WEP
Warwick
Evans
Publishing

International Journal of Mechanical and Electrical Engineering

ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 3, Number 3, Year 2024
DOI: https://doi.org/10.62051/ijmee.v3n3.10
Journal homepage: https://wepub.org/index.php/IJMEE/index

A Review of Chatter Stability in Thin-Walled Mirror Milling

Xingguo Chang, Yongxiang Jiang *, Xifeng Wang, Xiang Kong, Xiangyan Wu

School of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin 300222, China

* Corresponding author: Yongxiang Jiang (Email: jiangyongxiang@tute.edu.cn)

ABSTRACT

This paper addresses the chatter problem in thin-walled part milling, reviewing the advancements in mirror milling technology for thin-walled parts. It provides an in-depth discussion of the fundamental causes of chatter during thin-walled part milling. A comparative analysis of the advantages and disadvantages of empirical, finite element, and analytical models for milling force in thin-walled parts is presented. The paper also discusses the experimental methods, finite element modal analysis, and structural coupling methods used to obtain the frequency response functions of workpieces and tools, comparing their respective strengths and weaknesses. Furthermore, time-domain and frequency-domain methods for stability prediction are analyzed and compared, with a discussion on the future prospects of chatter stability prediction in mirror milling.

KEYWORDS

Thin-Walled Parts; Mirror Milling; Stability.

1. INTRODUCTION

Thin-walled parts are widely used in aerospace, automotive manufacturing, and other fields due to their lightweight, low rigidity, and complex shapes, especially playing a critical role in the production of high-performance components. However, due to the weak rigidity of thin-walled parts, they are highly prone to deformation and vibration during machining, leading to a decline in surface quality, reduced machining accuracy, and even excessive tool wear, which significantly limits the machining efficiency and quality of thin-walled parts. Therefore, predicting the stability of mirror milling has become a focal point in recent years.

As a specialized machining method, mirror milling aims to reduce or counteract the cutting forces generated during machining by reasonably designing the machining path along the plane of symmetry, thereby effectively controlling the deformation and vibration of thin-walled parts. However, many factors influence the machining stability in mirror milling, such as cutting depth, spindle speed, feed rate, and support force. The complex interactions between these parameters directly affect the machining stability and surface quality of thin-walled parts. Thus, optimizing these process parameters to ensure machining stability and product quality remains a critical issue in the current research on thin-walled part machining.

Based on the summary of mirror milling processes, this paper discusses the research progress of chatter theoretical models in thin-walled part milling. A comparative analysis is conducted on the advantages and disadvantages of existing empirical models, finite element models, and analytical models for thin-walled milling forces. Subsequently, the dynamic characteristics of the thin-walled mirror milling system are examined, with an in-depth discussion on the frequency-domain and time-domain methods for solving stability. Finally, the paper summarizes and discusses the stability criteria for thin-walled milling processes.

1.1. Mirror Milling Process

The term 'mirror milling' was introduced by Dufieux to replace traditional chemical milling processes for the production of thin-walled parts. However, the mirror milling machines developed by the company are limited in their processing range, making it challenging to machine thin-walled parts with complex curvatures. To suppress chatter and deformation during the mirror milling process, researchers have studied various aspects of the process, including the structure of the support head, clamping methods for thin-walled parts, and path planning during the milling process.

In the mirror milling process, the support head moves synchronously with the milling cutter and makes direct contact with the thin-walled part. The support head provides support at the machining position of the thin-walled part, increasing local stiffness and reducing deformation and chatter at the machining location. However, the movement of the support head can cause frictional damage to the surface of the thin-walled part. To address this issue, A. Mahmud [1] and others designed a follow-up support system based on magnetic adsorption, which uses magnetic attraction to achieve synchronous movement of the support with the milling cutter. This support head structure simplifies the mirror milling system. Li Z[2]. et al. reviewed a fluid lubricating support-based aircraft skin mirror milling process, where a fluid layer is formed on the back of the workpiece to achieve dynamic and stable support, significantly reducing workpiece vibration and deformation, thereby improving the machining accuracy and surface quality of thin-walled structures. Xiao J L[3] et al. researched a method for vibration suppression in thin-walled parts mirror milling using a multi-point flexible following support head. This method combines multi-point support and a flexible following support head to provide dynamic support to the workpiece, effectively reducing vibration and deformation during machining, significantly improving the machining accuracy and surface quality of thin-walled structures. Lan J[4] et al. investigated the path planning method for support heads in a mirror-milling machining system. By optimizing the movement path of the support heads, this method provides efficient dynamic support to the workpiece, reducing vibration and deformation during machining, thus enhancing the machining accuracy and surface quality of thin-walled parts.

Bao Y[5] et al. studied the multipoint support technology for mirror milling of aircraft skins. This technology employs multipoint support during the machining process, significantly reducing vibration and deformation of thin-walled part. Hao X Z[6] et al. proposed a tool path transplantation method for adaptive machining of large-sized and thin-walled free-form surface parts based on error distribution. By analyzing the error distribution of the workpiece, this method optimizes the tool path, enabling dynamic adjustments during the machining process to reduce errors and improve the accuracy and quality of thin-walled free-form surfaces. Liu S W[7] et al. proposed a feature-based uncut region tool path optimization method for skin parts machined by a mirror milling system. This method identifies uncut regions and optimizes the tool path, improving machining efficiency and reducing residual uncut areas, thereby enhancing the accuracy and surface quality of thin-walled skin parts. Yang M [8] et al. proposed an image morphology-based path generation method for high-speed pocketing. This method utilizes image morphology techniques to generate machining paths, effectively improving the efficiency of high-speed pocketing, reducing machining time, and enhancing path optimization and surface quality during the process.

Sheng X[9] et al. proposed a coordinated motion strategy for a multi-manipulator system based on joint space synchronized cross-coupled control. This strategy achieves synchronized control in joint space, optimizing the coordinated motion of the multi-manipulator system, enhancing stability and precision, making it suitable for high-precision collaborative operations in complex tasks. Pas O and Serkov N[10] developed an algorithm to control the accuracy of milling aerospace parts with a cellular structure by using copying machine-tools with CNC of SVO type. The algorithm optimizes the machining path of copying machine-tools to ensure high-precision machining of complex cellular structure parts, meeting the manufacturing requirements for aerospace components. Wei H Y[11] et al. proposed a deformation control and compensation method using the whole mirror milling method for machining thin-walled parts of tanks. This method involves real-time monitoring and compensation of deformations during the machining process, significantly reducing machining errors and improving the accuracy and quality of thin-walled parts, making it suitable for high-precision machining of large thin-walled structures. Sheng X J and Zhang X[12] proposed a fuzzy adaptive hybrid impedance control method for a mirror milling system. By combining fuzzy adaptive control techniques with impedance control, this method achieves precise control over force and displacement during the machining process, significantly enhancing the stability and surface quality of thin-walled parts during mirror milling. Sheng X J[13] et al. proposed a position-based explicit force control strategy based on online trajectory prediction. This strategy enables precise force control by predicting trajectories in real time, significantly improving control accuracy and stability in robotic systems, especially in applications requiring high precision in both force and position. Wang Y Q[14] et al. proposed a mirror milling chatter identification method using Q-factor and Support Vector Machine (SVM). This method analyzes the vibration characteristics of the workpiece through the Q-factor and utilizes an SVM classification model to accurately identify chatter during the mirror milling process, thereby enhancing process stability and surface quality.

2. MILLING FORCE MODEL FOR THIN-WALLED PARTS

Ge M J[15] et al. conducted experimental research on the milling force model of titanium alloy thin-walled workpieces. Through experimental measurement and analysis, a milling force model suitable for machining titanium alloy thin-walled parts was established, revealing the relationship between cutting forces and workpiece deformation during milling, thus providing theoretical support for improving the machining accuracy of thin-walled parts. WU Kai [16] et al. studied the machining deformations and their control approaches for thin-web components in end milling. The research analyzed the deformation mechanisms caused by cutting forces and insufficient rigidity of the thin-web during the milling process. It proposed effective methods for controlling deformations by optimizing cutting parameters, improving support strategies, and employing deformation compensation techniques, thereby enhancing machining accuracy. HE Yongqiang and CAO Yan[17] studied the application of force models in milling thin-walled parts. The research explored the deformation issues caused by cutting forces during the milling process of thin-walled parts, developed a milling force model, and analyzed its role in predicting and controlling deformations, proposing strategies to optimize cutting parameters for improved machining accuracy.

Qiao F[18] et al. conducted modeling and experimental research on the end milling of thin-walled parts. The study developed a mechanical model for end milling thin-walled parts and validated it through experiments, analyzing the relationship between cutting forces and workpiece deformation. The experimental results demonstrated that the model could effectively predict deformation during the milling process, providing theoretical support for improving the machining accuracy of thin-walled parts. ZHENG Jinxing[19] explored the application of a particle-swarm optimization-trained artificial neural network in high-speed milling force modeling. The study combined particle-swarm optimization with artificial neural networks to develop a cutting force model for high-speed milling. Experimental results showed that this model could accurately predict changes in cutting forces, providing an effective method for optimizing high-speed milling processes.

Tsai J S and Liao C L[20] conducted finite-element modeling of static surface errors in the peripheral milling of thin-walled workpieces. The study developed a finite-element model to analyze the impact of cutting forces on surface errors of thin-walled parts and revealed the deformation mechanisms caused by insufficient workpiece rigidity. The findings provided theoretical support and optimization suggestions for improving the machining accuracy of thin-walled components. Ratchev S [21] et al.

proposed a flexible force model for end milling of low-rigidity parts. The model accounts for the deformation of the workpiece during machining due to its low rigidity, dynamically adjusting the prediction of cutting forces. Experimental results showed that the model effectively improves the machining accuracy and stability of low-rigidity thin-walled components.

M. Meshreki[22] studied the dynamics of thin-walled aerospace structures for fixture design in multi-axis milling. The research analyzed the dynamic behavior of thin-walled parts during multi-axis milling, providing theoretical foundations and optimization suggestions for fixture design to enhance stability and precision during the machining process, particularly for high-precision aerospace component manufacturing.

3. METHODS FOR SOLVING STABILITY LOBE DIAGRAMS

The concept of the stability lobe diagram was first introduced by Merritt[23]. The stability lobe diagram is typically obtained by solving the system's dynamic equations.

3.1. Stability Solving Methods

The methods for solving stability can be divided into frequency domain methods and time domain methods. The frequency domain method is an analytical approach for solving the stability boundary within the frequency domain. In this method, the cutting force coefficients are averaged in the cutting direction, the periodic matrix is expanded into a Fourier series, and stability analysis is performed. Based on the order involved in the computation, the method can be classified into zero-order and higher-order frequency domain methods. The zero-order frequency domain method only selects the zero-order constant for calculation, resulting in a faster computation speed.

Feng J L[24] et al. proposed an efficient method to predict the chatter stability of titanium alloy thin-walled workpieces during high-speed milling by considering varying dynamic parameters. By incorporating dynamic characteristics into the model, this method provides more accurate predictions of the chatter limits, offering important theoretical support for improving machining stability and precision, especially for high-precision machining of titanium alloy thin-walled structures. Zhu L D, Liu B G, and Chen H Y [25] researched chatter stability in milling and parameter optimization based on process damping. The study analyzed the influence of process damping on chatter stability during milling and proposed methods for optimizing machining parameters to enhance stability and efficiency, reducing the occurrence of chatter. Altintas Y, Stepan G, Merdol D[26] et al. studied the chatter stability of milling in both frequency and discrete time domains. The research analyzed the mechanisms of chatter during milling in these two domains and proposed methods to predict chatter stability, providing theoretical support for optimizing milling parameters and improving process stability. Merdol S D and Altintas Y [27] investigated the multi-frequency solution of chatter stability for low immersion milling. The study utilized a multi-frequency analysis to explore the chatter phenomenon across different frequencies during low immersion milling. A multi-frequency-based chatter stability prediction model was proposed, which accurately predicts the chatter limits under low immersion conditions, optimizing machining parameters and improving process stability and efficiency. Tang A J and Liu Z Q[28] investigated the three-dimensional stability lobe and maximum material removal rate in end milling of thin-walled plates. The study constructed a 3D stability lobe diagram to analyze the impact of various machining parameters on milling process stability and optimized the machining parameters for end milling. A method to achieve the maximum material removal rate while ensuring process stability was proposed, thus enhancing the machining efficiency of thin-walled parts. Wang M H, Gao L, and Zheng Y H[29] studied the prediction of regenerative chatter in the high-speed vertical milling of thin-walled workpieces made of titanium alloy. By developing a regenerative chatter model and considering the dynamic characteristics of titanium alloy thin-walled parts, the study investigated the conditions under which chatter occurs during high-speed milling and proposed an effective prediction method. The results provide theoretical support for optimizing machining parameters and improving process stability.

Yan B L and Zhu L D [30] researched the milling stability of thin-walled parts based on an improved multi-frequency solution. The study analyzed the milling process of thin-walled parts using an enhanced multi-frequency approach, revealing the relationship between cutting forces and workpiece vibrations. Methods for optimizing machining parameters to improve stability were proposed. The results demonstrated that this method could effectively predict chatter during milling, improving machining efficiency and accuracy. Zhang Z, Li H G, Liu X B[31] et al. studied chatter mitigation for the milling of thin-walled workpieces. The research analyzed the chatter mechanisms occurring during the milling of thin-walled parts and proposed several strategies for chatter suppression, including optimizing cutting parameters and employing improved support methods to enhance machining stability and surface quality. Experimental results showed that these methods effectively reduced the occurrence of chatter. Insperger T and Stépán G [32] proposed an updated semi-discretization method for periodic delay-differential equations with discrete delay. This method improves the computational efficiency and accuracy of solving periodic delay systems by utilizing an enhanced semi-discretization technique, making it widely applicable in stability analysis and dynamic system modeling in engineering. Song Q H, Ai X, and Tang W X[33] investigated the prediction of simultaneous dynamic stability limits in a time-variable parameter system during the high-speed milling of thin-walled workpieces. The study developed a time-variable parameter system model to analyze chatter phenomena in high-speed milling and proposed a method to predict dynamic stability limits, optimizing milling parameters to enhance process stability and efficiency.

3.2. Stability Criteria.

Micro milling has unique advantages in the machining of meso-scale thin-walled parts. Liu Y, Li P F, Liu K[34]et al. investigated the micro milling of copper thin-wall structures. The study experimentally analyzed the effects of cutting forces, surface roughness, and workpiece deformation during the micro milling process, optimizing milling parameters to enhance machining accuracy and surface quality of thin-walled copper structures. The results provide strong support for high-precision machining in micro-manufacturing. Zariatin D L, Kiswanto G, and Ko T J[35] investigated the micro-milling process of thin-wall features in aluminum alloy 1100. The study experimentally analyzed the effects of cutting forces, tool wear, and surface roughness during the micro-milling process, and optimized milling parameters to improve the machining accuracy and surface quality of thin-walled aluminum structures, providing theoretical and experimental support for high-precision micro-milling of thin-wall components. Kim C J, Bono M, and Ni J [36] conducted an experimental analysis of chip formation in micro-milling. The study observed the chip formation mechanisms during micro-milling and analyzed the relationship between cutting parameters, cutting forces, and chip morphology, revealing the unique characteristics of the milling process at the micro-scale and providing insights for optimizing micro-milling process parameters. Vogler M P, Devor R E, and Kapoor S G[37] studied the modeling and analysis of machining performance in micro-end milling. Part I focused on surface generation, where the researchers developed a model to analyze the impact of cutting parameters on surface quality during the micro-end milling process. The study revealed the unique surface generation characteristics at the micro-scale, providing a theoretical basis for optimizing micro-machining processes. Friedrich C R[38] studied the micromechanical machining of high aspect ratio prototypes. The research explored process parameters, tool wear, and surface quality when machining high aspect ratio microstructures, and optimized the micromechanical machining process, making it particularly suitable for the fabrication of micro parts requiring high precision and high aspect ratios. Popov K, Dimov S, Pham D[38] T et al. investigated micro milling strategies for machining thin features. The study explored how different micro milling strategies affect the machining of thin-walled features, analyzing the influence of cutting parameters, tool paths, and workpiece support methods on machining accuracy and surface quality. Effective methods for optimizing micro milling processes were proposed to enhance the efficiency and stability of thin-walled structure machining.

4. CONCLUSION

This paper discusses chatter in thin-walled mirror milling. It provides a comprehensive overview of the current development of mirror milling technology, methods for modeling milling forces in thin-walled parts, and the current research status of stability solving methods. Current research on thin-walled part machining primarily focuses on the support methods and functioning of the support head. Future studies could focus on the behavior of thin-walled parts under the combined effects of both the support head and the milling cutter. Currently, research on dynamic models of thin-walled part milling with respect to damping is relatively limited, with most studies focusing on thin-walled frames and panel-like parts. There is a lack of research on the chatter stability of thin-walled parts with complex curved geometries. Existing studies on meso-scale thin-walled micro-milling technology are still in the early stages, and there is an urgent need for in-depth research on the mechanism of chatter in micro-milling processes and its suppression techniques.

REFERENCES

[1] A. Mahmud, J.R.R. Mayer, L. Baron: Determining the minimum clamping force by cutting force simulation in aerospace fuselage pocket machining, The International Journal of Advanced Manufacturing Technology, Vol. 80 (2015), p. 1751-1758.

[2] Z. Li, Y. Bao, R.K. Kang, et al.: An advanced support method of aircraft skin mirror milling - fluid lubricating support, Materials Science Forum, Vol. 874 (2016) No. 11, p. 469-474.

[3] J.L. Xiao, Q.Y. Zhang, H.T. Liu, et al.: Research on vibration suppression by a multi-point flexible following support head in thin-walled parts mirror milling, The International Journal of Advanced Manufacturing Technology, Vol. 106 (2020), p. 3335-3344.

[4] J. Lan, B. Lin, T. Huang, et al.: Path planning for support heads in mirror-milling machining system, International Journal of Advanced Manufacturing Technology, Vol. 91 (2017) No. 1, p. 617-628.

[5] [1] Y. Bao, R.K. Kang, Z.G. Dong, et al.: Multipoint support technology for mirror milling of aircraft skins, Materials and Manufacturing Processes, Vol. 33 (2017) No. 9, p. 996-1002.

[6] X.Z. Hao, Y.G. Li, T.C. Deng, et al.: Tool path transplantation method for adaptive machining of large-sized and thin-walled free form surface parts based on error distribution, Robotics and Computer-Integrated Manufacturing, Vol. 56 (2019), p. 222-232.

[7] S.W. Liu, Y.G. Li, X.Z. Hao, et al.: Feature-based uncut region tool path optimization method for skin parts machined by mirror milling system, Acta Aeronautica et Astronautica Sinica, Vol. 37 (2016) No. 7, p. 2295-2302.

[8] M. Yang, K. Xu, Y. Li, et al.: Image morphology-based path generation for high-speed pocketing, Journal of Manufacturing Science and Engineering, Vol. 142 (2020) No. 4, p. 1-23.

[9] X. Sheng, Z. Wang, L. Xu, et al.: Coordinated motion strategy for multi-manipulators system based on joint space synchronized cross-coupled control, 8th International Conference on Intelligent Robotics and Applications (ICIRA), August 24-27, 2015, Portsmouth, United Kingdom, Springer Verlag, p. 396-407.

[10] O. Pas, N. Serkov: Developing an algorithm to control the accuracy of the milling of aerospace parts with cellular structure by using copying machine-tools with CNC of SVO type, International Conference of Young Scientists and Students "Topical Problems of Mechanical Engineering 2018", November 20-23, 2018, UK, IOP Publishing, p. 012057 (5 pp.).

[11] H.Y. Wei, J. Mao, N. Wang: Machining deformation control and compensation using whole mirror milling method for tank thin-walled parts, 2nd International Conference on Smart City and Systems Engineering (ICSCSE), November 11-12, 2017, Changsha, China, Institute of Electrical and Electronics Engineers Inc., p. 23-28.

[12] X.J. Sheng, X. Zhang: Fuzzy adaptive hybrid impedance control for mirror milling system, Mechatronics, Vol. 53 (2018), p. 20-27.

[13] X.J. Sheng, L. Xu, Z. Wang: A position-based explicit force control strategy based on online trajectory prediction, International Journal of Robotics and Automation, Vol. 32 (2017) No. 1, p. 93-100.

[14] Y.Q. Wang, Q.L. Bo, H.B. Liu, et al.: Mirror milling chatter identification using Q-factor and SVM, The International Journal of Advanced Manufacturing Technology, Vol. 98 (2018) No. 5, p. 1163-1177.

[15] M.J. Ge, G.F. Shan, J. Yu, et al.: Experimental research on milling force model of titanium alloy thin wall workpiece, Tool Engineering, Vol. 49 (2015) No. 10, p. 44-47.

[16] K. Wu, N. He, W.H. Liao, et al.: Study on machining deformations and their control approaches of the thin-web in end milling, China Mechanical Engineering, Vol. 15 (2004) No. 8, p. 670-674.

[17] Y.Q. He, Y. Cao: Study on application of force models of thin-wall part milling, Mechanical Engineer, No. 10 (2007), p. 4-6.

[18] F. Qiao, F. Ren, X. Liu, et al.: Modeling and experimental research on end milling of thin-walled parts, Machinery, Vol. 57 (2019) No. 8, p. 80-83.

[19] J.X. Zheng: Application of particle-swarm optimization-trained artificial neural network in high-speed milling force modeling, Computer Integrated Manufacturing Systems, Vol. 14 (2008) No. 9, p. 1710-1716

[20] J.S. Tsai, C.L. Liao: Finite-element modeling of static surface errors in the peripheral milling of thin-walled workpieces, Journal of Materials Processing Technology, Vol. 94 (1999) No. 2/3, p. 235-246.

[21] S. Ratchev, S. Liu, W. Huang, et al.: A flexible force model for end milling of low-rigidity parts, Journal of Materials Processing Technology, Vol. 153/154 (2004) No. 1/2/3, p. 134-138.

[22] M. Meshreki: Dynamics of thin-walled aerospace structures for fixture design in multi-axis milling, Montreal: McGill University ProQuest Dissertations Publishing, 2009.

[23] H.E. Merritt: Theory of self-excited machine-tool chatter: contribution to machine-tool chatter research—1, Journal of Engineering for Industry, Vol. 87 (1965) No. 4, p. 447-454.

[24] J.L. Feng, N. Hou, Z. Jian, et al.: An efficient method to predict the chatter stability of titanium alloy thin-walled workpieces during high-speed milling by considering varying dynamic parameters, International Journal of Advanced Manufacturing Technology, Vol. 106 (2020) No. 11/12, p. 5407-5420.

[25] L.D. Zhu, B.G. Liu, H.Y. Chen: Research on chatter stability in milling and parameter optimization based on process damping, Journal of Vibration and Control, Vol. 24 (2018) No. 12, p. 2642-2655.

[26] Y. Altintas, G. Stepan, D. Merdol, et al.: Chatter stability of milling in frequency and discrete time domain, CIRP Journal of Manufacturing Science and Technology, Vol. 1 (2008) No. 1, p. 35-44.

[27] S.D. Merdol, Y. Altintas: Multi frequency solution of chatter stability for low immersion milling, Journal of Manufacturing Science and Engineering, Transactions of the ASME, Vol. 126 (2004) No. 3, p. 459-466.

[28] A.J. Tang, Z.Q. Liu: Three-dimensional stability lobe and maximum material removal rate in end milling of thin-walled plate, International Journal of Advanced Manufacturing Technology, Vol. 43 (2009) No. 1/2, p. 33-39.

[29] M.H. Wang, L. Gao, Y.H. Zheng: Prediction of regenerative chatter in the high-speed vertical milling of thin-walled workpiece made of titanium alloy, International Journal of Advanced Manufacturing Technology, Vol. 72 (2014) No. 5/6/7/8, p. 707-716.

[30] B.L. Yan, L.D. Zhu: Research on milling stability of thin-walled parts based on improved multi-frequency solution, International Journal of Advanced Manufacturing Technology, Vol. 102 (2019) No. 1/2/3/4, p. 431-441.

[31] Z. Zhang, H.G. Li, X.B. Liu, et al.: Chatter mitigation for the milling of thin-walled workpiece, International Journal of Mechanical Sciences, Vol. 138/139 (2018), p. 262-271.

[32] T. Insperger, G. Stépán: Updated semi-discretization method for periodic delay-differential equations with discrete delay, International Journal for Numerical Methods in Engineering, Vol. 61 (2004) No. 1, p. 117-141.

[33] Q.H. Song, X. Ai, W.X. Tang: Prediction of simultaneous dynamic stability limit of time-variable parameters system in thin-walled workpiece high-speed milling processes, International Journal of Advanced Manufacturing Technology, Vol. 55 (2011) No. 9/10/11/12, p. 883-889.

[34] Y. Liu, P.F. Li, K. Liu, et al.: Micro milling of copper thin wall structure, International Journal of Advanced Manufacturing Technology, Vol. 90 (2016) No. 1/2/3/4, p. 405-412.

[35] D.L. Zariatin, G. Kiswanto, T.J. Ko: Investigation of the micro-milling process of thin-wall features of aluminum alloy 1100, International Journal of Advanced Manufacturing Technology, Vol. 93 (2017) No. 5/6/7/8, p. 2625-2637.

[36] C.J. Kim, M. Bono, J. Ni: Experimental analysis of chip formation in micro-milling, Technical Paper - Society of Manufacturing Engineers, No. MR02-159 (2002), p. 1-8.

[37] M.P. Vogler, R.E. Devor, S.G. Kapoor: On the modeling and analysis of machining performance in micro-end milling. Part I: Surface generation, Journal of Manufacturing Science and Engineering, Transactions of the ASME, Vol. 126 (2004) No. 4, p. 685-694.

[38] C.R. Friedrich: Micromechanical machining of high aspect ratio prototypes, Microsystem Technologies, Vol. 8 (2002) No. 4/5, p. 343-347.

[39] K. Popov, S. Dimov, D.T. Pham, et al.: Micromilling strategies for machining thin features, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 220 (2006) No. 11, p. 1677-1684.