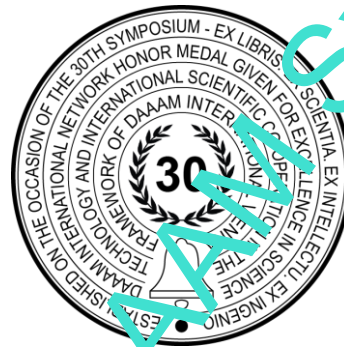


ENERGY CONSUMPTION IN MILLING ALUMINIUM WITH DIFFERENT TOOLPATHS

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Abstract

This study analyses the impact of the toolpath selection on energy consumption, machining time, and surface quality when milling 6061-aluminium alloy. Ten cavities were milled using a 9.525 mm flat milling cutter, with a three-axis CNC. Five toolpaths were defined: Spiral, Zigzag, NT Spiral, NT Zigzag and Vortex. Each cavity's energy consumption and time were recorded while performing the milling process. Once the block was milled, the surface roughness was measured using the Ra parameter. Roughness results were in the range of 1.0 to 2.5 μm . It was found that the cutting parameters had a greater influence on the increase in surface roughness. Toolpath does not seem to have a remarkable influence on roughness, using the same cutting conditions. The results showed that the Spiral trajectory took up to 69% less time than the other trajectories, it is among the trajectories that consumed the least energy (up to 13%) and the roughness was up to 33% lower. Spiral seems to be the better alternative according to the variables analysed in this paper.

Keywords: milling; toolpath; energy consumption; surface quality; machining; sustainable.

1. Introduction

Nowadays, the environmental impact of every human activity is a constant concern. It is well known that production processes can cause significant environmental impacts. Therefore, different approaches are used to reduce or eliminate them. The Sustainability of machining processes may be achieved by improving their efficiency from an energy perspective. This approach is included in the Sustainable Development Goals, where it is proposed that "By 2030, double the global rate of improvement in energy efficiency". Where it should be considered that the industry, one of the greater energy consumers, has recently exceeded 50% of worldwide consumption [1].

The environmental impact of conventional machining covers energy consumption, auxiliary materials, and transportation of materials and waste, among others, that could pollute the air, ground, and water directly or indirectly [2]. There are different ways to influence machining sustainability and reduce negative effects, for example: eliminating, substituting, or reducing metalworking fluids; tool life extension; and energy consumption optimization [3], [4].

For milling processes, several researchers have evaluated the energy consumption for different materials. It is possible to find studies that generate models to calculate consumption [3], [4], [5] or focused on establishing relationships between the cutting conditions [6], [7] or tool wear influence [8], [7] and the energy consumed.

In particular, the toolpath selected for cutting is a key factor to determine energy consumption. There were found in the literature two definitions of a toolpath. One of them refers purely to geometry while the other identifies a type of geometry among the strategies available within a CAM software. The advantage of this approach is that it allows directly obtaining a recommendation to implement in the daily work in a workshop.

Several studies have presented advances in this topic. Aramcharoen et al. [9] designed an analytical model of the energy consumption based on tool trajectory, which identifies opportunities for reducing energy demand. Pavanaskar et al. [10] proposed an application that estimates the energy consumption based on the NC code; nonetheless, this proposal has limitations. Ma et al. [4] proposed a model that considers different options to estimate the energy consumed depending on the toolpath (i.e., curve or straight line). This study established the relationship between power consumption and tool movement. However, it does not help to select a particular toolpath in the CAM software. Zhang et al. [11] elaborated a model in which the complexity of the part is quantified. They also concluded that the complexity of the piece from the geometrical point of view is related to energy consumption.

Rangarajan et al. [12] presented a particular analysis of the trajectory. These researchers studied the best orientation of a given toolpath and a workpiece for the Y-axis of the machine based on the cycle time. Although, this case is not related to energy consumption. Similarly, Del Sol et al. [13] compared different trajectories and its effects on the macro and micro geometrical characteristics of the parts. The orientation of the trajectory is also addressed by Campatelli et al. [14], who explained why the energy consumption of the axes varies. The authors reported savings between 3% and 4%, in global terms, and up to 23% if only the energy consumed by the axes is considered. On the one hand, Edem et al. [15] followed this approach and found out the best alignment corresponds to the alignment of the piece with the axis that has less weight. On the other hand, they also analysed the type of trajectory, concluding that a reduction in the retractions lowers the energy values. In addition, they pointed out that helical paths reduce energy consumption and improve better surface finish.

Kong et al. [16] developed a software to evaluate energy consumption considering the milling path. This research found that the pattern followed to machine a part influenced the energy consumption. Nevertheless, no specific toolpath is selected. The study presented by Pervaiz et al. [17], analysed four types of trajectories. It pointed out the spiral strategy as the one with the lowest consumption due to the empty movements of the tool. Minquiz et al. [18] proposed a toolpath evaluation for a face milling. In this case, the so-called dynamic strategy is more favourable from the energetic point of view than the zigzag alternative. Altıntaş et al. [3] studied the impact of the trajectory on two features, for an open pocket and a closed pocket, in both cases, the energy consumption is lower with the zigzag trajectory. These authors also proposed a model to predict the real consumption, but the cutting component fits worst to the proposed energy model. Rahman Hemdi et al. [19] presented a design of experiments for several types of trajectories, finding that the feed rate is the more influential factor in energy consumption. However, it is not concluded which is the best trajectory based on this parameter.

Therefore, the combined influence of the toolpath and the cutting parameters on the energy consumption has not been completely established. For this reason, this paper analyses the influence of five milling toolpaths on the energy consumption, time cycle and surface quality of an aluminium part under conventional machining parameters.

2. Experimental Procedure

Toolpaths were compared in terms of energy consumption, time cycle, and surface quality. For this purpose, twenty pockets (27mm wide, 47mm high and 8mm deep) were milled. An HSS flat mill, two flutes and 9.525 mm diameter (Fig. 1, a). The tests were performed on a CNC Milltronics MM3017, with a three-axis, spindle power of 13 kW, a maximum spindle of 8000 rev/min, and a maximum feed rate of 7.6 m/min (Fig. 1, b & Fig. 1, c) illustrates the milling process, which was performed under lubrication. The machined material was an aluminium alloy 6061 T6511 plate (Fig. 1, d).

Five toolpaths (Fig. 2.) were selected and each one was machined under four sets of cutting parameters (Table 1), modifying the feed per tooth, the cutting speed, and the depth of cut, keeping constant the average chip load with the recommended value of 0.203 mm/tooth [20]. The NC code was obtained using Autodesk Feature CAM Ultimate 2022.

The impact of the trajectories on power consumption was measured acquiring the signal of the servo controllers of the spindle motor. A Fluke 435-II power analyser was installed (Fig. 3.) to acquire the electrical voltage, current measurements, and the energy consumption.

Roughness was measured using a roughness tester Mitutoyo SURFTEST SJ-210 following the standard ISO 4287:1997. Roughness Average (Ra) was selected as surface quality parameter.

Cutting parameters	Feed per tooth f_z (mm/tooth)	Cutting speed v_c (m/min)	Depth of cut a_p (mm)
1	0.103	139.4	1.5
2	0.141	158.3	2.0
3	0.173	174.2	2.5
4	0.194	196.1	3.0

Table 1. Cutting parameters

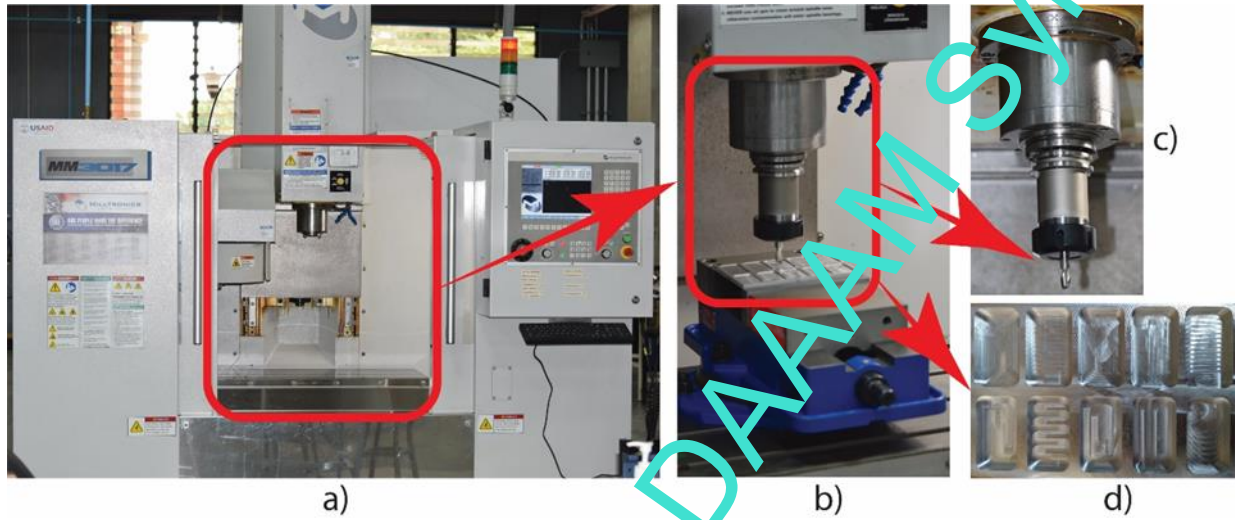


Fig. 1. Assembly of the workpiece and tool used for the tests: a) CNC Milltronics MM3017, b) process disposition, c) flat mill HSS and d) workpiece

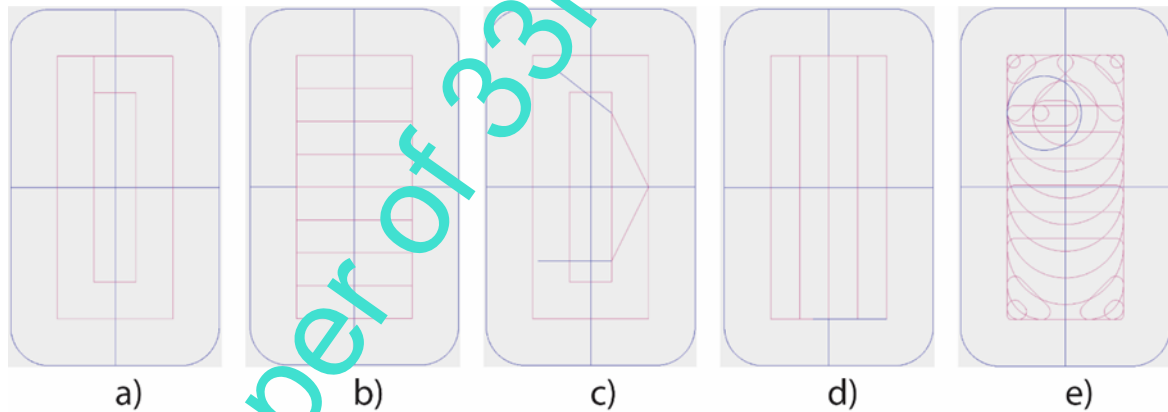


Fig. 2. Schematic illustration of toolpaths a) Spiral, b) Zigzag, c) NT Spiral, d) NT Zigzag and e) Vortex

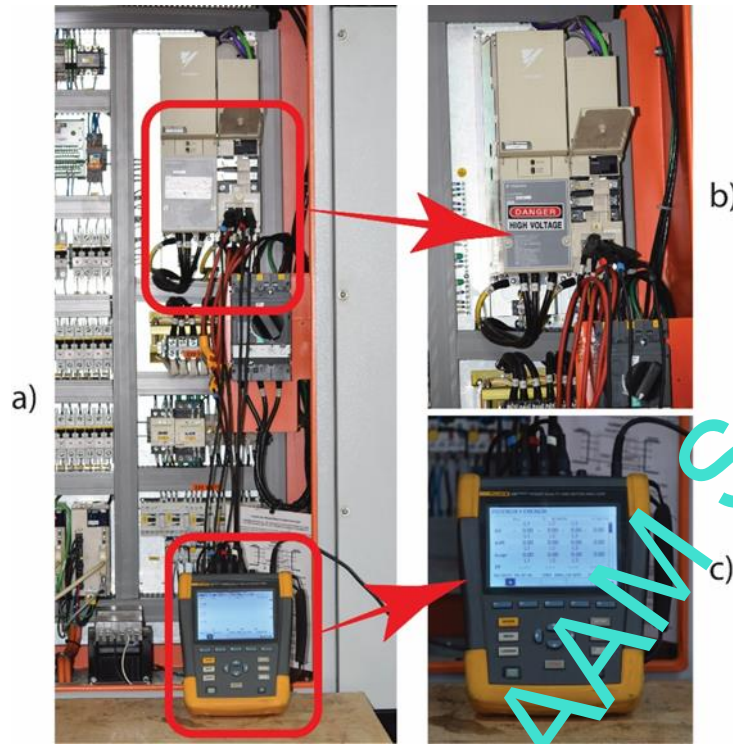


Fig. 3. Measurements of electrical variables on CNC: a) CNC Milltrotic MM3017 control cabinet, b) Yaskawa CACR-JU065ADAB Drives-AC Servo, c) Fluke 435-II

3. Results and Discussion

3.1. Roughness

Fig. 4. shows Ra values for every test performed. It was observed that increasing cutting parameters (cutting speed, feed, and depth of cut) produced higher roughness values.

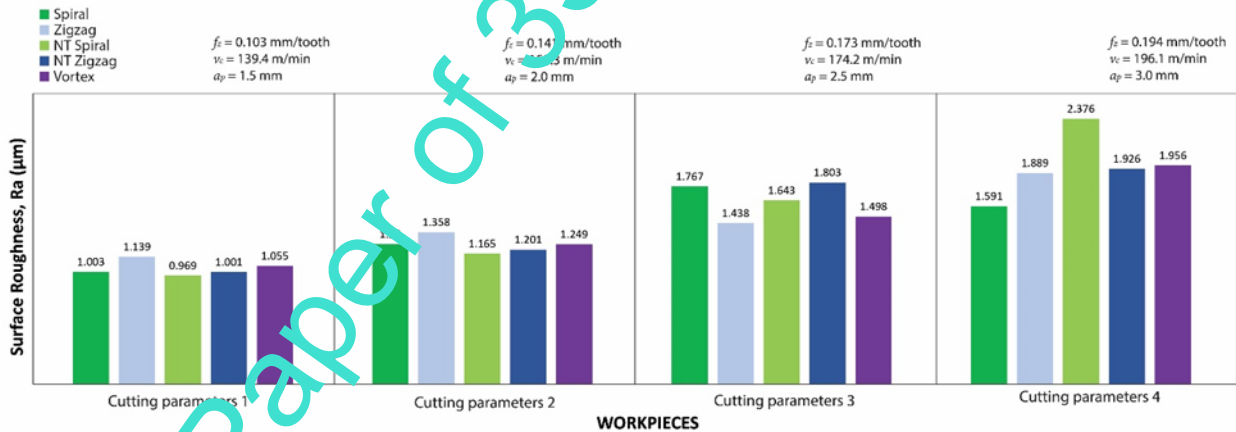


Fig. 4. Bar charts as a panel of surface roughness measurements Ra (μm) in all toolpaths.

The best quality surface was obtained for the lowest cutting parameters ($f_z=0.103$ mm/tooth, $v_c=139.4$ m/min, $a_p=1.5$ mm). It is remarkable, under these conditions, that toolpath does not seem to have a significant effect on roughness. The trend of the results is in agreement with those presented by Minquiz et al. [18], who analysed this problem for steel milling. However, these authors used higher speed and lower feed and depth of cut. Therefore, Ra values were $0.28 \mu\text{m}$ lower, and the researchers did not select any particular toolpath based on this parameter. It must be noted that the difference between the lowest and the highest values obtained by Minquiz et al. was $0.08 \mu\text{m}$ when comparing toolpaths.

As expected, the highest Ra was reached using the highest cutting parameters ($f_z=0.19$ mm/tooth, $v_c=196$ m/min, $a_p=3.0$ mm). For higher cutting parameters, it seems that the chosen trajectory affects the surface quality. The worst results

were obtained with NT spiral toolpath (2.376 μm) and the best with Spiral (1.591 μm). Ra was increased by 49% for the most aggressive parameters.

3.2. Energy consumption

Fig. 5. shows the results regarding energy consumption. Generally, the energy consumption decreased for an increase on the cutting parameters.

Comparing the toolpaths, the lowest energy consumption is obtained for the Spiral, while the NT Zigzag milling strategy required 27% more energy compared to the Spiral. However, there is a difference for high values of f_z , v_c and a_p . In this case, Spiral and Zigzag trajectories registered the lowest consumption and the difference compared to NT Zigzag, which goes up to 36%.

Looking at Cutting parameters 1 and Cutting parameters 4, it was found that the lowest energy consumption occurred in Spiral and Zigzag toolpath. The highest cutting parameters in these trajectories produced 22% lower energy consumption in comparison to the higher ones. These results agree with those of Pervaiz et al. [17], where Spiral toolpath got the lowest energy consumption (180 kWh) for a cutting speed of 100 m/min and feed rate of 0.05 mm/tooth.

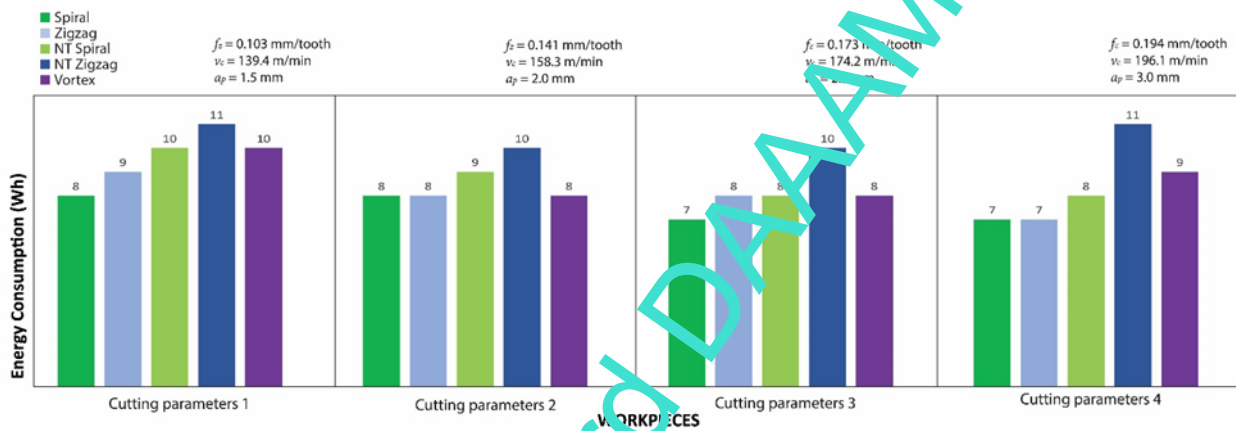


Fig. 5. Bar charts as a panel of energy consumption (Wh) measurements in all toolpaths

3.3. Time cycle

Fig. 6. presents the time cycle for every toolpath and set of cutting conditions. As it was expected, an increasing on the cutting parameters decrease the machining time. For instance, Spiral strategy time was reduced up to 69% for ($f_z=0.194$ mm/tooth, $v_c=196.1$ m/min, $a_p=3.0$ mm) compared to the lower cutting parameters ($f_z=0.103$ mm/tooth, $v_c=139.4$ m/min, $a_p=1.5$ mm). Nevertheless, their selection of the cutting parameters should consider the surface quality requirements of the final part.

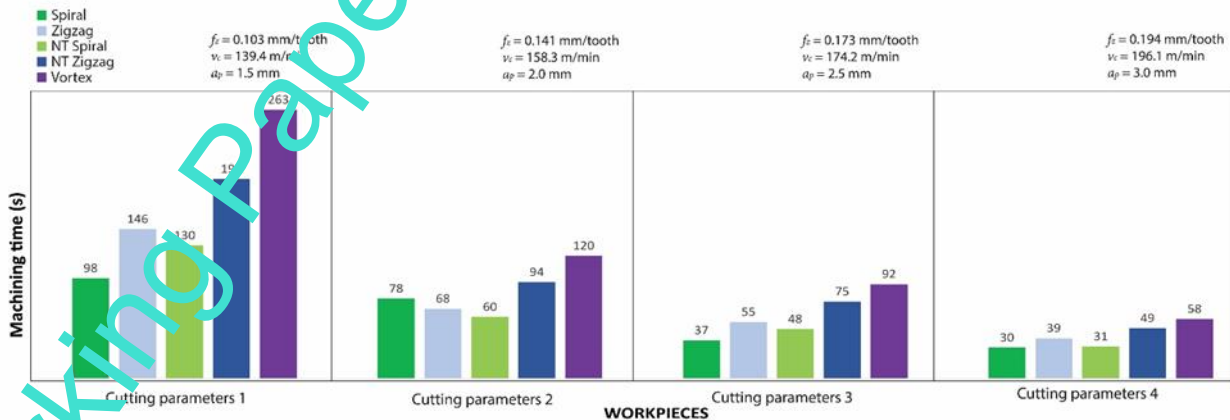


Fig. 6. Bar graphs as a panel of machining time (s) measurements in all toolpaths

Regarding the strategy selection, Vortex strategy presented the maximum time cycle values for every cutting condition, which took up to 63% longer than Spiral. These results are comparable to those by Rahman Hemdi et al. [19], who also found that spirals had the lowest milling times.

3.4. Global comparison

A resume of the values obtained for the three evaluation parameters (roughness, energy consumed and machining time) is presented in Fig. 7.

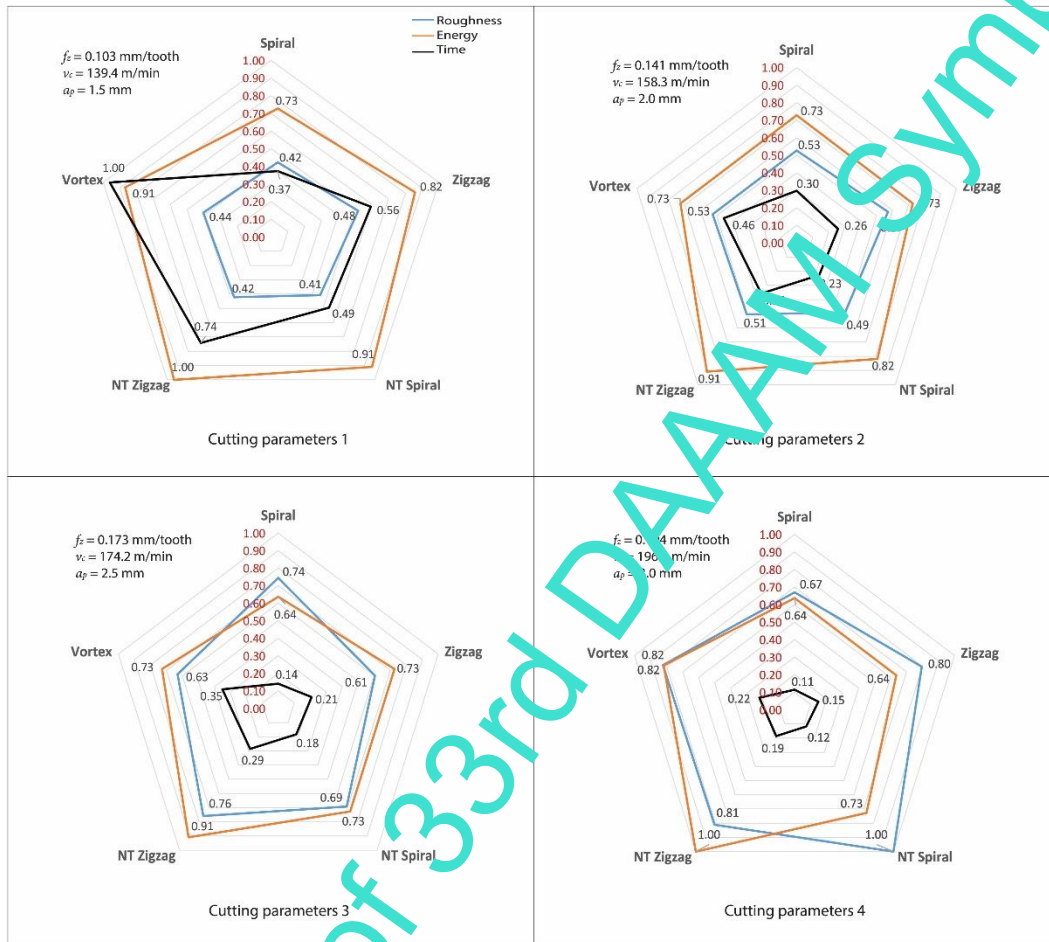


Fig. 7. Plots of normalized results of surface roughness, energy consumed, and milling time variables.

In general roughness values are similar for all the trajectories and the main difference is produced by the cutting parameters. NT Zigzag generally increase the energy consumption while the Vortex strategy increases the machining time.

Spiral and Zigzag trajectories could be selected at the higher cutting conditions to get the lowest energy consumption and cycle time when roughness values are not considered critical. NT Spiral was found among the average values for every evaluation parameter.

NT zigzag and Vortex would not be recommended when lower cutting parameters are used because the evaluated performance variables seem to worsen. Finally, the Spiral trajectory is the one that registered the lowest values of roughness, time, and energy. It considerably improves the machining time for low-cutting parameters if compared to Vortex strategy.

4. Conclusions

This paper analyses the impact of the trajectories on the energy consumption, the machining time, and the surface quality to select the better trajectory, considering the effect under conventional machining parameters for the milling of 6061 aluminium alloy. The analysis of the experimental results leads to the following conclusions:

1. Trajectories are not the most influential factor for roughness values. Therefore, surface quality may be determined through the cutting parameter selection.
2. A combination of the cutting parameters and the toolpath strategy allows to obtain acceptable values in both variables, energy, and roughness.
3. Machining time is highly influenced by the feed rate and the cutting speed but also by the toolpath strategy. Spiral trajectory optimized the machining time.
4. Spiral trajectory and low cutting parameters ($f_z=0.103$ mm/tooth, $v_c=139.4$ m/min, $a_p=1.5$ mm) were selected as the better machining conditions after a cross-comparison to optimize the three variables, energy consumption, surface quality and machining time.

Future research may explore other variables, such as lubricant or more in-depth cutting parameters optimization, which may be considered to improve the environmental impact of the machining process and ensure the sustainability of the process.

5. References

- [1] Girouard, N. & Tam, C. (2011). Environment: Transforming the energy sector to deliver greener growth – OECD, Available from: <https://www.oecd.org/newsroom/environmenttransformingtheenergysectortodelivergreenergrowth.htm>. Accessed: 2022-04-26.
- [2] Tomaskova, T. & Bicova, K. (2021). Impact of machining on the environment. *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, Vol. 32, No. 1, pp. 623–630, DOI: 10.2507/32nd.daaam.proceedings.088.
- [3] Altıntaş, R.; Kahya, M. & Ünver, H. (2016). Modelling and optimization of energy consumption for feature based milling, *International Journal of Advanced Manufacturing Technology*, Vol. 86, No. 9–12, pp. 3345–3363, DOI: 10.1007/s00170-016-8441-7.
- [4] Ma, F.; Zhang, H.; Cao, H. & Hon, K. (2017). An energy consumption optimization strategy for CNC milling, *International Journal of Advanced Manufacturing Technology*, Vol. 90, No. 5–8, pp. 1715–1726, DOI: 10.1007/s00170-016-9497-0.
- [5] Pawar, S.; Bera, T.; & Sangwan, K. (2022). Energy consumption modelling in milling of variable curved geometry, *International Journal of Advanced Manufacturing Technology*, Vol. 120, No. 3–4, pp. 1967–1987, DOI: 10.1007/s00170-022-08854-5.
- [6] Liu, Z.; Sealy, M.; Li, W.; Zhang, D.; Fang, X.; Guo, Y. & Liu, Q. (2018). Energy consumption characteristics in finish hard milling, *Journal of Manufacturing Processes*, vol. 35, pp. 500–507, DOI: 10.1016/j.jmapro.2018.08.036.
- [7] Del Sol, I.; Rivero, A. & Gámez, A. (2019). Effect of machining parameters on the quality in machining of aluminum alloys thin plates, *Metals (Basel)*, Vol. 9, No. 9, DOI: 10.3390/met9090927.
- [8] Zhang, X.; Yu, T.; Dai, Y.; Qu, S. & Zhao, J. (2020). Energy consumption considering tool wear and optimization of cutting parameters in micro milling process, *International Journal of Mechanical Sciences*, Vol. 178, DOI: 10.1016/j.ijmecsci.2020.105628.
- [9] Aramcharoen, A.; & Mativenga, P. (2014). Critical factors in energy demand modelling for CNC milling and impact of toolpath strategy, *Journal of Cleaner Production*, Vol. 78, pp. 63–74, DOI: 10.1016/j.jclepro.2014.04.065.
- [10] Pavanaskar, S. & McMains, S. (2012). Machine Specific Energy Consumption Analysis for CNC milling toolpaths, Available from: <http://www.asme.org/about-asme/terms-of-use>.
- [11] Zhao, J.; Li, L.; Wang, Y. & Sunderland, J. (2019). Impact of surface machining complexity on energy consumption and efficiency in CNC milling, *International Journal of Advanced Manufacturing Technology*, Vol. 102, No. 9–12, pp. 2891–2905, DOI: 10.1007/s00170-019-03334-9.
- [12] Rangarajan, A. & Dornfeld, D. (2017). Efficient Tool Paths and Part Orientation for Face Milling, 2004.
- [13] Del Sol, I.; Rivero, A.; Salguero, J.; Fernández-Vidal, S. & Marcos, M. (2017). Tool-path effect on the geometric deviations in the machining of UNS A92024 aeronautic skins, *Procedia Manufacturing*, Vol. 13, pp. 639–646, DOI: 10.1016/j.promfg.2017.09.134.
- [14] Campatelli, G.; Sappa, A.; Lorenzini, L. & Sato, R. (2015). Optimal workpiece orientation to reduce the energy consumption on a milling process, *International Journal of Precision Engineering and Manufacturing - Green Technology*, Vol. 2, No. 1, pp. 5–13, DOI: 10.1007/s40684-015-0001-3.
- [15] Edem, I. & Mativenga, P. (2017). Energy Demand Reduction in Milling Based on Component and Toolpath Orientation, *Procedia Manufacturing*, Vol. 7, pp. 253–261, DOI: 10.1016/j.promfg.2016.12.060.
- [16] Kong, D.; Choi, S.; Yasui, Y.; Pavanaskar, S.; Dornfeld, D. & Wright, P. (2011). Software-based tool path evaluation for environmental sustainability, *Journal of Manufacturing Systems*, Vol. 30, No. 4, pp. 241–247, DOI: 10.1016/j.jmsy.2011.08.005.
- [17] Pavaz, S.; Deiab, I.; Rashid, A. & Nicolescu, M. (2012). An Experimental Analysis of Energy Consumption in Milling Strategies.
- [18] Minquíz, G.; Borja, V.; López-Parra, M.; Reivich, A.; Huerta, L.; Lázaro, R.; Sánchez, A.; Leal, H.; Solana, M. & Méndez, J. (2020). Machining Parameters and Toolpath Productivity Optimization Using a Factorial Design and Fit

Regression Model in Face Milling and Drilling Operations, Mathematical Problems in Engineering, Vol. 2020, DOI: 10.1155/2020/8718597.

- [19] Hemdi, A.; Ali, U.; Noor, R.; Yahaya, M.; Mahadzir, M.; Zubair, A.; Othman, M.; Yola, M.; Saman, M. & Sharif, S. (2020). Cutting Path-Associated Energy Consumption of Milling Machining Process, IOP Conference Series: Materials Science and Engineering, Vol. 1003, No. 1, DOI: 10.1088/1757-899X/1003/1/012071.
- [20] Oberg, E.; Jones, F.; Horton, H. & Ryffel, H. (2016). Machinery's Handbook, Industrial Press.

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