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MODELLING AND CUTTING PARAMETER OPTIMISATION OF THE INCONEL 718 MICROMILLING PROCESS

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Abstract: Micromachining is taking an increasing area in the mechanical engineering and production technologies. Understanding the workpiece material mechanical removal process during micromilling is one of the main tasks on the way to successful optimization and control of the cutting process. In this paper, the micromilling process of the superalloy Inconel 718 is analysed. This superalloy has low machinability, due to its special mechanical and chemical properties. In the framework of the experimental research, the depth of cut and feed per tooth were varied on tree level, while the milling width and cutting speed were kept at the constant level. Based on the experimental data, a significant influence of the depth of cut and feed per tooth on the cutting forces, and the feed per tooth on the roughness of the machined surface was observed. Using logarithmic transformation and the least squares method, exponential models with sufficient response accuracy were developed. Using the models, the input cutting process parameters were optimized using the classical gradient method. Optimization resulted in parameters that ensure maximizing the quality of the machined surface and minimizing dimensional errors.

Keywords: micromilling, super-alloy, roughness, accuracy, analysis, modelling.

1. INTRODUCTION

Microcomponents, i.e. parts with at least two perpendicular dimensions below 1 mm, are occupying an increasingly significant area of the global industrial market [1]. The use of special materials for microcomponents manufacturing, such are heat-treated steels, superalloys,

aluminium alloys, composites, etc., contributes to enhanced reliability and functionality under extremal exploitation conditions. On the other hand, mentioned materials are characterized by difficulties in machining. The high efficiency and success of the machining process depend on the workpiece material properties largely. These market trends are

accompanied by increasingly strictly demands for development of new, and improvement of existing micromachining methods and processes.

The micromilling process enables rough, semi-finish, and finish machining of metallic microcomponents. Due to the complex kinematics of relative movements, it allows for relatively more flexible process, and more productive manufacturing of microparts with complex geometries. Compared to other production methods, micromilling provides relative high machined surface quality, high dimensional accuracy, avoidance of thermal effects on the part surface layers which are typical for non-conventional methods, and etc.

The mechanism of mechanical workpiece material removal process, and consequently, the dependence of cutting process output parameters differs between machining on macro and micro level significantly. In microcutting process, a phenomenon known as the size effect occurs (Figure 1).

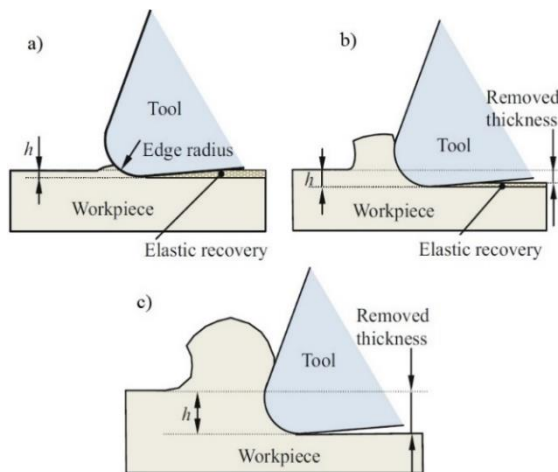


Figure 1. Size effect [2]

This effect refers to the disproportion between the technological cutting process parameters and the cutting tool geometrical parameters, as well as the workpiece material crystal structure. As a result of the size effect, the workpiece

material ploughing phenomenon becomes increasingly significant during machining, and cannot be neglected.

In accordance with the above, it can be concluded that the special alloys micromilling process efficiency depends on the synergistic interaction between cutting process parameters, cutting tool properties, and machining conditions [3, 4]. The analysis of performance and the characterization of micromilling process behaviour indicators is one of the key factors in achieving maximum machining efficiency. At the microscale, the influence of indicators, such as surface roughness and dimensional accuracy on the functionality of microcomponents becomes even more pronounced. The key performance indicators of the machining process include factors connected to machined surface quality, part dimension accuracy, process productivity and economy, ecology, and similar factors.

Numerous scientific studies have focused on the analysis, modelling, and optimization of the special alloys micromilling process, with the aim of establishing a foundation for production process control, and achieving the required part properties. These studies have examined the influence of machining parameters, cutting tool properties, and cooling strategies on the machining process indicators that define the microcomponent quality and accuracy, as well as on the productivity, cost-efficiency, and environmental sustainability of the cutting process. In [5], the micromilling of Inconel 718 alloy was analysed. A dynamic analysis was performed, and a part deformation model based on cutting forces was established. Authors developed surface roughness model connected to tool deformation. In [6], experimental analysis and modelling of deformation in thin-walled microcomponents was conducted. Appropriate wall deflection models were

developed using the so-called birth/death technique. Lu et al. [7] employed a Taguchi experimental design to modelling the effect of cutting process parameters on surface roughness and material removal rate. The developed first-order models served as the basis for genetic algorithm optimization. The study identified depth of cut as the most influential factor affecting surface roughness. In [8], the influence of cutting process parameters and various tool coatings on the surface topography of Inconel 718 was investigated. Similar to the previous study, a significant impact of both depth of cut and cutting speed was observed. In addition to cutting process parameters, also considered the initial surface condition of the workpiece in [9]. Among other findings, the study revealed that the initial surface condition significantly affects the final surface roughness. The results also indicated that high tool loading leads to poorer surface quality and increased tool wear. In [10], the influence of process and tool parameters on the geometry of the dead metal zone and cutting forces was examined. The authors developed mechanistic models, which were then integrated into a finite element micromilling model. The analysis showed a significant influence of feed per tooth and cutting edge radius on cutting forces. Kiswanto et al. [11] studied micromachining of Inconel 718 at low cutting speeds. They found a notable influence of both feed per tooth and cutting speed on surface roughness. A comprehensive experimental performance analysis of the micromilling process for Inconel 718 was conducted in [12]. There are highlighting the significant impact of milling parameters and cooling strategies on process performance. Liang et al. [13] analysed and optimized micromilling performance using a finite element method model to simulate chip formation,

and to conclude the output cutting parameters values.

The aim of this research is to analyse the machining quality and accuracy in the micromilling of Inconel 718. The focus is placed on the development of appropriate mathematical models that describe the influence of cutting process input parameters on dimensional accuracy and surface quality indicators. Furthermore, the goal is to use the developed models as a basis for the cutting parameters optimization. Machining time is analysed in order to provide a reference for the micromilling process productivity, and comparison with other manufacturing methods.

2. EXPERIMENTAL SETUP

For experimental setup machining centre Sodick MC430L with LN2X control was used (Figure 2). It is three axis micro-milling CNC tool machine, with high speed main spindle. In experiments was used coated two flute extra-long end micro-mill cutter, with diameter of 600 μm , and neck length of 8 mm. Its cutting edge length is 0.8 mm, helix revolution angle is 7.25°, and tool tip corner radius 0.05 mm. Cutting tool was mounted in HSK holder.

Workpiece was nickel-chromium super alloy Inconel 718, with tensile strength 1350 MPa, and hardness 40 HRc. Its chemical composition consist next chemical elements: 53% Ni, 19% Cr, 18% Fe, 5.1% Nb, 3% Mo, 1.1% Ti, 1% Co, 0.5% Al, 0.35% Si, and 0.08% C). Inconel has excellent oxidation and high temperature resistance. Regard to this, it is used for responsible mechanical parts that operates in extreme mechanical and thermal conditions.

As experimental plan full factorial plan is used [14]. Two controlled milling process input parameters, was used: depth of cut a_p (mm), and feed per tooth f_z (mm/tooth),

each on tree level. Varied values of depth of cut were: 0.01, 0.02, and 0.03 mm. Varied values of feed per tooth were: 0.008, 0.012, and 0.018 mm/tooth.



Figure 2. Experimental setup

Experimental plan was results in nine experimental combinations (runs). Cutting speed was set to constant value of $v_c = 40$ m/min (spindle speed $n = 21222$ rev/min), and milling width of 0.6 mm. Microchannel milling was used for each experimental run. Channel was 10 mm long. MQL technique was used for lubrication of cutting zone. The synthetic oil aerosol was supplied under flow ratio of $Q = 25$ ml/h, and pressure of $p = 5$ bar.

For measuring of cutting force component Kistler 9257B dynamometer was used. It was mounted on machine table, and aligned with the axis of the tool machine. Measuring axis for cutting force component F_y is directed in milling tool auxiliary movement. Cutting force signals were collected using A/D devices and *LabView* software. Measuring of surface roughness was performed on *Alicona Infinite Focus SL* device optical scanning device. It measures according to the standard ISO 4287. This device work on principle photographing of machined surface with focus variations, and image sharpened regions separating. Based on separated regions on images, algorithm

generates a three-dimensional representation of scanned surface, on micro-level resolution. Experimental and measuring data processing, statistical analysis, model development, and optimization were carried out using *Design Express 7* software.

3. RESULTS AND DISCUSSION

On Figure 3, the dependence of F_x cutting force component values on the variation of feed per tooth and depth of cut is shown. It can be observed that cutting forces component increase with the increase of both depth of cut and feed per tooth. For the smallest depth of cut value, the cutting force component exhibits an almost linear dependence on the feed per tooth. However, at higher depths of cut, a nonlinear relationship becomes evident. At lower feed per tooth values, the cutting forces component values that corresponding to minimum and medium depth of cuts are relatively close. On the other hand, at higher feed per tooth values, the cutting forces component values associated with medium and maximum depth of cuts are closer in values.

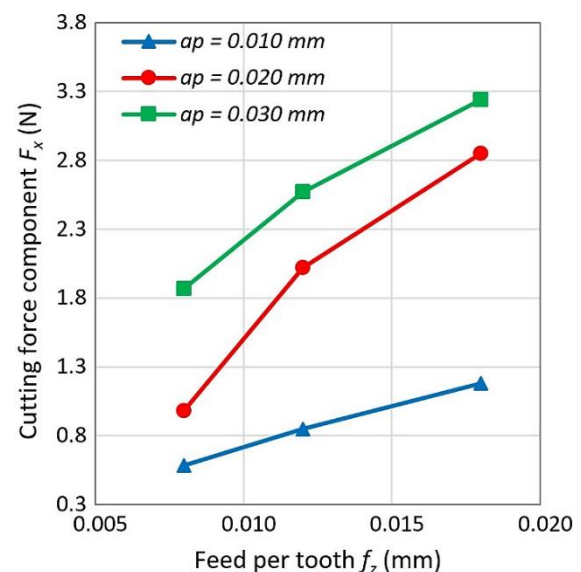


Figure 3. Cutting force component F_x

Similar conclusions can be noted for the F_y cutting force component, as cutting force component that acts along the direction of the cutting tool auxiliary movement, by examining the dependency diagram shown in Figure 4. A relative more uniform variation of the cutting force component values, with respect to changes in the depth of cut, can be observed. Similar to previous, at lower feed per tooth values, the cutting forces component values that corresponding to minimum and medium depth of cuts are relatively close. At higher feed per tooth values, the cutting forces component values have a more uniform difference.

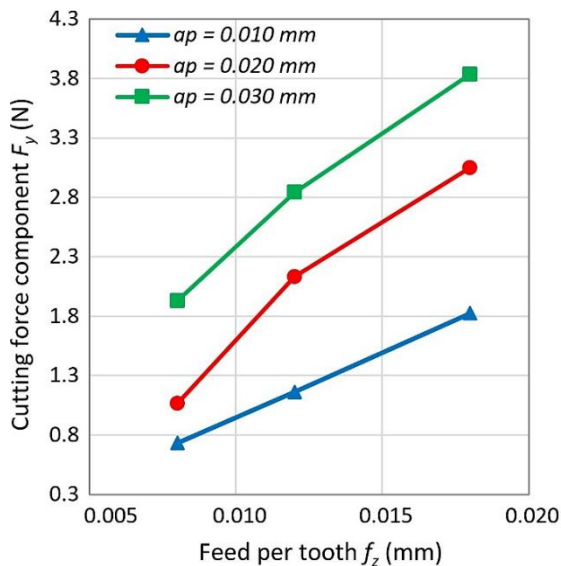


Figure 4. Cutting force component F_y

For cutting force values, it is evident that both analyzed components increase with the increase of depth of cut and feed per tooth. However, an increase in these cutting process parameters leads to a larger uncut chip cross-section area. As the uncut chip cross-section area increases, so the force required for chip mechanical separation increases. The influence of depth of cut, and especially feed per tooth cannot be considered as linear. This is consequences of mechanistic and the complex thermo-mechanical phenomena occurring in the cutting zone. During

microcutting process, not only mechanical chip separation occur, but also material deformation through the ploughing mechanism, which is primarily caused by the size effect.

The influence of depth of cut and feed per tooth on the average surface roughness height R_a is shown on the diagram in Figure 5. Analysis of the diagram reveals a significant impact of feed per tooth on mentioned output parameter. In most cases, an increase in feed per tooth results in a sudden increase in surface roughness. Changes in depth of cut do not lead to sudden variations in surface roughness. Although minimal, the effect of depth of cut varies depending on the feed per tooth value. As can be observed, at different feed levels, maximum surface roughness occurs at different depth of cut values. At the lowest feed per tooth, the maximum surface roughness is recorded at a medium depth of cut. At this point, the maximum of surface roughness parameter value deviates significantly from the values that corresponding to the other two depth of cut levels. At the medium feed per tooth, the highest surface roughness occurs at the smallest depth of cut, while at the maximum feed per tooth, it is observed at the maximum depth of cut value.

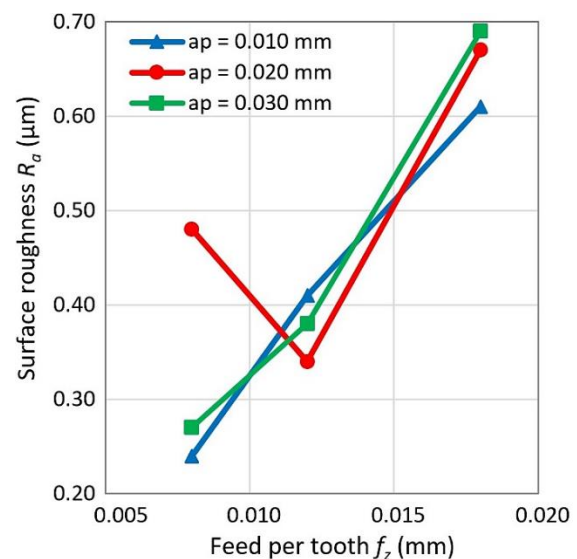


Figure 5. Surface roughness R_a

Previous concluded variations in the influence of feed per tooth and depth of cut on average surface roughness height, can be attributed to the pronounced influence of the size effect. It becomes more significant at lower uncut chip thicknesses, i.e., at lower feed per tooth values. Size effect may also be intensified by the disproportion between the feed per tooth and depth of cut values. Such significant variations and data dispersion can lead to difficulties in the mathematical modelling of the influence of cutting process parameters on the process output indicators.

3.1 Modelling and optimisation

As the initial model function that describing the influence of input parameters on the output variables of the micromilling process, an exponential function was selected. This function includes one coefficient and exponents of the two input variables: depth of cut and feed per tooth. For the purpose of determining the model coefficient and exponents, the initial function was linearized to enable the application of the least squares method.

Based on experimentally obtained data, a model for the cutting force component in the direction perpendicular to the cutting tool auxiliary movement F_x [N] was developed. It is mathematical function with variables depth of cut a_p [mm], and feed per tooth f_z [mm/tooth]:

$$F_x = 5892 \cdot a_p^{1.005} \cdot f_z^{0.953} \quad (1)$$

A statistical analysis of variance (ANOVA) was conducted based on the experimental data and the response of the developed model. Based on the p-values, the model was determined to be

significant, with a notable significant influence of depth of cut and feed per tooth (Table 1). The given abbreviations refer to statistical next parameters: sum of squares (SoS), degree of freedom (DoF), and mean square (MSQ).

Table 1. Statistical parameters for F_x model

Source	SoS	DoF	MSQ	t value	p value
Model	2.77	2	1.38	79.92	< 0.0001
$\ln(f_z)$	1.87	1	1.87	108.13	< 0.0001
$\ln(a_p)$	0.90	1	0.90	51.71	0.0004
Residual	0.10	6	0.017		
Total	2.87	8			

Mean value of data is $\bar{x} = 1.79$, and standard deviation of $SD = 1.01$. Coefficient of determination is $R^2 = 0.97$, and signal to noise value is $S/N = 24.7$. Model response mean absolute percentage error is $MAPE = 8\%$. Based on previous statistical parameters, can be concluded that model is adequate. Model response diagram is given on Figure 6.

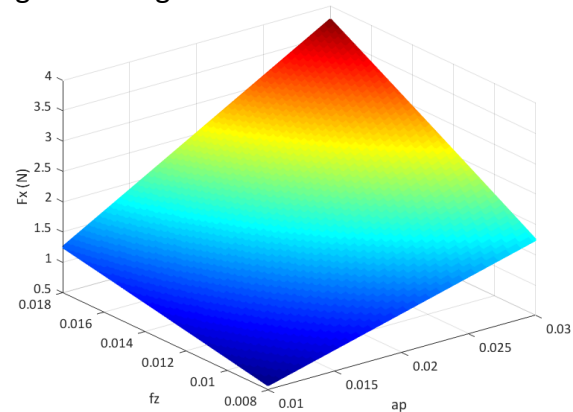


Figure 6. Response of F_x model

Following a same procedure, a model was developed for the cutting force component in the direction of the cutting tool auxiliary movement F_y [N]. Model is in form of mathematical function with

variables depth of cut a_p [mm], and feed per tooth f_z [mm/tooth]:

$$F_y = 5244 \cdot a_p^{0.784} \cdot f_z^{1.090} \quad (2)$$

The results of the statistical analysis of the model and variables significance are presented in Table 2. Based on the given data, a significant influence of both depth of cut and feed per tooth can be concluded.

Table 2. Statistical parameters for F_y model

Source	SoS	DoF	MSQ	t value	p value
Model	2.31	2	1.15	116.81	< 0.0001
$\ln(f_z)$	1.14	1	1.14	115.05	< 0.0001
$\ln(a_p)$	1.17	1	1.17	118.58	< 0.0001
Residual	0.059	6	$9.9 \cdot 10^{-3}$		
Total	2.37	8			

The other determined statistical parameters are: mean value of $\bar{x} = 2.07$, standard deviation of $SD = 1.09$, coefficient of determination of $R^2 = 0.98$, signal to noise value of $S/N = 30.4$. Model response mean absolute percentage error is $MAPE = 6\%$. On Figure 6 is shown model response diagram.

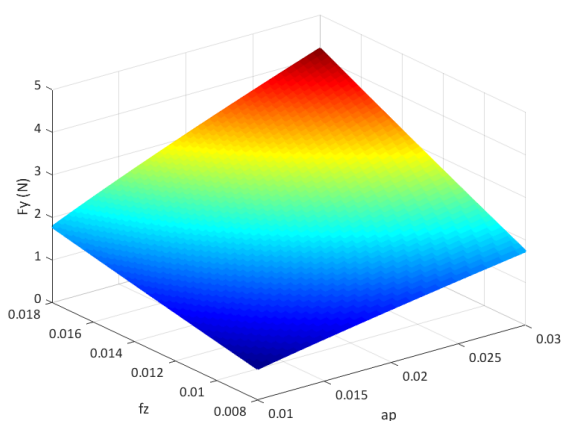


Figure 7. Response of F_y model

The surface roughness model was developed using the previous procedure. Statistical analysis showed that the depth of cut doesn't have a significant effect on

the values of R_a . To avoid large model errors and low correlation between experimental data and corresponding model responses, the depth of cut, was excluded from the model. Consequently, model of R_a [μm] is obtained, and depends on feed per tooth f_z [mm/tooth]:

$$R_a = 23.46 \cdot f_z^{0.916} \quad (3)$$

Statistical parameters values for surface roughness parameter are given in Table 3. It is evident that feed per tooth has a statistically significant influence on model responses.

Table 3. Statistical parameters for R_a model

Source	SoS	DoF	MSQ	t value	p value
Model	0.81	1	0.81	15.19	0.0059
$\ln(f_z)$	0.81	1	0.81	15.19	0.0059
Residual	0.37	7	0.053		
Total	1.18	8			

Based on obtained data, there are calculated: mean value of $\bar{x} = 0.43$, standard deviation of $SD = 0.13$, coefficient $R^2 = 0.87$, signal to noise value of $S/N = 6.75$. Surface roughness model response has $MAPE = 13\%$. Despite a slightly higher model response error, it can be concluded that the previous model is adequate. Model response graph is shown on Figure 8.

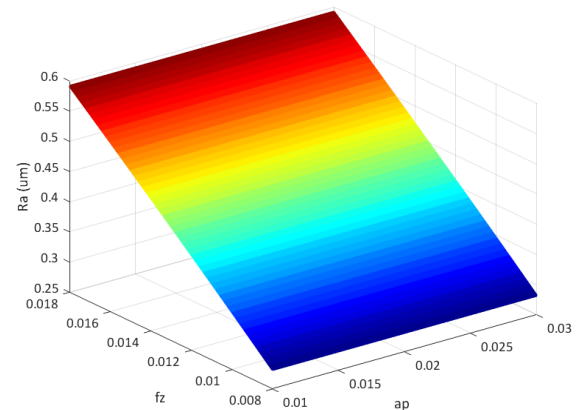


Figure 8. Response of R_a model

In addition to the previously mentioned output parameters of the micromilling process, the machining time was also taken into consideration. There, it is referred to the time required to machining of the one micro-channel. The machining time t_c [min] was obtained through analytical calculation, as the ratio of the channel length to the feed rate. The feed rate is the product of the cutter teeth number, feed per tooth, and spindle speed.

The optimization was carried out with the aim of minimizing dimensional error during machining and maximizing the quality of the machined surface. Minimization of machining time was considered as an objective also. The mathematical framework for the process parameters optimization is shown in Table 4.

Table 4. Optimization framework

Name	Goal	Limit		Weight	
		Lower	Upper	Low	Up
a_p	in range	0.010	0.030	1	1
f_z	in range	0.008	0.018	1	1
$\ln(R_a)$	minimize	-1.4271	-0.3711	1	1
$\ln(F_x)$	minimize	-0.5361	1.1756	1	1
$\ln(F_y)$	minimize	-0.3119	1.3444	1	1
$\ln(t_c)$	minimize	-0.2416	0.5693	1	1

Indirectly, minimizing dimensional accuracy was represented as the minimization of tool deflection, i.e., cutting forces. Maximizing quality was expressed as the minimization of surface roughness. All input parameters and their domains boundaries were assigned equal importance. According to the previously, it is clear that the minimization of machining time is in opposite with the minimizing of cutting forces and maximizing of surface quality [1]. The optimization was performed using the gradient method, which gave ten possible solutions. The optimal results of the process parameters were obtained as follows: depth of cut $a_p =$

0.010 mm, and feed per tooth $f_z = 0.011$ mm/tooth. Optimisation aims achievement is 61%. The optimization results desirability diagram, with respect to the values of the input process parameters, is shown in Figure 9.

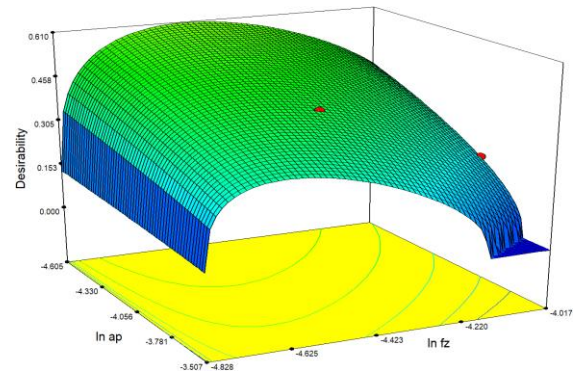


Figure 9. Desirability of results in optimisation

4. CONCLUSION

This paper presents an experimental study of the superalloy Inconel 718 micromilling. The experimental research was conducted with the aim of analysing the influence of depth of cut and feed per tooth on the micromilling process performance indicators. There are measured and analysed the cutting force component in the cutting tool auxiliary movement direction, and the cutting force component perpendicular to mentioned direction. The average surface roughness height was analysed also.

Based on the experimental data, and using the least squares method, models were developed. Statistical analysis shown a significant influence of the input cutting parameters on the process indicators. Depth of cut, and feed per tooth have significantly influence on cutting forces. Surface roughness was influenced by the feed per tooth.

Based on the models, optimization of the input parameters was performed. The obtained optimal process parameters were depth of cut of $a_p = 0.010$ mm, and feed per

tooth of $f_z = 0.011$ mm/tooth. Future research is planned to investigate the influence of other process parameters and conditions, as well as different modelling and optimization methods.

REFERENCES

- [1] K. Cheng, D. Huo, *Micro-Cutting: Fundamentals and Applications*, John Wiley and Sons, New York, 2013. <https://doi.org/10.1002/9781118536605>
- [2] J. Chae, S.S. Park, T. Freiheit, Investigation of micro-cutting operations, *International Journal of Machine Tools and Manufacture*, Vol. 46, No. 3-4, pp. 313–332, 2006. <https://doi.org/10.1016/j.ijmachtools.2005.05.015>
- [3] D. Serje, J. Pacheco, E. Diez, Micromilling research: current trends and future prospects, *The International Journal of Advanced Manufacturing Technology*, Vol. 111, pp. 1889-1916, 2020. <https://doi.org/10.1007/s00170-020-06205-w>
- [4] N. Ullah, M. Rehan, M.U. Farooq, H. Li, W.S. Yip, S.S. To, A comprehensive review of micro-milling: fundamental mechanics, challenges, and future prospective, *The International Journal of Advanced Manufacturing Technology*, Vol. 137, pp. 4309-4351, 2025. <https://doi.org/10.1007/s00170-025-15388-z>
- [5] X. Lu, X. Hu, Z. Jia, M. Liu, S. Gao, C. Qu, S.Y. Liang, Model for the prediction of 3D surface topography and surface roughness in micro-milling Inconel 718, *The International Journal of Advanced Manufacturing Technology*, Vol. 94, pp. 2043-2056, 2018. <https://doi.org/10.1007/s00170-017-1001-y>
- [6] Z. Jia, X. Lu, H. Gu, F. Ruan, S.Y. Liang, Deflection prediction of micro-milling Inconel 718 thin-walled parts, *Journal of Materials Processing Technology*, Vol. 291, 7003, 2021. <https://doi.org/10.1016/j.jmatprotec.2020.117003>
- [7] X. Lu, F. R. Wang, L. Xue, Y. Feng, S. Y. Liang, Investigation of material removal rate and surface roughness using multi-objective optimization for micro-milling of Inconel 718, *Industrial Lubrication and Tribology*, Vol. 71, No. 6, pp. 787-794, 2019. <https://doi.org/10.1108/ILT-07-2018-0259>
- [8] A. Muhammad, M.K. Gupta, T. Mikołajczyk, D.Y. Pimenov, K. Giasin, Effect of tool coating and cutting parameters on surface roughness and burr formation during micromilling of Inconel 718, *Metals*, Vol. 11, No. 1, 167, 2021. <https://doi.org/10.3390/met11010167>
- [9] D. de Oliveira, M. Ziberov, R.L. de Paiva, M. B. da Silva, An experimental evaluation of cutting parameters influence on the surface integrity and tool wear mechanisms on the dry micromilling of austenitic alloy Inconel 718, *Wear*, Vol. 571, 205789, 2025. <https://doi.org/10.1016/j.wear.2025.205789>
- [10] K.V. Rao, B.H. Babu, V.U.V. Prasad, A study on effect of dead metal zone on tool vibration, cutting and thrust forces in micro milling of Inconel 718, *Journal of Alloys and Compounds*, Vol. 793, pp. 343-351, 2019. <https://doi.org/10.1016/j.jallcom.2019.04.194>
- [11] G. Kiswanto, M. Azmi, A. Mandala, T.J. Ko, The effect of machining parameters to the surface roughness in low speed machining micro-milling Inconel 718, *IOP Conference Series: Materials Science and Engineering*, Vol. 654, 012014, 2019. <https://doi.org/10.1088/1757-899X/654/1/012014>
- [12] M. Gueli, J. Ma, N. Cococcetta, D. Pearl, M.P. Jahan, Experimental investigation into tool wear, cutting forces, and resulting surface finish during dry and flood coolant slot milling of Inconel 718, *Procedia Manufacturing*, Vol. 53, pp. 236-245, 2021. <https://doi.org/10.1016/j.promfg.2021.06.026>
- [13] J. Liang, X. Cheng, Y. Tian, W. Wang, Q. Yang, Z. Mu, J. Sun, M. Tang, Study on the chip morphology and machining quality of micro helical milling of superalloy small holes, *Materials Today Communications*, Vol. 43, 111834, 2025. <https://doi.org/10.1016/j.mtcomm.2025.111834>

- [14] B. Sredanović, D. Cica, S. Borojevic, S. Tesic, D. Kramar, Optimization of superalloy Inconel 718 micro-milling process by combined Taguchi and multi-criteria decision making method, Journal of the Brazilian society of mechanical sciences and engineering, Vol. 46, pp. 1 - 14, 2024.

<https://doi.org/10.1007/s40430-024-04996-7>