Influence of orthogonal turn-milling kinematic parameters on surface roughness of aluminium alloy EN AW 2011-T8

Sonja Jozić[1], Ivana Dumanić Labetić[1], Dražen Bajić[1] and Martina Filipović[1]

1) University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, 2100 Split, Republic of Croatia

Corresponding author: sjozic@fesb.hr

Original Scientific Paper

Abstract: The combination of different machining operations on a single machine tool has become increasingly important with the development of new manufacturing philosophies and CNC flexible machining centres. By combining turning and milling operations and replacing the turning tool with a driven milling cutter, the turning-milling process was introduced. Turn-milling is commonly used for machining rotating workpieces with circular, non-circular, and other complex geometries. The process enables high material removal rates while maintaining excellent surface quality. This paper analyses the influence of orthogonal turn-milling kinematic parameters on the surface roughness of aluminium alloy EN AW 2011-T8. The experiments were carried out on a Haas ST-10Y turning centre using a driven milling tool. The workpiece rotational speed, tool rotational speed, and axial feed rate were varied. Surface quality was evaluated using a KLM 3D profilometer for 2D and 3D surface roughness measurements. The results demonstrate that all investigated machining parameters significantly affect both the linear roughness (*Ra*) and the areal surface roughness (*Sa*), resulting in pronounced surface anisotropy of the machined workpiece.

Keywords: *orthogonal turn-milling, kinematic parameters, surface roughness, aluminium alloy EN AW 2011-T8*

1. Introduction

The machining of geometrically complex surfaces with high precision is increasingly important in today's metalworking industry. This demand can be met by turn-milling machine tools, which are suitable for machining highly complex parts requiring short cycle times. Turn-milling operations offer the advantage of performing both turning and milling operations simultaneously on a single machine, thereby reducing machine setup time and improving productivity. Research on turn-milling began in the early 1990s. Among the pioneering researchers, Schulz made significant contributions from 1990 and 1994. Schulz et al. defined the basic features of turn-milling process, such as the classification into orthogonal and coaxial configurations, better process productivity and quality of the machined surface compared to turning or milling, kinematic conditions influencing tool wear especially when machining hardened steels. They also reported that coaxial turn-milling does not require coolant and can achieve a surface quality comparable to grinding.

From a kinematic point of view [1], turn-milling requires the rotation of both the workpiece and the tool, together with linear motions of the tool to set the depth of cut, provide axial feed, and establish either a centric or eccentric cutter position relative to the workpiece. The milling tool is mounted on a high-speed spindle, while the workpiece is clamped in a rotating chuck that rotates at a lower speed than the milling spindle. During turn-milling, a milling cutter with multiple cutting edges is used, periodically entering and leaving the cut, producing relatively short chips with a variable cross-section [2]. Consequently, the cutting edge remains engaged for a shorter period of time, and therefore tool wear is reduced. By combining the rotational motions of the workpiece and the tool and the feed motion of the tool, higher material removal rates (MRR) can be achieved with improved surface quality [3]. On the other hand, an inappropriate selection of cutting parameters can result in excessive cutting forces and self-excited vibrations, which may generate poor surface quality, tool breakage, or spindle

bearings damage, limiting the full productivity potential of the turn-milling operation [4]. Therefore, safe and efficient cutting parameters must be selected prior to production. Boozarpoor et al. [5] investigated the influence of the rotational speed of the workpiece and the tool, the feed rate, and the eccentricity of the tool relative to the workpiece on the surface roughness and residual stresses in the workpiece material. One of the important advantages of turn-milling operations is the lower power consumption. Most of the power required for the process is spent on the rotation of the milling cutter, as this is the main motion. This is especially important for larger workpieces, where turning would require significantly higher power consumption. Tang et al. [6] modelled energy consumption in orthogonal turn-milling and found optimal parameters that would minimize energy consumption while maintaining the required quality of the machined surface and material removal rate. Kaibu et al. [7] concluded that the ratio between the rotational speeds of the milling cutter and the workpiece is significant in generating the surface texture. Selecting machining parameters in turn-milling is challenging because of the additional kinematic and geometric constraints associated with the process. Berenji et al. [8] investigated the effects of various process parameters, particularly tool eccentricity, on chip formation and surface generation. It was shown that small changes in tool eccentricity has a strong influence on the surface finish in turn-milling.
The machined surface quality is one of the most important indicators of machining success because it affects wear, friction, fatigue life, and functionality of machine parts. This study investigates the influence of tool and workpiece rotational speed and axial feed rate on the quality of the machined surface during orthogonal turn-milling. The workpiece material is aluminium alloy EN AW 2011-T8, which is widely used in the automotive, aerospace and mechanical engineering industries because of low density, excellent machinability, and favourable mechanical properties.

2. Theoretical basis of the orthogonal turn-milling process

Orthogonal turn-milling can be regarded as a special variant of turning in which the turning tool is replaced by a driven milling cutter, Figure 1. The axes of the tool and the workpiece are perpendicular to each other. This configuration allows for efficient machining of cylindrical surfaces with lower cutting loads and improved heat dissipation from the cutting zone.

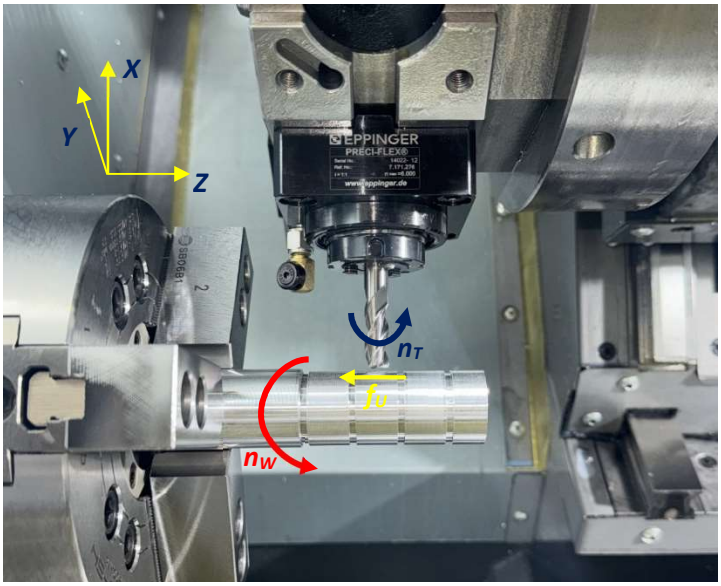


Figure 1. *Orthogonal turn-milling operation with assigned motions*

Compared with conventional turning, orthogonal turn-milling can achieve material removal rates that are 1.2 to 4 times higher, depending on the number of cutter teeth. Under identical cutting parameters as in turning, the quality of the machined surface is generally better than in turning ($Ra \approx 0.2$ µm).

Power consumption is significantly lower since most of the power required for the process is spent driving the milling cutter, which is the main motion. This is especially important for larger workpieces, where turning would require significantly more power. Additional advantages of turn-milling include: higher machining speeds because only the relatively lightweight cutter rotates at high speed, reduced cutting forces, improved dimensional and form accuracy, reduced deformation of large or unbalanced workpieces due to their low rotational speed, short chips that are easily evacuated from the cutting zone, which is particularly advantageous in machining centres.
The quality of the machined surface is affected by several factors including the workpiece rotational speed, tool rotational speed, axial feed rate, depth of cut, tool geometry, and possible system vibrations. In this study, kinematic parameters were primarily analyzed. This study focuses primarily on the influence of the kinematic parameters.

3. Material and Experimental Setup

3.1. Machine tool, cutting tool and workpiece material

The experiments were conducted on a Haas Automation ST-10Y turning centre equipped with a driven milling tool. Such a configuration allows simultaneous rotation of the workpiece and the milling cutter, which is a prerequisite for performing a turn-milling operation. A high-speed steel milling cutter with a diameter of 5 mm was used for orthogonal turn-milling.
The experiments were performed on workpieces measuring 100 mm in length and 45 mm in diameter, made of aluminum alloy EN AW 2011-T8. The chemical composition and mechanical properties of the alloy are presented in Table 1.
This alloy is characterized by very good machinability, high strength, good dimensional stability and wide application in the production of precision machine parts. The addition of copper provides excellent machinability and surface finish, making the alloy suitable for manufacturing shafts, screws, fasteners, and precision mechanical components.

Table 1. *Chemical composition and mechanical properties of the workpiece material*

Chemical composition %						
Si	Fe	Cu	Zn	Pb	Bi	Al
0.17	0.50	5.70	0.03	0.60	0.60	Balance
Mechanical properties						
Rm [MPa]	$Rp_{0.2}$ [MPa]		*A* [%]		Hardness [HBW]	
388	286		16		117.2	

3.2. Experimental Setup

During the experimental research, three basic process parameters were varied such as workpiece rotation speed, tool rotation speed and axial feed. By combining them, according to the Box Behnken response surface design of experiments (BBD), different machining conditions were obtained in order to examine their influence on the final surface quality. Three factorial Box Behnken design of experiments demands 12 experiments (each factor on 3 levels), and 5 central experiments, what makes total of 17 experiments. Software package Design-Expert was used to generate 17 experimental points shown in Table 2. After machining, the surface roughness was measured using a 3D profilometer, figure 2. Linear roughness (*Ra*) and surface roughness are given in Table 2. The acquired topography data were processed using Profilm Analysis software. Prior to the quantitative evaluation, invalid measurement points were corrected, isolated outliers were removed, and the measured surfaces were levelled to eliminate specimen tilt. Subsequently, the areal surface roughness parameter *Sa* was evaluated in accordance with ISO 25178.

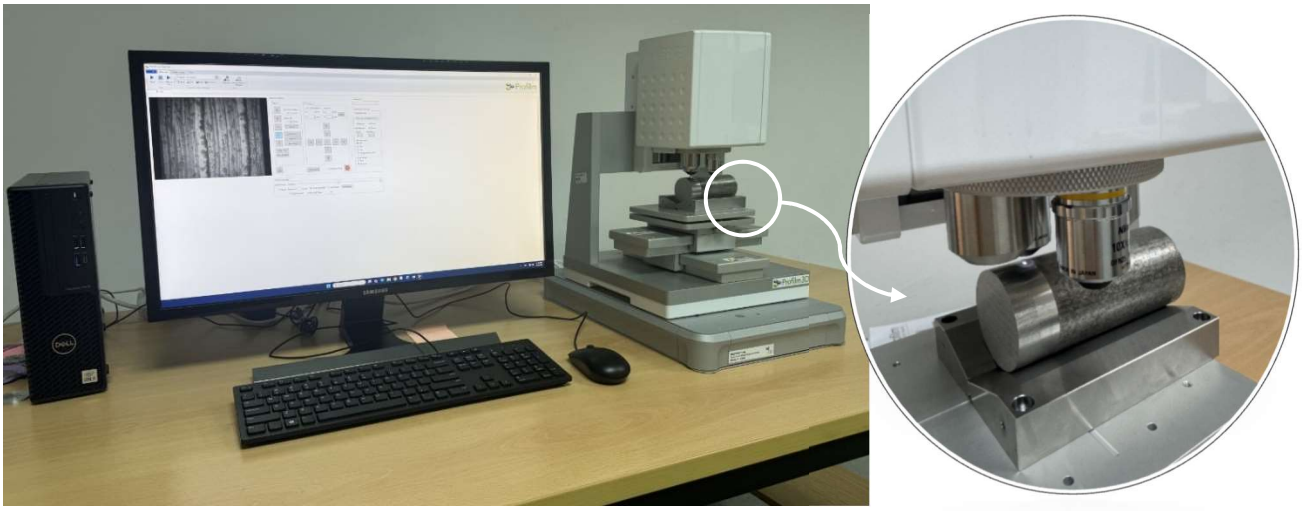


Figure 2. *Surface roughness measuring*

Table 2. *Experimental layout using Box Behnken design of experiments and performance results*

Run	n_W [min^{-1}]	n_T [min^{-1}]	v_{fa} [mm/min]	*Ra* [µm]	*Sa* [µm]
1	25	3000	10	7.15	8.18
2	70	3000	10	2.50	5.96
3	25	3000	30	8.10	5.62
4	70	3000	30	7.00	8.07
5	25	2000	20	8.00	14.56
6	70	2000	20	4.80	7.41
7	25	4000	20	8.75	12.19
8	70	4000	20	4.35	6.02
9	47.5	2000	10	4.50	6.15
10	47.5	2000	30	8.75	11.34
11	47.5	4000	10	3.20	5.05
12	47.5	4000	30	7.60	11.48
13	47.5	3000	20	7.10	8.86
14	47.5	3000	20	7.25	9.01
15	47.5	3000	20	7.15	8.99
16	47.5	3000	20	7.21	8.87
17	47.5	3000	20	7.09	8.75

4. Discussion

4.1. Mathematical model

Following regression analysis (RA) and analysis of variance (ANOVA), predictive models describing the relationship between machining parameters and surface roughness were established. After eliminating the non-significant terms, the final models for were obtained:

$$Ra = 2.166 - 0{,}065 \cdot n_W + 0.264 \cdot v_{fa} - 5.029 \cdot 10^{-4} \cdot n_W^2 - 7.171 \cdot 10^{-3} \cdot v_f^2 \quad (1)$$

$$Sa = 12.839 - 0{,}239 \cdot n_W + 0.648 \cdot v_{fa} - 2.298 \cdot 10^{-3} \cdot n_T - 5.912 \cdot 10^{-3} \cdot n_W \cdot v_{fa} + 2.08 \cdot n_W^2 \quad (2)$$

Response surface plots of the predictive model for the areal surface roughness parameter *Sa* (Figure 2) show that increasing the axial feed rate has a smaller effect on *Sa* at higher workpiece rotational

speeds than at lower workpiece rotational speeds. At lower workpiece rotational speeds, increasing the axial feed rates results in a pronounced increase in surface roughness. In contrast, the interaction between tool rotational speed and axial feed rate indicates that the effect of increasing the axial feed rate on *Sa* is similar at both low and high tool rotational speeds.

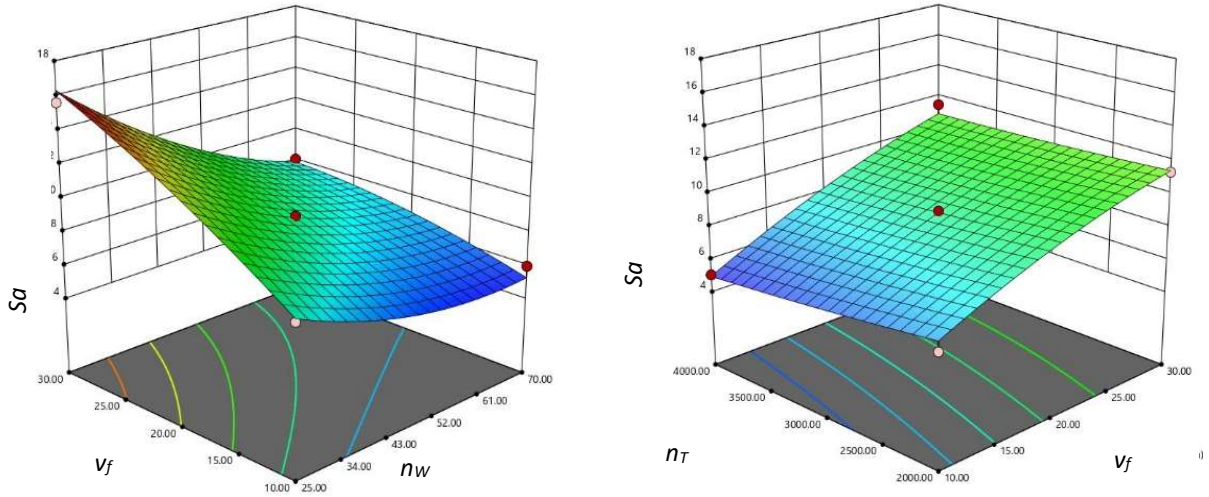


Figure 2. *Influence of cutting parameters on surface roughness: (a) feed rate and workpiece rotational speed and (b) tool rotational speed and feed rate*

4.2. Surface topography analysis

Three-dimensional surface topography analysis revealed a pronounced anisotropy of the machined surface, indicating that the measured roughness depends on the measurement direction. This behaviour results from the specific kinematics of the orthogonal turn-milling process, in which the workpiece and the milling cutter rotate simultaneously. The combined rotational motions generate a characteristic pattern of cutting marks that differs from those produced by conventional turning or milling, as illustrated in Figure 3. For clarity, Figure 3 presents the surface topographies obtained in experimental runs 1 and 3 (a) and runs 2 and 4 (b). In experiments 1 and 2 the axial feed rate has lower value than in experiments 3 and 4. Increasing the axial feed rate increases the distance between the adjacent tool paths. As a result, more pronounced surface waviness is generated, leading to a deterioration in surface finish quality. Lower axial feed rates enable finer surface treatment and improved surface quality.

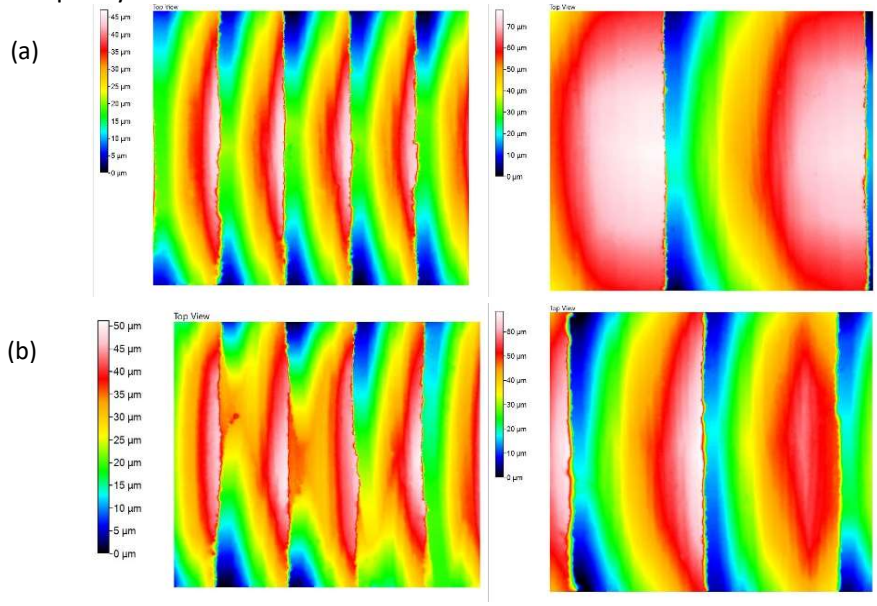


Figure 3. *Surface topography obtained by 3D optical measurement (a) experiments number 1, 3; (b) experiments number 2,4*

5. Conclusion

The research has shown that the kinematic parameters of the orthogonal turn-milling process significantly affect the roughness and topography of the surface of the EN AW 2011-T8 aluminium alloy. The axial feed rate proved to be a particularly influential, as it directly determines the formation of cutting marks and, consequently, the final surface quality. Measurements conducted using 2D and 3D methods confirmed that, through appropriate selection of process parameters, a very smooth surface can be achieved while maintaining high machining productivity. The results also revealed a pronounced anisotropy of the machined surface, which should be considered when evaluating surface quality and optimizing the machining process. These findings provide a valuable basis for further development and application of turn-milling technology in the precision machining of aluminium alloys.

The obtained results can contribute to the optimisation of industrial production, especially in the machining of aluminium alloys where high surface quality and productivity are required. At the same time, the research confirms the advantages of turn-milling technology compared to conventional machining, as it enables high material removal rates while maintaining favourable surface quality.

Future research should investigate the influence of the rotational speed of both the tool and the workpiece on the quality of the machined surface in combination with variation of axial feed rate.

Funding: This work was supported by the European Union under the NextGenerationEU instrument, through the Recovery and Resilience Mechanism, within the institutional research project AIMTECH 4.5 (IP-UNIST-07), implemented by the Ministry of Science, Education and Youth of the Republic of Croatia."

References

[1] L. Zhu. Z. Jiang. J. Shi. and C. Jin. ‘An overview of turn-milling technology’. *International Journal of Advanced Manufacturing Technology*. vol. 81. no. 1–4. pp. 493–505. Oct. 2015. doi: 10.1007/s00170-015-7187-y.

[2] H. Otalora-Ortega. P. Aristimuño Osoro. and P. Arrazola Arriola. ‘Uncut chip geometry determination for cutting forces prediction in orthogonal turn-milling operations considering the tool profile and eccentricity’. *Int. J. Mech. Sci*. vol. 198. May 2021. doi: 10.1016/j.ijmecsci.2021.106351.

[3] M. E. Kara and E. Budak. ‘Optimization of Turn-milling Processes’. in *Procedia CIRP*. Elsevier B.V.. 2015. pp. 476–483. doi: 10.1016/j.procir.2015.06.057.

[4] K. A. Vikram. Ch. Ratnam. and K. S. Narayana. ‘Vibration Diagnosis and Prognostics of Turn-milling Operations using HSS and Carbide End Mill Cutters’. *Procedia Technology*. vol. 23. pp. 217–224. 2016. doi: 10.1016/j.protcy.2016.03.020.

[5] M. Boozarpoor. R. Teimouri. and K. Yazdani. ‘Comprehensive study on effect of orthogonal turn-milling parameters on surface integrity of Inconel 718 considering production rate as constrain’. *International Journal of Lightweight Materials and Manufacture*. vol. 4. no. 2. pp. 145–155. Jun. 2021. doi: 10.1016/j.ijlmm.2020.09.002.

[6] K. E. Tang. G. Y. Lin. and C. W. Liu. ‘Sustainable orthogonal turn-mill process parameter decision-making based on specific consumption energy model and NSGA-II multi-objective optimization algorithm’. *International Journal of Advanced Manufacturing Technology*. vol. 137. no. 11. pp. 6107–6121. Apr. 2025. doi: 10.1007/s00170-025-15490-2.

[7] S. Kaibu. A. Ikeda. and Y. Ihara. ‘Study on Cutting Marks by Turn Mill Process’. in *Procedia CIRP*. Elsevier B.V.. 2018. pp. 251–254. doi: 10.1016/j.procir.2018.09.008.

[8] K. Rahimzadeh Berenji. U. Karagüzel. E. Özlü. and E. Budak. ‘Effects of turn-milling conditions on chip formation and surface finish’. *CIRP Annals*. vol. 68. no. 1. pp. 113–116. Jan. 2019. doi: 10.1016/j.cirp.2019.04.067.