# CUTTING TOOL DESIGN FOR MILLING OF THIN-WALLED INCONEL 718 COMPONENTS MADE BY WAAM

**MAREK VOZAR[1], FRANTISEK JURINA[1], TOMAS VOPAT[1]**

[1]Institute of Production Technologies, Faculty of Materials
Science and Technology in Trnava, Slovak University of
Technology in Bratislava, Bratislava, Slovakia

**DOI: 10.17973/MMSJ.2024_06_2024033**

**marek.vozar@stuba.sk**

The paper deals with the issue of chatter reduction by modification of both the cutting tool geometry and the machining strategy. Tool wear, cutting forces, surface roughness, and flatness of milled thin-walled parts produced by WAAM (Wire and Arc Additive Manufacturing) technology are evaluated. The machining strategy and parameters of the cutting tool macrogeometry were designed on the basis of experimental machining. Due to the combination of custom geometry of the cutting tool and adapted machining strategy, it is possible to significantly reduce chatter during milling and thereby reduce the roughness of the machined surface, as well as improve machining precision. The experimental results contribute to the effort to expand the knowledge in the field of machining thin-walled parts.

**KEYWORDS**

milling, thin-walled parts, tool geometry, surface roughness

## 1 INTRODUCTION

Milling thin-walled components in general poses several technical challenges due to the susceptibility to chatter initiation resulting in vibrations during machining [Du & Long 2022, Munoa et al. 2016]. Chatter not only negatively influences machined surface quality [Abebe & Gopal 2023] but can also affect dimensional accuracy [van Dijk et al. 2011, Wang & Si 2018], making it imperative to develop effective strategies for chatter reduction. The experiment described in this article investigates the crucial issue of chatter reduction through a combined approach involving the optimization of cutting tool geometry and machining strategy. Specifically focusing on parts manufactured via Wire and Arc Additive Manufacturing (WAAM) technology, the study evaluates the surface roughness and flatness of milled thin-walled components. Applying the initial results gained from experimental machining, as well as literature study [Zawada-Michałovska 2020, Yu et al. 2022] the paper proposes tailored machining strategy and cutting tool geometries aimed at mitigating chatter and enhancing machining precision of thin-walled parts. The experimental findings presented herein aim to contribute to advancing the understanding of machining thin-walled components, thereby facilitating the development of more efficient and reliable manufacturing processes.

Milling thin-walled parts made from nickel alloys presents a distinctive set of challenges owing to the material's inherent properties and the structural complexities associated with thin-walled geometries [Zhang et al. 2018, Zhang et al. 2020]. Nickel alloys, such as Inconel 718, are known for their exceptional strength, high-temperature resistance, and corrosion resistance, making them indispensable in aerospace, automotive, and other high-performance industries [Jia & Gu 2014, Deffley 2012]. However, these alloys are notoriously difficult to machine due to their high strength, low thermal conductivity, and tendency to work harden during cutting [Shishkovsky et al. 2015].

When it comes to high feed milling of thin-walled components, these challenges are further compounded by the risk of vibration-induced chatter during milling operations [Mane et al. 2008]. Chatter can arise from various sources, including tool deflection, inadequate damping, and insufficient rigidity of the workpiece setup [Altinas & Weck 2004, Alberteli et al. 2019]. In the case of nickel alloy thin-walled parts, the balance between material removal and structural integrity must be carefully managed to prevent distortion, deformation, or even catastrophic failure [Gao et al. 2016, Li et al. 2024].

Furthermore, the machining process must contend with the inherent variability in the material properties of nickel alloys, which can lead to unpredictable tool wear, surface finish inconsistencies, and dimensional inaccuracies [Akhtar et al. 2018, Jia et al. 2021]. Achieving the desired surface quality and dimensional precision while minimizing the risk of chatter requires a holistic approach that encompasses not only cutting tool selection and geometry but also machining parameters, toolpath optimization, and workpiece fixturing strategies [Li & Zhu 2019, Makhesana & Patel 2018].

In this context, research and development efforts aimed at refining milling techniques for nickel alloy thin-walled parts are essential for enhancing manufacturing efficiency, reducing production costs, and ensuring the reliability and performance of finished components. By addressing the unique challenges posed by these materials and geometries, advancements in milling technology can bring about new opportunities for innovation and competitiveness across a range of industries.

Therefore, the purpose of the experiment described herein was to test a novel cutting tool geometry for HFM (high feed machining) of thin-walled parts. Due to modified tool geometry, it allows for combined roughing and finishing operation, reducing machining time even further. General parameters of the microgeometry of the tool were designed during preliminary experiments and the parameter of helix angle was tested in the last stage of the experiments as described in the article.

A characteristic feature of the cutting part of the tool is that the largest material removal occurs at the helical flutes. The concept of the designed tools is that the cutting edge on the cylindrical part of the tool should serve to finish the surface and ensure low roughness of the machined surface. Together with the gradual removal of material along the spiral, it is possible to obtain higher geometric accuracy. In this machining method, the material is removed in comparatively small axial depths combined with large radial depths of cut. The smallest tool wear occurs on the flanks of the helical flutes, because this part of the tool is only responsible for finishing the machined surface. By gradually ramping the tool along the spiral path, the cutting edge on the cylindrical part of the tool is getting consistently introduced into the cutting zone. When a sufficient depth is reached, the material is removed at the tool face and the surface on the sidewall is finished at the same time. Fig. 1 shows the formation of theoretical roughness when using a classic HFM tool and a designed tool. In the first case, theoretical roughness arises depending on the size of the transition radius and, of course, on the cutting conditions. In the second case, a cutting part is used on the cylindrical part of the tool to finish the surface.

Objective of the experiment described in the article was achieving acceptable machined surface integrity and sufficient part accuracy by chatter reduction or elimination through adjusting tool geometry and milling strategy. A custom tool geometry was designed after the commercially available tools suffered repeated critical failure before managing to machine a single workpiece sample, which is also the reason for not including them for a comparative analysis. Focus on WAAM technology is due to the unique challenges when it comes to machining as a result of relatively low accuracy and the material being severely heat affected as a part of the manufacturing process, increasing the hardness of the surface layer.

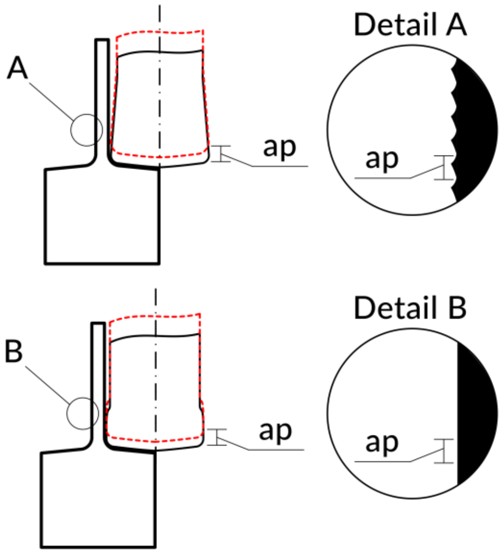

**Figure 1.** Comparison of theoretical surface roughness for the HFM tool (A) and designed tool (B)

## 2 MATERIALS AND METHODS

For the purposes of the experiment, a nickel-based material, commonly known as Inconel 718, was used as a workpiece material. This superalloy belongs to the category of difficult-to-cut materials due to its chemical composition and mechanical properties. The alloy has high strength, thermal and cryogenic resistance, and corrosion resistance. The workpiece samples were made by WAAM technology, resulting in different dimensions of each sample. General dimensions of the workpiece and resulting machined part can be seen in Fig. 2.

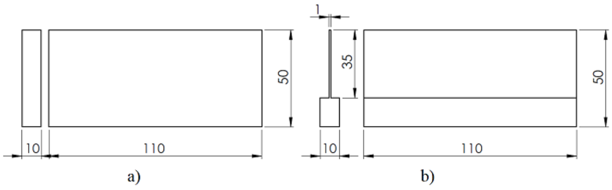

**Figure 2.** Dimensions of the workpiece in millimetres
a) before machining b) after machining

Workpiece samples were machined after the manufacturing process with no heat treatment involved. Measured mechanical properties of the workpiece samples are listed in Tab. 3.

| Offset Yield *Rp0,2* [MPa] | Tensile Strength *Rm* [MPa] | Elongation *A* [%] | Vickers Hardness *HV 0,1* |
|---|---|---|---|
| 465.33 | 821.33 | 35.17 | 821.33 |

**Table 1.** Mechanical properties of sample material

Sintered carbide CTS24Z from Ceratizit Group was used for the production of custom cutting tools. The blank for the production of cutting tools had dimensions of 10 x 6 x 73 mm. The material is used to manufacture high-performance cutting tools for machining difficult-to-machine tools. Tab. 5 shows the basic properties of the cutting tool material.

| PCG Grade | ISO Group | Co Volume | Hardness HRA | Density |
|---|---|---|---|---|
| F10 | K20-K40 | 12% | 91,7 | 14,1 kg.m$^{-3}$ |

**Table 2**. Cutting tool material properties

The mills were manufactured by grinding on a tool grinder Reinecker WZS 60, with the tool geometry designed in software NumrotoPlus. The initial tool geometry was loosely based on commercially available HFM tools, however it was modified specifically for the purpose of milling thin-walled parts. Model of the cutting tool along with basic description of the geometry features can be seen in Fig. 3.

After the grinding process, the tools were measured on a tool measuring device Zoller Genius 3s in order to verify the parameters of macrogeometry and compare the differences between the tools. Since the parameters of the cutting tools were custom made, the toolpaths used for machining with these tools had to be modified as well to fully utilize the capabilities of the tools. Due to the geometry derived from high feed milling tools and long overhang, it was necessary to maintain low axial depth of cut. Low axial depth of cut in combination with the tool geometry ensures optimal direction of cutting forces into the machine spindle as well as minimizes the initiation of chatter during the machining process.

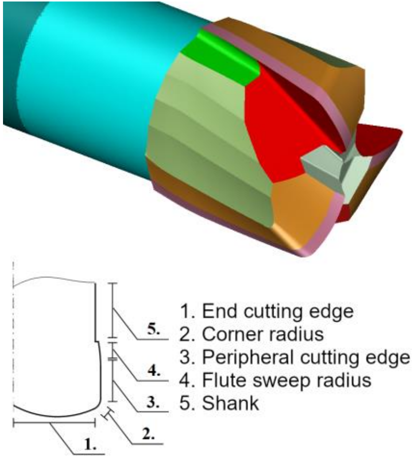

**Figure 3**. Cutting tool geometry

Due to the low thermal conductivity of Inconel 718 material, it is important to ensure sufficient cooling during the machining process to prevent the formation of a hardened subsurface layer on the machined surface. Water-based coolant Blaser EcoCut MD25 with concentration of 5%, was used during the experiments. Cutting fluid was brought into the cutting zone by standard nozzles directed at the cutting part of the tool with the pressure of 1,5 bar.

The measurement of the cutting force components was performed after the tool wear measurement so that the measured values correspond to the current wear value. After the dimensions of the part were reached, the use of the tool was stopped. Fig. 4 shows the clamping of the part on the dynamometer using the designed fixture. Low-profile clamps were used to fix the position and clamp the workpiece. A Kistler 5070A dynamometer working on the principle of piezoelectric phenomenon was used to monitor the cutting forces during machining. It also served as an indirect means of chatter measurement. Machining tests were carried out on a DMG DMU 85 machine tool with the dynamometer clamped to the worktable.

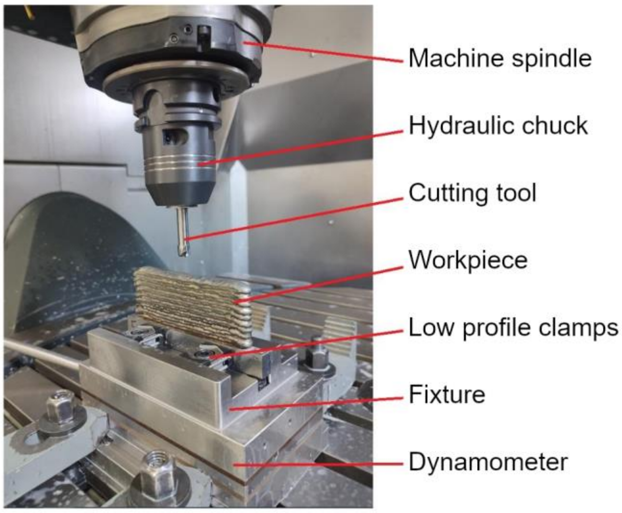

**Figure 4.** Machining setup

Cutting parameters for the experiments were tested and adjusted based on the preliminary cutting tests, and the final values are listed in Tab. 2. Variable radial depth of cut is what makes machining of additively manufactured parts made by WAAM challenging.

| Parameter | Label | Value | Unit |
|---|---|---|---|
| Axial depth of cut | *ap* | 0,4 | mm |
| Radial depth of cut | *ae* | ≈4,5 | mm |
| Cutting speed | $v_c$ | 38 | m.min$^{-1}$ |
| Feed per flute | $f_z$ | 0,16 | mm |
| Feed rate | $f$ | 590 | mm.min$^{-1}$ |
| Revolutions | $n$ | 1190 | min$^{-1}$ |

**Table 3.** Cutting parameters

For the measurement of tool wear an optical digital microscope Dino-Lite was used with 110x magnification. Parameter of width of the flank wear (VB) was measured on each flute individually and the values were averaged afterwards.

Roughness of the machined surface was measured by Mitutoyo SJ-210 roughness tester. Parameters of the surface roughness were measured on multiple levels on the machined parts in order to better determine the influence of chatter during the machining process on the surface quality of the parts.

Dimensional accuracy was measured by an optical 3D scanner ATOS Triple Scan II, by which the entire surface of the machined parts was digitized and evaluated. The most important parameter of this measurement was the flatness of the machined part.

## 3 RESULTS

During the machining operation multiple observed aspects were measured and recorded periodically.

### 3.1 Tool wear

Development of flank wear was tracked and evaluated to better understand the influence of helix angle on the machining process. Values of average flank wear VB were tracked on three different locations along the cutting edge of the tool – on the end flutes, peripheral flutes and on the corner radius. Development of tool wear differed slightly depending on the measured location.

Based on the observed flank wear width on the end flutes of the tool, as displayed in the Fig. 5, the cutting tool with a helix angle of 18 degrees performed the best, reaching the lowest flank wear width value. A larger helix angle typically allows for more efficient chip evacuation and reduces the tendency for built-up edge formation. This can result in less tool wear and improved tool life compared to tools with smaller helix angles. Additionally, a larger helix angle may provide better cutting performance and surface finish, especially when machining difficult-to-cut materials or performing high-speed machining operations.

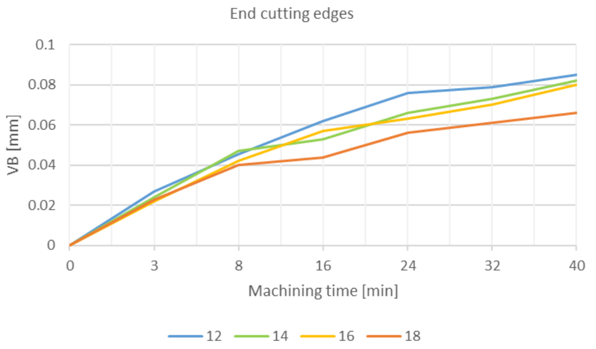

**Figure 5.** Flank wear on the end cutting edges

Similar results of tool wear were observed on the peripheral cutting edges as well, as can be seen in Fig. 6. The tool with helix angle of 18 degrees has maintained the lowest flank wear value throughout the machining process.

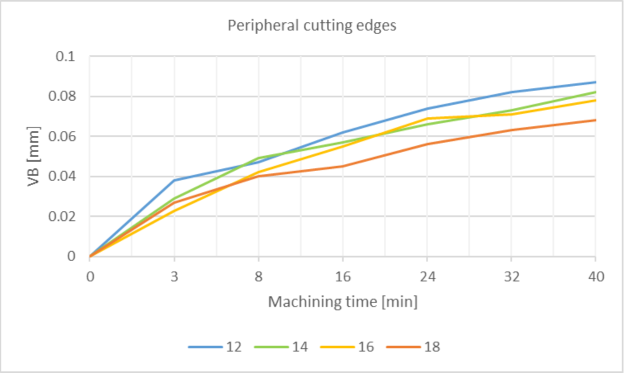

**Figure 6**. Flank wear on the peripheral cutting edges

While the tool with helix angle of 18 degrees exhibited the least wear on both the end and peripheral cutting edges, when comparing the flank wear of the tools on the corner radius, the results were different. This is displayed in Fig. 7. The lowest value of flank wear by the end of the machining process in this location was observed for the tool with the helix angle of 12 degrees, followed by the 18-degree tool.

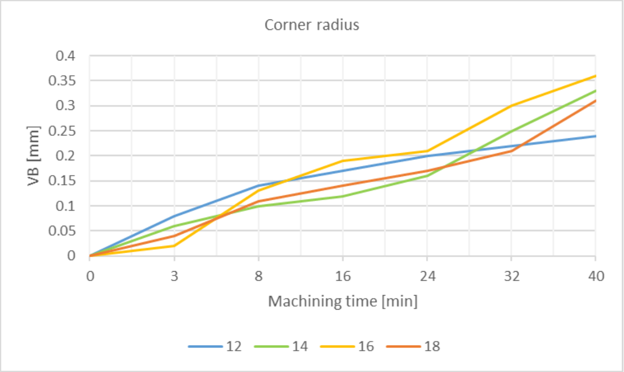

**Figure 7**. Flank wear on the corner radius

### 3.2 Cutting forces

Alongside the tool wear, two components of the cutting forces were observed during the machining process.

The cutting tool with a helix angle of 18 degrees performed the best based on the measured cutting force values plotted in Fig. 8. A larger helix angle results in improved chip evacuation and reduced cutting forces due to better chip flow and reduction of friction on the contact of the tool with the workpiece. Consequently, for the tool with a helix angle of 18 degrees were measured the lowest cutting forces, indicating more efficient cutting performance and potentially lower tool wear. This suggests that the tool with the 18-degree helix angle is better suited for the HFM operation, enhancing process stability and consequently longer tool life, which aligns with the measured values of average flank wear.

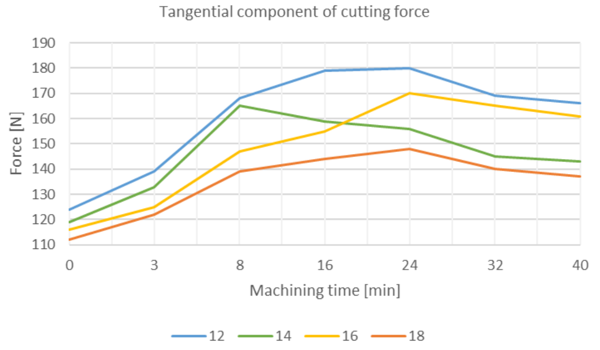

**Figure 8.** Tangential component of cutting forces

Among the four cutting tools evaluated, the tool featuring an 18-degree helix angle has shown again an improved performance in terms of the maximum cutting force component observed in the feed direction, as shown in Fig. 9. The reduced cutting force associated with the 18-degree helix angle suggests smoother chip evacuation and less resistance during cutting operations. This indicates that the tool offers enhanced machining efficiency and lower susceptibility to chatter initiation.

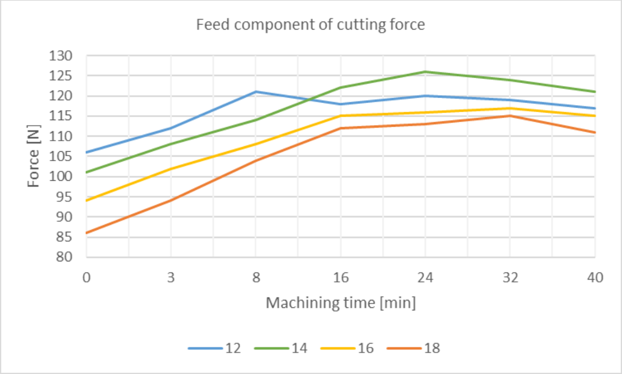

**Figure 9**. Feed component of cutting forces

## 3.3 Machined surface roughness

After machining, the parameters of surface roughness Ra and Rz were measured across lay. Repeated measurements were performed on multiple height levels of the machined surface, measured from the top of the samples. It can be observed from Fig. 10 that the roughness parameter Ra of the part's machined surface was almost uniform along the height of the sample, however it started to rise at the lowest measured level. This is most likely caused by a combination of increased tool wear and deflection of the tool from the part.

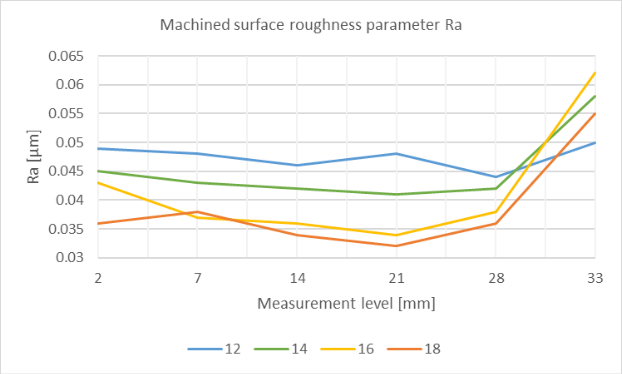

**Figure 10.** Parameter Ra of the machined surface roughness

Measurement of the Rz parameter of machined surface roughness shows similar development as the Ra parameter, keeping constant character and beginning to rise at the lowest measurement level as can be seen in Fig. 11.

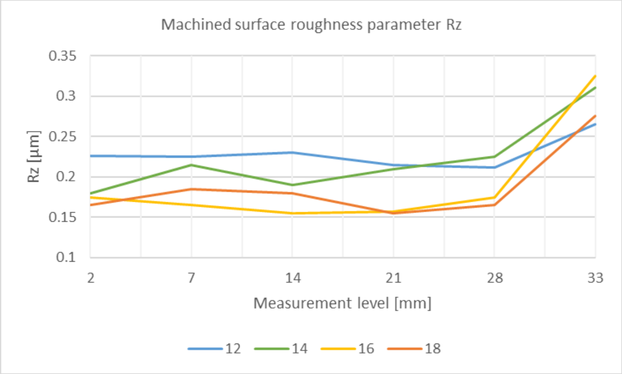

**Figure 11.** Parameter Rz of the machined surface roughness

## 3.4 Accuracy

Additional characteristic of the machined samples was their accuracy of shape with a focus on the flatness. Avoiding deformation of machined thin-walled parts is one of the issues that often arise, therefore the design of the tool needed to be verified from this standpoint as well. Obtained values of flatness of the samples machined by each tool are listed in the Fig. 12. It can be seen that the best flatness which corresponds with the lowest deformation of the sample was achieved by the tool with helix angle of 12 degrees. Flatness of the part that was machined by the cutting tool with the helix angle of 18 degrees was the worst out of the compared tools.

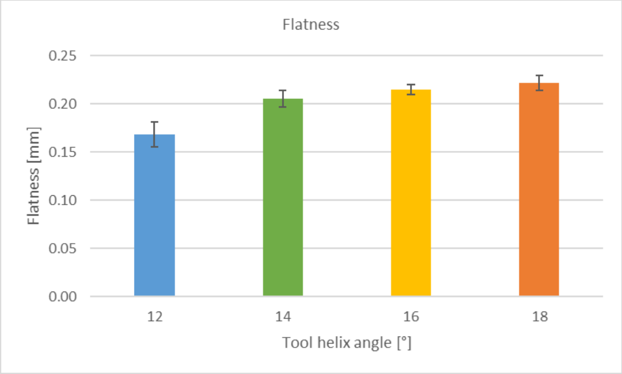

**Figure 12.** Measured values of flatness

In addition to the evaluation of the flatness, colour map of deviations was created in order to investigate where the highest deviations were occurring. As can be seen from Fig. 13, most of the inaccuracies were observed in the corners of the samples. This could potentially be attributed to the angle of tool approach before the engagement.

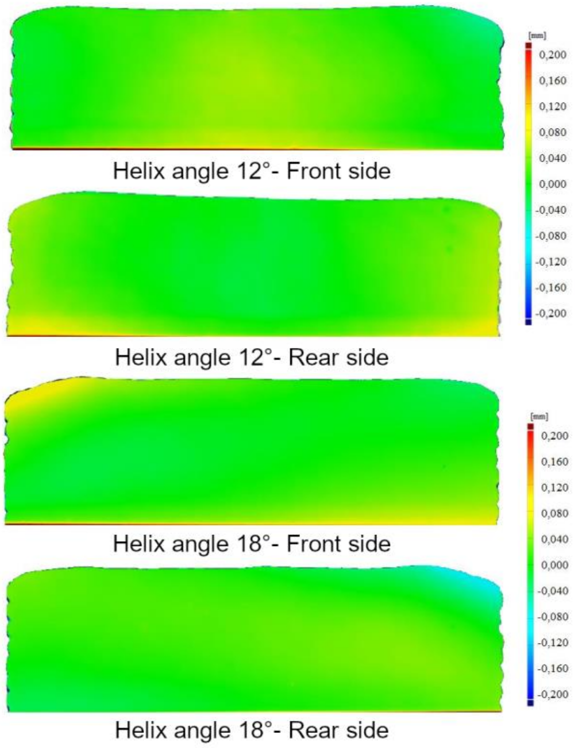

**Figure 13.** Machined surface and colour map of deviations

## 4 DISCUSSION

The presented experimental results provide insights into the influence of helix angle on various aspects of the machining process of thin walled parts made by WAAM technology from difficult-to-machine nickel alloy Inconel 718.

The findings with regard to the tool wear indicate that the tool with a helix angle of 18 degrees reached the lowest overall flank wear width compared to other tested tools, suggesting improved chip evacuation and reduced built-up edge formation. This is consistent with the findings by other authors that larger helix angles facilitate smoother chip flow and lower friction, leading to slower development of tool wear and an extension of tool life [Bolar & Joshi 2020, Plodzien et al. 2020]. However, when comparing the tools based on the average flank wear width on the corner radius, the tool with the helix angle of 18 degrees did not perform the best, the tool with the helix angle of 12 degrees reached the lowest value of flank wear instead. This part of the cutting edge is engaged both in the radial and axial directions of the cut, which may result in the increased wear and reduced process stability.

Corroborative results of the tool wear development were obtained from the measurement of the cutting forces. The cutting tool with a helix angle of 18 degrees also demonstrated the lowest maximum tangential cutting forces. This can be attributed to more even engagement of the tool flutes and reduced friction associated with larger helix angles, resulting in more efficient cutting performance and potentially lower tool wear. Similar findings were observed by other authors [Plodzien et al. 2020, Zhang et al. 2020] The reduced cutting forces contribute to enhanced machining stability and reduced chatter initiation, which is important for both high-feed machining operations and milling of thin-walled components.

In addition to the investigation of the tool performance, an analysis of the machined surface roughness of the samples revealed that the tool with the highest helix angle of 18 degrees achieved the lowest average roughness parameters for both Ra and Rz. These results are in line with findings by other authors [Liu et al. 2023, Cepova et al. 2023]. The uniformity of surface roughness along the height of the sample indicates consistent machining performance, although an increase in roughness was observed at the lowest measurement level, likely due to tool wear and deflection.

Another investigated characteristic of the machined samples was geometrical accuracy. Evaluation of flatness showed that the tool with a helix angle of 12 degrees achieved the best flatness, indicating minimal deformation of the machined samples. This conclusion is only partially supported by the results of experiments performed by other researchers [Agarwal & Desai 2020, Zawada-Michałowska, 2021]. The tool with the helix angle of 18 degrees that performed the best for all other measured characteristics performed the worst when it comes to the value of flatness of the machined sample. However, it's important to note that flatness is influenced by various other factors than the tool geometry, including machine rigidity, cutting parameters, workpiece material properties and for thin-walled components also heat generation. Therefore, while the helix pitch angle can indirectly influence flatness, it is just one of many factors that must be considered in achieving dimensional accuracy and surface quality in machining processes. This is particularly important for thin-walled components, where maintaining dimensional and geometrical accuracy as well as shape integrity is essential. The colour map of deviations further highlighted areas of inaccuracies, particularly in the upper corners of the samples, suggesting potential areas for improvement of the tool engagement during the machining process. Further investigation into the influence of toolpath generation for machining of thin walled parts by tools with custom geometry should be carried out to clarify the results concerning machining accuracy.

In summary, the obtained results from the performed experiments show the influence of helix angle on the machining process, highlighting the importance of tool geometry parameters selection to improve machining performance and achieve desired outcomes in terms of tool wear, cutting forces, surface roughness, and accuracy. Further research could explore the influence of other machining and tool geometry parameters on the performance of helical cutting tools in machining thin-walled components manufactured from difficult-to-cut materials.

## 5 CONCLUSIONS

The positive influence on the machining process was confirmed by the use of a tool with a modified macrogeometry shape of the main cutting edge. The aim was to evaluate the suitability of the proposed geometry for the machining of thin-walled parts made from a difficult-to-machine material.

The secondary objective of the research was to design tools with modified geometry for the accurate machining thin-walled parts. The influence of increasing helix angle on the reduction of cutting forces was confirmed. The pitch angle of the helix also had an effect on the achieved tool wear. As the pitch angle of the helix increased, slower development of the flank wear was observed on both the end and peripheral cutting edges of the tool. However, this does not apply to the wear in the transition radius of the cutting tool, where there was observed faster tool wear development was observed. In this case, the opposite character was observed depending on the pitch angle of the helix. The positive effect of increasing the pitch angle of the helix was also observed for the monitored roughness parameters Ra and Rz. The tool with a helix pitch angle of 18 degrees showed the smallest measured values of surface roughness parameters. The measured values of the flatness of the machined surface worsened with increasing helix pitch angle, in contrast to the roughness of the surface. By using a tool with a helix angle of 12 degrees, the best value of the flatness of the workpiece was achieved. The results of the experiment show that by adjusting the shape of the macrogeometry of the main cutting edge of the tool, an improvement in the precision and quality of the machined surface was achieved. In order to further improve the achieved machined surface roughness, use of special tool holder with fluid intake around the entire diameter of the tool with the pressure of 40 bar is planned for future experiments. Authors anticipate decrease of surface roughness by utilizing this approach. Moreover, it is possible that the specific tool design is applicable mainly for machining parts made by WAAM technology, its application being limited for other additive manufacturing technologies such as PBF (Powder Bed Fusion) or DED (Directed Energy Deposition) because the presence of metal powder would most likely negatively affect the tool's performance.

## ACKNOWLEDGMENTS

This work was supported by the Slovak Research and Development Agency of the Slovak Republic under Contract no. APVV-21-0071 and VEGA grant agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences, no. 1/0266/23.

"Development of new progressive cutting tools for machining parts produced by WAAM additive manufacturing technology to reduce the number of cutting tools when machining parts from different types of materials" (ITMS2014+: 313011BWQ8).

## REFERENCES

[Abebe & Gopal 2023] Abebe, R., & Gopal, M. Exploring the effects of vibration on surface roughness during CNC face milling on aluminum 6061-T6 using sound chatter. Materials Today: Proceedings, 2023, 90: 43-49.

[Agarwal & Desai 2020] Agarwal, A., & Desai, K. A. Predictive framework for cutting force induced cylindricity error estimation in end milling of thin-walled components. Precision Engineering, 2020, 66: 209-219.

[Akhtar et al. 2018] Akhtar, W., Sun, J., Sun, P., Chen, W., & Saleem, Z. Tool wear mechanisms in the machining of Nickel based super-alloys: A review. Frontiers of Mechanical Engineering, 2014, 9: 106-119.

[Alberteli et al. 2019] Albertelli, P., Braghieri, L., Torta, M., & Monno, M. Development of a generalized chatter detection methodology for variable speed machining. Mechanical Systems and Signal Processing, 2019, 123: 26-42.

[Altinas & Weck 2004] Altintas, Y., Weck, M. Chatter stability of metal cutting and grinding. CIRP annals, 2004, 53.2: 619-642.

[Bolar & Joshi 2020] Bolar, G., & Joshi, S. N. Investigations into the influence of tool helix angle during end milling of open straight and curved thin-wall parts. International Journal of Machining and Machinability of Materials, 2020, 22.3-4: 212-232.

[Cepova et al. 2023] Cepova, L., Cep, R., Chalko, L., Dvorackova, S., Trochta, M., Rucki, M., ... & Chyshkala, V. The Effect of Cutting Tool Geometry on Surface Integrity: A Case Study of CBN Tools and the Inner Surface of Bearing Rings. Applied Sciences, 2023, 13.6: 3543.

[Deffley 2012] Deffley, R. J. Development of processing strategies for the additive layer manufacture of aerospace components in Inconel 718. 2012. PhD Thesis. University of Sheffield.

[Du & Long 2022] Du, J., & Long, X Chatter suppression for milling of thin-walled workpieces based on active modal control. Journal of Manufacturing Processes, 2022, 84: 1042-1053.

[van Dijk et al. 2011] van Dijk, N. J., van de Wouw, N., Doppenberg, E. J., Oosterling, H. A., & Nijmeijer, H. Robust active chatter control in the high-speed milling process. IEEE Transactions on Control Systems Technology, 2011, 20.4: 901-917.

[Gao et al. 2016] Gao, Y. Y., Ma, J. W., Jia, Z. Y., Wang, F. J., Si, L. K., & Song, D. N. Tool path planning and machining deformation compensation in high-speed milling for difficult-to-machine material thin-walled parts with curved surface. The International Journal of Advanced Manufacturing Technology, 2016, 84: 1757-1767.

[Jia et al. 2021] Jia, Z., Lu, X., Gu, H., Ruan, F., & Liang, S. Y. Deflection prediction of micro-milling Inconel 718 thin-walled parts. Journal of Materials Processing Technology, 2021, 291: 117003.

[Jia & Gu 2021] Jia, Q., & Gu, D. Selective laser melting additive manufacturing of Inconel 718 superalloy parts: Densification, microstructure and properties. Journal of Alloys and Compounds, 2014, 585: 713-721.

[Li et al. 2024] Li, Z., Zeng, Z., Yang, Y., Ouyang, Z., Ding, P., Sun, J., & Zhu, S. Research progress in machining technology of aerospace thin-walled components. Journal of Manufacturing Processes, 2024, 119: 463-482.

[Li & Zhu 2019] Li, Z. L., & Zhu, L. M. Compensation of deformation errors in five-axis flank milling of thin-walled parts via tool path optimization. Precision Engineering, 2019, 55: 77-87.

[Liu et al. 2023] Liu, Y., Geng, D., Zhang, D., Zhai, Y., Liu, L., Sun, Z., ... & Jiang, X. Cutting performance and surface integrity for rotary ultrasonic elliptical milling of Inconel 718 with the ball end milling cutter. Journal of Materials Processing Technology, 2023, 319: 118094.

[Makhesana & Patel 2018] Makhesana, M. A., & Patel, K. M Optimization of parameters and sustainability assessment under minimum quantity solid lubrication-assisted machining of Inconel 718. Process Integration and Optimization for Sustainability, 2021, 5.3: 625-644.

[Mane et al. 2008] Mane, I., Gagnol, V., Bouzgarrou, B. C., & Ray, P. Stability-based spindle speed control during flexible workpiece high-speed milling. International Journal of Machine Tools and Manufacture, 2008, 48.2: 184-194.

[Munoa et al. 2016] Munoa, J., Beudaert, X., Dombovari, Z., Altintas, Y., Budak, E., Brecher, C., & Stepan, G. Chatter suppression techniques in metal cutting. CIRP annals, 2016, 65.2: 785-808.

[Shishkovsky et al. 2015] Shishkovsky, I. V., Nazarov, A. P., Kotoban, D. V., & Kakovkina, N. G. Comparison of additive technologies for gradient aerospace part fabrication from nickel-based superalloys. InTech Publ, 2015.

[Wang & Si 2018] Wang, L., & Si, H. Machining deformation prediction of thin-walled workpieces in five-axis flank milling. The International Journal of Advanced Manufacturing Technology, 2018, 97.9: 4179-4193.

[Zawada-Michałovska 2020] Zawada-Michałowska, Magdalena, Kuczmaszewski, J., Legutko, S., & Pieśko, P. Techniques for Thin-Walled Element Milling with Respect to Minimising Post-Machining Deformations. Materials, 2020, 13.21: 4723.

[Zawada-Michałowska 2021] Zawada-Michałowska, M., Pieśko, P., Józwik, J., Legutko, S., & Kukiełka, L. A Comparison of the Geometrical Accuracy of Thin-Walled Elements Made of Different Aluminum Alloys. Materials, 2021, 14.23: 7242.

[Zhang et al. 2018] Zhang, Xin, Ma, J. W., Jia, Z. Y., & Song, D. N. Machining parameter optimisation for aviation aluminium-alloy thin-walled parts in high-speed milling. International Journal of Machining and Machinability of Materials, 2018, 20.2: 180-192.

[Zhang et al. 2020] Zhang, Z., Zhang, Z., Zhang, D., & Luo, M. Milling distortion prediction for thin-walled component based on the average MIRS in specimen machining. The International Journal of Advanced Manufacturing Technology, 2020, 111: 3379-3392.

[Zhang et al. 2020] Zhang, X., Yang, L., Zhao, Z., & Yin, J. Research on the excitation characteristics of milling force for a general helix cutter. The International Journal of Advanced Manufacturing Technology, 2022, 1-16.

[Yu et al. 2022] Yu, H., Zhong, H., Chen, Y., Lin, L., Shi, J., Yue, T., & Shen, Y. Experimental study on cutting factors of multi-layer machining for large aerospace thin-walled structural parts. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 2022, 236.2: 321-332.

**CONTACTS:**

Ing. Marek Vozar, PhD.
Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Institute of Production Technologies
Jana Bottu 25, 91724 Trnava, Slovakia
+421948038796, marek.vozar@stuba.sk