35	0.12	0.94
	3	200	1.27	0.22		
	3.5	199	1.24	0.13		
	Overall	597				
f_{rev} [mm/rev]	0.002	117	0.305	-12.2	166.3	0.00
	0.006	120	1.002	-1.01		
	0.010	120	1.452	3.30		
	0.014	120	1.922	5.08		
	0.018	120	1.954	4.66		
	Overall	597				
AOI [deg]	10	120	0.32	-13.8	245.5	0.00
	20	120	1.13	-3.35		
	30	120	1.85	3.47		
	40	120	2.16	6.65		
	50	117	2.29	7.07		
	Overall	597				

Table 3 Kruskal-Wallis test results

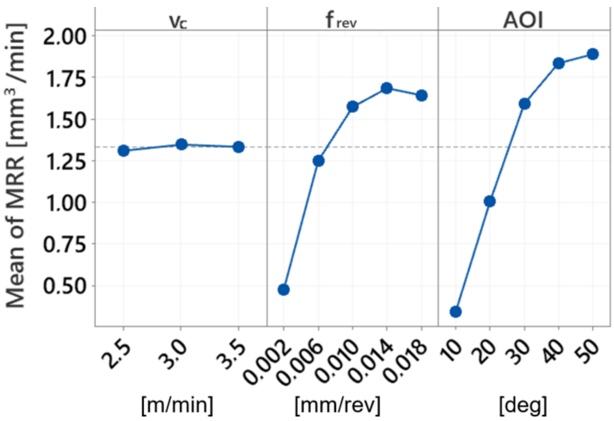

Figure 2 Main effect plot for MRR

Due to the application of low *AOI* values = 10 deg (Figure 3a), a removal rate of 0.17–0.53 mm^3/min is achieved in the given cutting conditions. When increasing the *AOI* to 30 deg up to 50 deg (Figure 3b-c), an increase in *MRR* = 0.52–2.13 mm^3/mm and 0.58–2.49 mm^3/mm, is observed. Furthermore, the influence of specific cutting parameters on *MRR* was evaluated. An increase in the feed rate f_{rev} proved to be the dominant factor in increasing productivity. This trend is closely related to conventional turning technologies, where increasing the feed rate is the primary factor in increasing *MRR* (He et al., 2018; Sousa & Silva, 2020) At the highest *AOI* values, the results correlated well with existing literature (Zettl et al., 2021a), indicating that maximum ablation efficiency typically occurs between 40–50 deg.

Conditions with *AOI* = 60 deg were also tested during the experiment. However, the formation of highly uneven surfaces led to reduced functionality of the *RI*. Due to the strictly set *RI* parameters of camera which are suitable for well machined surfaces with standard surface topographies, the *RI* did not function effectively under these conditions. Therefore, the *APC* approach with defined *RI* constraints is not recommended for *AOI* > 50°. If higher *AOI* values are used, it would be necessary to implement other measurement methods based on a different measurement technique.

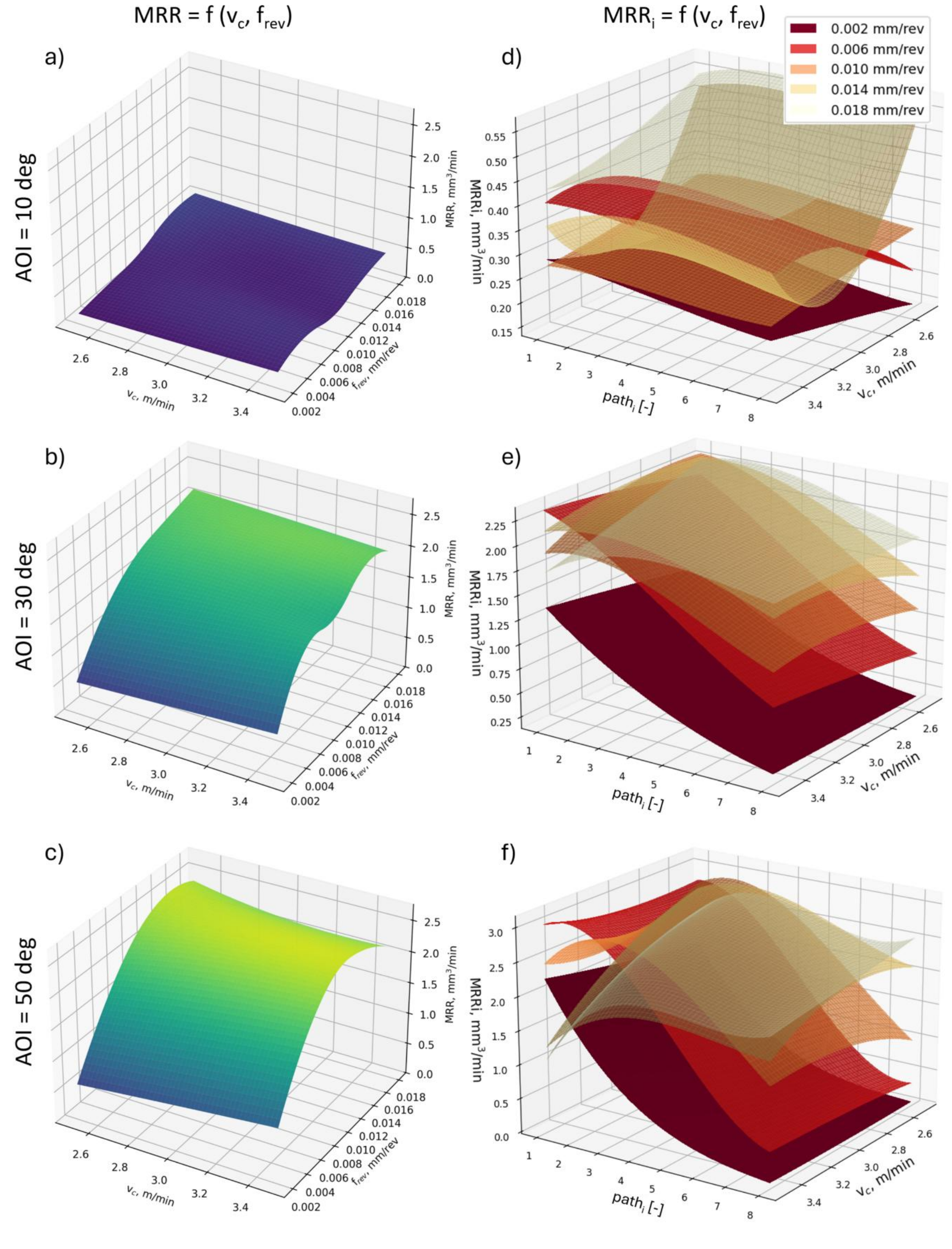

Figure 3 Effect of different boundary conditions (AOI in range 10 to 50 degrees) in terms of: (i) overall material removal rate MMR (a-c); (ii) material removal rate in each individual path MMRi (d-f)

The second part of the analysis focused on MRR_i, reflecting material removal per individual laser path in the tangential laser micromachining process under certain *AOI* value, evaluated across five data sets (parameter f_{rev}). This decomposition provided deeper insights into the influence of cutting conditions.

At low *AOI* = 10 deg (Figure 3d), MRR_i was too small to precisely determine the influence of specific parameters, which is consistent with finishing operations where the f_{rev} parameter does not have a significant influence. Therefore, the different effects of cutting conditions (v_c, f_{rev}) are negligible for such small *AOI* values. As *AOI* increased (30–50 deg), the influence of f_{rev} became more pronounced compared to v_c. At an angle of 30 deg (Figure 3e), the increasing influence of f_{rev} on MRR_i is evident across the entire range of increasing f_{rev} values. At *AOI* = 50° (Figure 3f), local drops of MRR_i appeared at f_{rev} from 10 to 18 µm (with high v_c in range 3.0 to 3.5 m/min), indicating less efficient machining in the initial paths (larger diameters). This behavior may be caused by insufficient pulse energy E_p in the machining process and will be verified in further research.

The MRR_i data can also be used to obtain the relative difference in the consecutive diameters D_{rel}, which can be expressed as $D_{rel}(\%) = D_{i-1}/D_i$. This parameter represents the percentage difference between the previous D_{i-1} and subsequent D_i diameter. This parameter is also influenced by the specific size of the current diameter D_i and can vary from slight changes (< 1%) to tens of percent (> 86%) depending on the selected process conditions and the specific diameter D_i. The aim will be to use this data to prepare precisely defined finishing conditions, where the goal is to achieve regular repeatability in very precise tolerance grades IT5 – IT3.

4 CONCLUSION

This study successfully introduced and demonstrated the adaptive path control (*APC*) strategy for tangential laser micromachining. Proposed study enables adaptive adjustment of the laser beam path position based on continuous measurement of the workpiece diameter during the tangential laser micromachining. The *APC* approach allows the optimal angle of incidence (*AOI*) to be maintained using user-selected boundary conditions. In this work, the *APC* method was verified under constant *AOI* conditions, which demonstrated a significant increase in material removal rate (*MRR*). Removal rate in each path MRR_i also provides very detailed data, creating a potential for flexible and variable control of adaptive process conditions.

Experimental results have shown that increasing the *AOI* up to 50 deg significantly increases the *MRR* up to 2.49 mm^3/min when applying 200 µJ at 1030 nm and femtosecond pulse duration. Feed per revolution f_{rev} belongs among the main factors affecting productivity, which corresponds to trends known from conventional turning. However, at *AOI* values above 50 deg, it has been shown that the current recognition interface (*RI*) settings are insufficient due to increased surface roughness, indicating the technological limits of *APC* applicability under the tested conditions.

These results from *MRR* due to the finding of local minima further showed that it will be necessary to repeat the data sets in future tests to identify any stable and unstable cutting conditions. This knowledge will continue to be useful for continuing with more advanced algorithms. Further optimization will be needed in way of process repeatability from the point of view of local maxima and minima. The evaluated *MRR* curves at different *AOI* values showed local minima and maxima, particularly visible at 10 deg and 30 deg.

Further investigation is required to understand the origins of these local minimums. Additional data collection is planned to assess process repeatability, enabling statistical validation of stable and unstable cutting conditions for consistent *MRR* targets in *APC* strategies. For *AOI* = 50 deg, a suitable window of cutting conditions across the full range of cutting speeds v_c was identified without unexpected drops, enabling *MRR* values up to 2.5 mm^3/min.

The results show that implementing the APC laser strategy is a good way to improve process efficiency and provides a robust basis for developing smart micromachining systems. The study also reveals opportunities for increasing the productivity of laser turning; however, these techniques need further enhancement, and more research is needed to fully explore their potential.

ACKNOWLEDGMENTS

The presented research was supported by the European Union under the project ”ROBOPROX – Robotics and Advanced Industrial Production”, reg. no. CZ.02.01.01/00/22_008/0004590 and created also within the project National Centre of Competence in ENGINEERING (TN02000018), which is co-financed from the state budget by the Technology agency of the Czech Republic under the National Centre of Competence Progamme. The authors would also like to acknowledge usage of the RICAIP infrastructure for experimental part of the work.

REFERENCES

[Chen et al. 2021] Chen, N., Li, H. N., Wu, J., Li, Z., Li, L., Liu, G., & He, N. (2021). Advances in micro milling: From tool fabrication to process outcomes. *International Journal of Machine Tools and Manufacture*, *160*. https://doi.org/10.1016/j.ijmachtools.2020.103670

[Filiz et al. 2008] Filiz, S., Xie, L., Weiss, L. E., & Ozdoganlar, O. B. (2008). Micromilling of microbarbs for medical implants. International Journal of Machine Tools and Manufacture, 48(3-4), 459-472. https://doi.org/10.1016/j.ijmachtools.2007.08.020

[Franz et al. 2023] Franz, D., Yang, Y., Michel, L., Esen, C., & Hellmann, R. (2023). Evaluation of an ultrashort pulsed laser robot system for flexible and large-area micromachining. Journal of Laser Applications, 35(4). https://doi.org/10.2351/7.0001171

[Häfner et al. 2020] Häfner, C., Hajri, M., Büttner, H., & Konrad Wegener, J. P. (2020). FEM-Design & fabrication of a micro-milling tool by tangential laser machining. Procedia CIRP, 2020(vol. 95), 903-908. https://doi.org/10.1016/j.procir.2020.03.130

[Hajri et al. 2018] Hajri, M., Pfaff, J., Büttner, H., Voegtlin, M., Kaufmann, R., & Wegener, K. (2018). Fabrication of a ball end nose micro milling tool by tangential laser ablation. Procedia CIRP, 77, 654-657. https://doi.org/10.1016/j.procir.2018.08.184

[He et al. 2018] He, C. L., Zong, W. J., & Zhang, J. J. (2018). Influencing factors and theoretical modeling methods of surface roughness in turning process: State-of-the-art. International Journal of Machine Tools and Manufacture, 129, 15-26. https://doi.org/10.1016/j.ijmachtools.2018.02.001

[Laser turning 2023] Laser turning: Watch axis. (2023). GFH Laser micromachining. Retrieved October 12, 2024, from https://gfh-gmbh.de/en/processes/laser-turning/

[Mezzapesa 2013] Mezzapesa, F., Columbo, L., Ancona, A., Dabbicco, M., Spagnolo, V., Brambilla, M., Pietro Mario Lugarà, & Scamarcio, G. (2013). On Line Sensing of Ultrafast Laser Microdrilling Processes by Optical Feedback Interferometry. Physics Procedia, 41, 670-676. https://doi.org/10.1016/j.phpro.2013.03.131

[Raciukaitis 2021] Raciukaitis, G. (2021). Ultra-Short Pulse Lasers for Microfabrication: A Review. IEEE Journal of Selected Topics in Quantum Electronics, 27(6), 1-12. https://doi.org/10.1109/JSTQE.2021.3097009

[Ruutiainen 2016] Ruutiainen, M. (2016). REAL-TIME ADAPTIVE CONTROL OF ULTRA-FAST LASER SCRIBING PROCESS WITH SPECTROMETER ONLINE MONITORING [Diploma thesis]. Lappeenranta University of Technology.

[Sousa et al. 2020] Sousa, V. F. C., & Silva, F. J. G. (2020). Recent Advances in Turning Processes Using Coated Tools—A Comprehensive Review. Metals, 10(2), 170. https://doi.org/10.3390/met10020170

[Syrovatka et al. 2021] Syrovatka, S., Cermak, A., Kozmin, P., Marsalek, O., & Zatloukal, T. (2021). Tangential Laser Machining Using Fs-pulsed Laser. In B. Katalinic (Ed.), Proceedings of the 32nd International DAAAM Symposium 2021 (pp. 0685-0691). DAAAM International Vienna. https://doi.org/10.2507/32nd.daaam.proceedings.096

[Zettl et al. 2021a] Zettl, J., Bischoff, C., Rung, S., Esen, C., Lasagni, A. F., & Hellmann, R. (2021). Laser turning using ultra-short laser pulses and intensity distribution techniques. In Lasers in Manufacturing Conference (2021st ed., p. 9). German Scientific Laser Society (WLT).

[Zettl et al. 2023] Zettl, J., Esen, C., & Hellmann, R. (2023). Fundamental Considerations and Analysis of the Energy Distribution in Laser Turning with Ultrashort Laser Pulses. Micromachines, 14(10). https://doi.org/10.3390/mi14101838

[Zettl et al. 2020] Zettl, J., Klar, M., Esen, C., & Hellmann, R. (2020). Generation of Rotationally Symmetric Micro Tools using Ultrashort Laser Pulses. Journal of Laser Micro/Nanoengineering, 2020(Vol. 15), 5. https://doi.org/10.2961/jlmn.2020.02.2007

[Zettl et al. 2021b] Zettl, J., Klar, M., Rung, S., Esen, C., & Hellmann, R. (2021). Laser turning with ultrashort laser pulses. Journal of Manufacturing Processes, 68, 1562-1568. https://doi.org/10.1016/j.jmapro.2021.06.025

[Zuric et al. 2022] Zuric, M., & Brenner, A. (2022). Real-time defect detection through lateral monitoring of secondary process emissions during ultrashort pulse laser microstructuring. Optical Engineering, 61(09). https://doi.org/10.1117/1.oe.61.9.094101

[Zuric et al. 2019] Zuric, M., Nottrodt, O., & Abels, P. (2019). Multi-Sensor System for Real-Time Monitoring of Laser Micro-Structuring. Journal of Laser Micro/Nanoengineering. https://doi.org/10.2961/jlmn.2019.03.0008

CONTACTS:

Ing. Adam Cermak, Ph.D.
Czech Technical University in Prague/ Faculty of Mechanical Engineering /University, Department
Technicka Street 4, Prague, 16000 , Czech Republic Address, City, Postal Code, Country
+420 721 725 263, a.cermak@rcmt.cvut.cz, www.rcmt.cvut.cz