

Alternative Trajectories for the Optimization of Trochoidal Milling in Hardened Steel

Kaciê K.A. Trindade^a , Josean da S. Lima Junior^a , Maxime Montoya^a ,

Alessandro R. Rodrigues^b , Kleber G.B. Alves^{a*} , Flávio J. da Silva^a 

^aUniversidade Federal de Pernambuco, Departamento de Engenharia Mecânica, Recife, PE, Brasil.

^bUniversidade de São Paulo, Departamento de Engenharia Mecânica, São Carlos, SP, Brasil.

Received: January 09, 2025; Revised: April 09, 2025; Accepted: April 21, 2025

This study investigates the machining performance of trochoidal toolpaths in hardened AISI 4340 steel. Three toolpaths—conventional, horizontal semi-ellipse, and vertical semi-ellipse—were analyzed in terms of machining time and machining forces under dry and flood coolant conditions. Computer Numerical Control (CNC) programs were optimized using circular interpolation and repetition commands to minimize number of command blocks and maintain effective feed rates. Results showed the vertical semi-ellipse trajectory reduced machining time by 18.9% compared to the conventional path, while the horizontal semi-ellipse presented stable machining forces across both dry and wet conditions but had the longest machining time. The use of coolant significantly decreased machining forces in the conventional and vertical semi-ellipse trajectories, enhancing performance. The semi-ellipse paths demonstrated smoother tool transitions and optimized material removal, offering superior force stability. These findings underscore the importance of selecting toolpath geometry and cooling strategies to balance efficiency and stability in industrial machining applications.

Keywords: *Trochoidal Milling, Machining Performance, Toolpath Optimization, CNC Programming.*

1. Introduction

Trochoidal milling has emerged as a revolutionary strategy in the machining of hardened steels, such as AISI 4340 quenched and tempered steel with a hardness of 40 HRC. These materials are widely used in high-demand industries, including aerospace, naval, petrochemical, and mold and die manufacturing. This process is particularly relevant in addressing the challenges posed by the low machinability of these materials, which exhibit high mechanical and thermal resistance, leading to increased tool wear¹⁻³.

Trochoidal milling involves the cutting tool following a circular or spiral path while progressively advancing along the workpiece. This strategy enables the use of a low radial depth of cut (a_p), combined with a reduced contact angle between the tool and the workpiece. Recent studies indicate that this results in lower mechanical and thermal stresses on the cutting tool, contributing to its durability and efficiency^{4,5}. Furthermore, the optimization of trochoidal milling parameters has shown significant improvements in tool life and material removal rates^{6,7}. Studies on hard milling of steels, such as the work by Gaitonde et al.⁸ on AISI D2 steel, demonstrate that careful selection of cutting parameters can enhance machining performance, which is pertinent to trochoidal milling applications.

One of the main advantages of trochoidal milling is the ability to utilize a high axial depth of cut (a_p), taking full advantage of the cutting edge length. This combination

enables high material removal rates, which are crucial in operations such as machining deep slots and cavities. Unlike conventional contour milling techniques, where the tool is subjected to high concentrated forces in a small contact area, trochoidal milling distributes machining forces uniformly, extending tool life and ensuring greater process stability^{9,10}. In addition, current literature highlights that high-speed milling techniques, including trochoidal strategies, are gaining prominence due to their potential to improve productivity and process reliability in the machining of metal alloys¹¹.

Moreover, the smooth transitions in the tool path reduce vibrations and minimize the risk of premature failures, especially in critical operations with hardened materials. This results in high-quality surfaces, reduced rework, and overall process efficiency¹². Additionally, research highlights the potential for integrating advanced simulation tools to predict the thermal and mechanical behavior of the tool during trochoidal milling, enabling further optimization of the process¹³⁻¹⁵.

The use of cutting fluids plays a critical role in machining processes, particularly in mitigating heat generation, reducing tool wear, and improving surface finish. Cutting fluids enhance the lubrication and cooling effects, significantly impacting the overall performance of milling strategies, including trochoidal milling. The application of cutting fluid under optimized conditions can prolong tool life and improve machining efficiency in high-performance operations^{16,17}. These findings highlight the importance of evaluating the influence of cutting fluids to better understand their effects

*e-mail: kleber.gbvalves@ufpe.br

on the process and to maximize the benefits of trochoidal milling.

Given these promising characteristics, this study aims to develop and compare three different trochoidal trajectories—conventional, semi-ellipse horizontal, and semi-ellipse vertical—in terms of machining time and machining forces performance, both under dry cutting conditions and with abundant cutting fluid application, in the milling of AISI 4340 quenched and tempered steel.

2. Experimental

The machining tests were carefully designed to evaluate and compare the performance of three different trochoidal trajectories—conventional, semi-ellipse horizontal, and semi-ellipse vertical—in terms of machining time and machining forces. These tests were conducted under two distinct cutting conditions: dry machining and abundant cutting fluid application, using a 10:1 water-to-oil mixture of a water-miscible cutting oil (Blasocut BC 40 NF, Blaser). The objective was to identify the optimal trajectory and conditions for machining AISI 4340 quenched and tempered steel, a material known for its high mechanical and thermal resistance.

2.1. Test specimen preparation

The test specimens were machined from AISI 4340 steel, which was quenched and tempered to a hardness of 40 ± 2 HRC, a typical value for hardened steels used in high-performance applications. The dimensions of each specimen were 165 mm in length, 40 mm in width, and 15 mm in height. These dimensions were chosen to simulate practical machining scenarios while ensuring compatibility with the trochoidal trajectories and dynamometer setup.

2.2. Experimental setup

The machining tests were conducted on a ROMI D600 CNC machining center equipped with a dynamometer for force measurement. A solid carbide end mill (EC-H7 10-20C10CFR.5M72) from Iscar Tool was utilized, featuring seven cutting edges, a diameter of 10 mm, and a 37° helix angle. The tool also includes a corner radius of 0.5 mm and a differential pitch design to minimize vibrations during machining. These characteristics were carefully chosen to enhance performance in trochoidal milling applications, ensuring optimal material removal rates and prolonged tool life. The tool was mounted on a high-precision hydraulic tool holder (CoroChuck 930) to ensure stability and minimize radial runout during the experiments. This high-precision holder, designed with a cylindrical clamping mechanism, provided exceptional grip force and vibration dampening. The cutting parameters were set and standardized as detailed below:

- Cutting speed: 200 m/min, calculated to suit the material properties and tool geometry.
- Feed per tooth: 0.03 mm, ensuring smooth engagement of the tool with the material while minimizing tool wear.
- Spindle speed: 6400 rpm, derived from the cutting speed and tool diameter.

- Radial depth of cut (a_r): 0.21 mm, chosen to optimize the trochoidal milling strategy.
- Axial depth of cut (a_p): 10 mm, taking full advantage of the tool's cutting edge length.

These parameters were selected based on preliminary studies and established guidelines for machining hardened steels. Machining tests were carried out using different feed rate values, during which cutting forces were also measured in order to calculate the specific cutting pressure of the material. This allowed for the determination of a prudent feed rate, compatible with the maximum measurement range of the dynamometer used in the experiments. The cutting speed values were defined empirically, based on tool manufacturers' recommendations for trochoidal milling applications.

For the determination of machining time, the reference point was defined as the moment when the tool engages with the workpiece during the second trochoid of the trajectory. This approach was chosen to eliminate potential inconsistencies associated with the initial stages of tool approach and positioning.

The total number of trochoids was individually adjusted for each trajectory. This adjustment was designed to ensure that all trajectories fully covered the specified 40 mm channel length, with the addition of one extra trochoid as a safety measure. This additional trochoid was incorporated to guarantee complete machining of the channel, compensating for potential variations in the tool's final displacement and ensuring a more uniform surface finish.

2.3. Trochoidal milling procedure

The trochoidal milling trials were performed on a straight channel with dimensions of 20 mm in width, 40 mm in length, and 10 mm in depth. Each trajectory (conventional, semi-ellipse horizontal, and semi-ellipse vertical) was programmed using G-code generated from CAM software and simulated in Siemens SinuTrain for Sinumerik Operate 840D SL. A single-pass operation was conducted for each toolpath trajectory to ensure a consistent comparison framework. Both dry machining and abundant cutting fluid application (10:1 mixture of water and synthetic oil) were tested for all three trajectories.

2.4. Force measurement and calibration

The machining forces were measured using a multicomponent dynamometer (type 9257BA), charge amplifier (type 5233A1), connecting cable, and DAQ system from Kistler, which was calibrated prior to the experiments to ensure accuracy. To verify the consistency of the results, the force measurement experiments were replicated under identical conditions. This allowed for cross-validation of the data and enhanced the reliability of the measurements.

To ensure the accuracy of force signal acquisition, the sampling frequency was determined based on the Nyquist-Shannon Theorem¹⁸, which establishes that the sampling frequency must be at least twice the excitation frequency of the system. Considering the tool's rotational speed of 6400 rpm, equivalent to an excitation frequency of 106.67 Hz, and the presence of seven cutting edges, the total excitation frequency was calculated as 746.67 Hz. To refine the calculation, the angular spacing between the cutting edges of the tool was

considered. Since the tool has seven equally spaced edges around its circumference, the angular interval between two consecutive edges is approximately 51.43° . To capture adequate data points along this angular interval, the objective was to acquire four data points per edge engagement. This was achieved by calculating the acquisition frequency as the product of the tool's excitation frequency (746.67 Hz) and the ratio of the full angular rotation (360°) to the angular interval per data point. The angular interval per data point was determined by dividing the spacing between cutting edges (51.43°) by four. Based on this calculation, the required acquisition frequency was approximately 20 kHz.

3. Results and Discussion

3.1. Comparison of trochoidal toolpaths

The three trochoidal toolpaths studied were developed based on strategies that balance efficiency, smooth motion, and reduced machining time. The creation of these toolpaths

considered principles presented in scientific literature and sought to optimize Computer Numerical Control (CNC) program execution by reducing the number of blocks and using circular interpolation to avoid decreases in the actual feed rate during machining. The CNC's ability to efficiently process instructions is crucial to prevent delays in feed rate, which can extend machining time¹⁹. Strategies such as using the WHILE command and appropriate interpolations were applied to mitigate these limitations, as illustrated in Figure 1.

3.1.1. Conventional trajectory

The conventional trochoidal trajectory, considered the simplest form of trochoidal milling, was designed based on overlapping circular movements (Figure 2). This approach seeks to balance programming simplicity and cutting efficiency. Despite its simplicity, the conventional trajectory faces challenges related to the large number of command blocks required, which can impact CNC performance on complex surfaces. Strategies such as using program area repetition

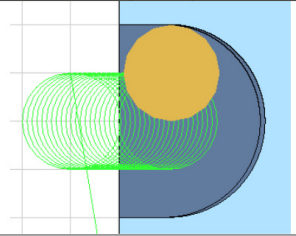
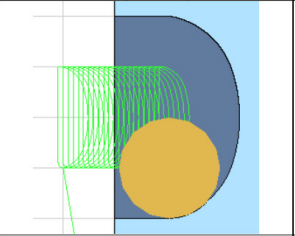
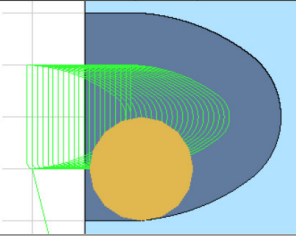
Conventional trochoidal trajectory	Horizontal semi-ellipse trajectory	Vertical semi-ellipse trajectory
		
O3007 G54G90G94G17G40 #101=0 #102=103 G0Z100 S6400M3 G1X-10.5Y0F3000 G1Z10F1000 G1Z-10F250 F1344 WHILE[#101LT#102]DO1 G91G3X0Y-10R5 G3X0.5Y10R5 #101=#101+1 END1 M01 G1Z10 G1Z200F3000	O3008 G54G90G94G17G40 #101=0 #102=109 G0Z100 S6400M3 G1X-14Y0F3000 G1Z10F1000 G1Z-10F250 F1344 WHILE[#101LT#102]DO1 G91G3X8Y3R15 G3X0Y4R2.5 G3X-8Y3R15 G1X-0.5Y0 G1X0Y-9.5 G3X0.5Y-0.5R0.5 G1X0.5Y0 #101=#101+1 END1 M01 G1Z10 G1Z200F3000	O3009 G54G90G94G17G40 #101=0 #102=98 G0Z100 S6400M3 G1X-7.5Y0F3000 G1Z10F1000 G1Z-10F250 F1344 WHILE[#101LT#102]DO1 G91G3X2Y2R3 G3X0Y6R10 G3X-2Y2R3 G1X-0.5Y0 G1X0Y-9.5 G3X0.5Y-0.5R0.5 G1X0.5Y0 #101=#101+1 END1 M01 G1Z10 G1Z200F3000

Figure 1. Comparison of trochoidal toolpath CNC codes.

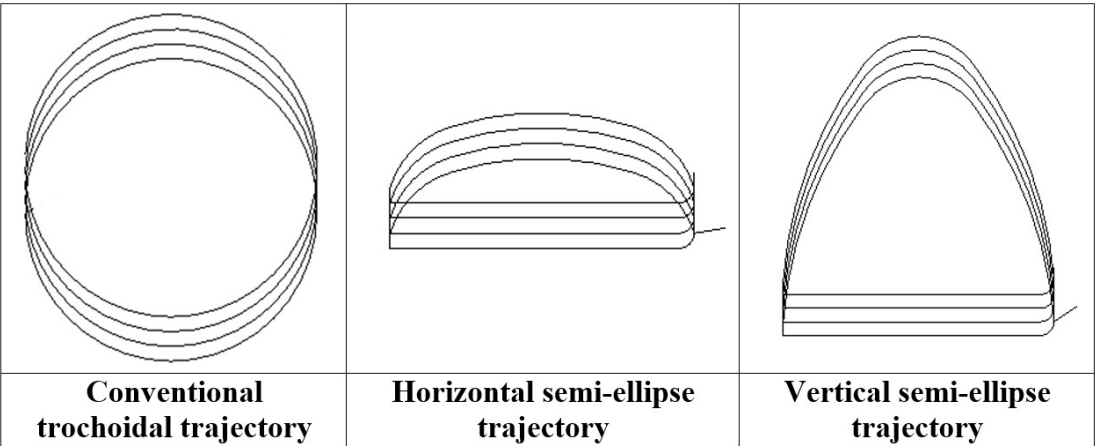


Figure 2. Trochoidal trajectories.

were incorporated to reduce the number of blocks, optimizing processing time and program execution.

3.1.2. Horizontal semi-ellipse trajectory

The horizontal semi-ellipse trajectory was based on the studies by Trindade²⁰ and Uhlmann et al.²¹, which reported advantages in using elliptical toolpaths to reduce the tool’s travel distance and machining time without significantly increasing machining forces. In this version, lateral tool movements predominate (Figure 2), with a smooth entry based on a 0.5 mm radius arc, similar to the solution used in modified semicircular toolpaths. The trajectory combines five arcs and a straight line (Figure 1), enabling smoother movements in the area in contact with the material being machined. This results in long and continuous cuts, with a lower frequency of abrupt accelerations, contributing to a uniform distribution of machining forces.

3.1.3. Vertical semi-ellipse trajectory

The vertical semi-ellipse trajectory was also inspired by the works^{20,21} but was designed to maximize efficiency in channels with curved edges. The adopted strategy included the addition of three arcs (two with a 4 mm radius at the ends and one with an 8 mm radius at the center), allowing the toolpath within the cut to take an elliptical shape (Figure 1 and Figure 2). A smooth tool entry, with a 0.5 mm arc, was incorporated to reduce impacts during motion transitions, preventing premature wear. This trajectory proved to be the most efficient in terms of reducing machining time, while maintaining smooth motion and stable machining forces.

3.2. Machining time analysis

The comparative analysis of the trochoidal toolpaths highlighted significant differences in machining time among the tested strategies, as illustrated in Table 1. The vertical semi-ellipse trajectory proved to be the most efficient, with an 18.9% reduction in machining time (113 seconds) compared to the conventional trajectory, which recorded a time of 164 seconds. On the other hand, the horizontal semi-ellipse trajectory had the longest machining time, at 196 seconds, representing a 19.5% increase compared to the conventional trajectory. Additionally, the horizontal

Table 1. Comparison of machining time for trochoidal toolpaths

Trochoidal Toolpath	Machining Time	Number of Trochoids
Conventional (C)	164 s	103
Vertical Semi-Ellipse (SV)	113 s (-18.9%)	109
Horizontal Semi-Ellipse (SH)	196 s (+19.5%)	98

semi-ellipse trajectory had the lowest number of trochoids (98), while the vertical semi-ellipse showed 109 trochoids, and the conventional trajectory presented 103 trochoids.

The segmentation of the trochoidal path is a critical factor influencing the stability of machining forces during the machining process. A greater number of trochoids, as observed in the vertical semi-ellipse trajectory, tends to distribute cutting effort more evenly along the toolpath, providing smoother and more stable applied forces. This behavior results from shorter and more frequent tool movements, which help reduce abrupt variations in machining forces, as well as improve heat dissipation and vibration control. On the other hand, toolpaths with fewer trochoids, such as the horizontal semi-ellipse trajectory, may result in longer or less frequent movements, which can lead to more pronounced force oscillations, especially in transition regions. This may cause instabilities, such as localized force spikes or uneven tool wear.

These findings indicate that the vertical semi-ellipse trajectory combines smooth transitions, a higher number of trochoids, and greater machining force stability, optimizing material removal. Conversely, the horizontal semi-ellipse trajectory, despite its simpler motion, proved to be less efficient in terms of machining time and more susceptible to variations in machining forces due to its geometry, which increases tool displacement. The conventional trajectory, with an intermediate number of trochoids, provides acceptable performance but lacks the significant benefits observed in the vertical semi-ellipse trajectory.

3.3. Graphical analysis of machining forces

Figure 3 presents a graphical analysis of the cutting forces, illustrating the impact of dry and coolant-enhanced

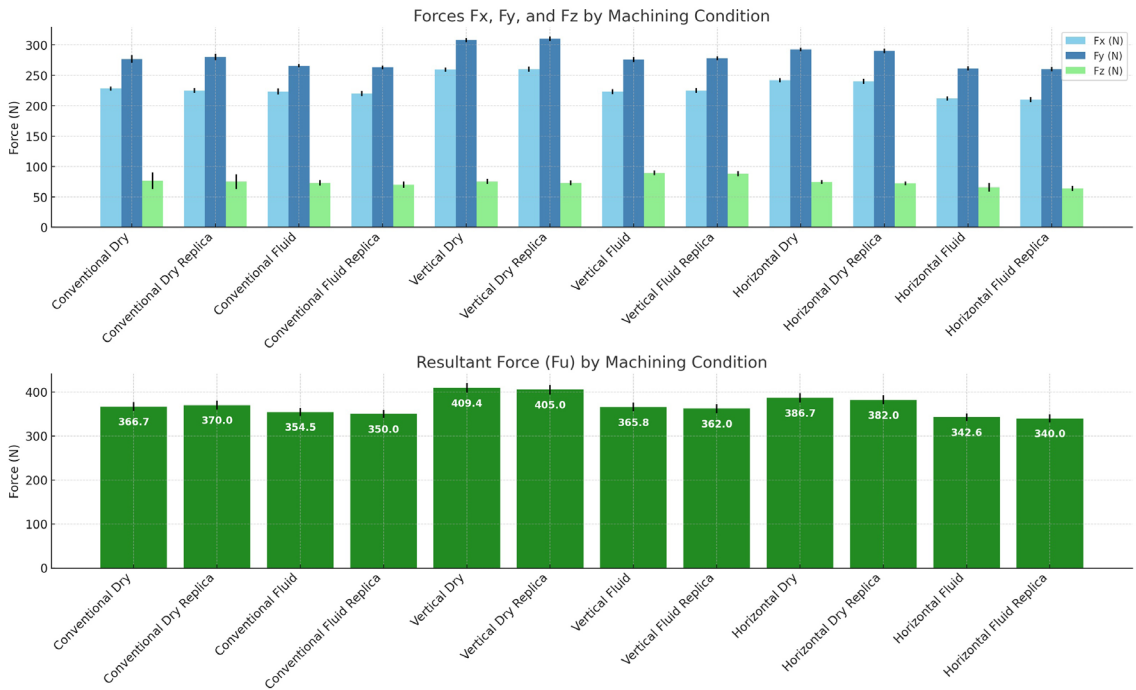


Figure 3. Influence of cooling type on machining force.

conditions on the three distinct trochoidal toolpath types. In the conventional trajectory, the use of coolant significantly reduced machining forces, indicating that the coolant helps to alleviate the cutting forces during machining. Similarly, in the vertical semi-ellipse trajectory, the use of coolant also resulted in lower cutting forces in all directions, reinforcing its efficiency under refrigerated conditions. On the other hand, in the horizontal semi-ellipse trajectory, there were no significant variations in cutting forces between dry and coolant conditions, suggesting that its geometry promotes a more uniform force distribution regardless of the cooling method.

This uniform force distribution in the horizontal semi-ellipse trajectory (Figure 4), even with the lowest number of trochoids, occurs due to its specific geometry. The horizontal movement prioritizes longer and more continuous lateral displacements, reducing the frequency of abrupt accelerations and decelerations of the tool, resulting in a more consistent application of machining forces. Additionally, the lower number of trochoids implies fewer transitions into and out of the material, minimizing the force peaks that may occur in toolpaths with more trochoids. The tool-material interaction is longer but less intense, smoothing the applied forces and ensuring constant contact between the tool and the material.

Finally, the horizontal semi-ellipse trajectory showed lower sensitivity to the use of coolant, indicating that its geometry inherently facilitates a uniform distribution of forces without requiring additional thermal dissipation or lubrication. This finding suggests that, despite the horizontal semi-ellipse's longer machining time, its geometry aids in machining force stabilization by mitigating force spikes and fostering a balanced machining process (Figure 4).

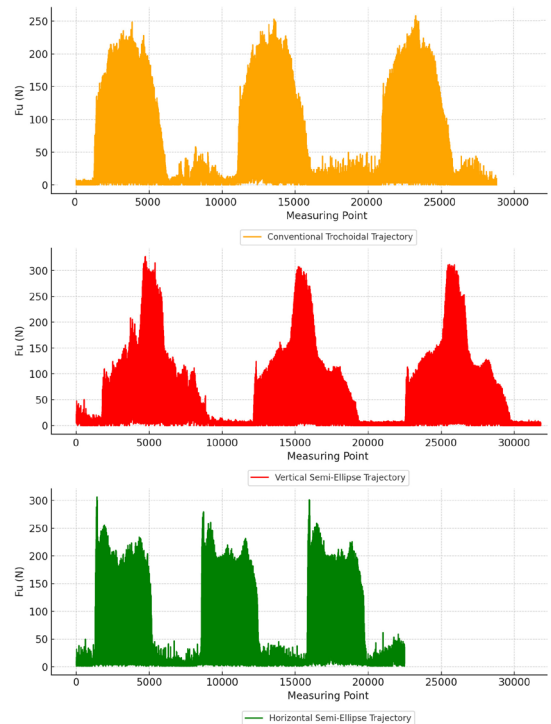


Figure 4. Machining force profile.

These findings emphasize the importance of considering the interaction between toolpath geometry and cutting conditions when selecting machining strategies.

4. Conclusion

This study demonstrated that trochoidal toolpath geometry plays a decisive role in the performance of machining deep channels in quenched and tempered AISI 4340 steel. The comparative analysis of three trajectories—conventional, horizontal semi-ellipse, and vertical semi-ellipse—revealed that the vertical semi-ellipse trajectory was the most efficient in terms of machining time, showing an 18.9% reduction compared to the conventional trajectory, while also maintaining force stability, particularly under abundant coolant conditions.

Although the horizontal semi-ellipse trajectory showed the least sensitivity to coolant usage, suggesting an inherently uniform force distribution due to its geometry, it resulted in the longest machining time, highlighting a trade-off between force stability and productivity. The conventional trajectory, while easier to program, exhibited intermediate performance and relied more heavily on cutting fluid to effectively reduce machining forces.

These findings confirm that toolpath selection directly influences the thermo-mechanical loads on the tool and the overall process efficiency. The vertical semi-ellipse trajectory is especially suitable for applications where time optimization and tool life are priorities, whereas the horizontal semi-ellipse trajectory may be beneficial in situations requiring more consistent cutting forces and lower tool wear, despite its longer cycle time. Thus, the choice of trochoidal trajectory should be guided by the specific priorities of the machining process, such as productivity and force stability, with careful consideration of CNC programming strategies and the application of appropriate cooling conditions for each path.

5. Acknowledgments

The authors acknowledge the financial support from the Brazilian agencies Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq (grants 311926/2023-1), CAPES, Fundação de Amparo à Ciência e Tecnologia de Pernambuco – FACEPE (grants APQ-1021-3.03/24). K.K.A.T thank CAPES for graduate scholarship. The authors thank Instituto Nacional de Tecnologia em União e Revestimento de Materiais (UFPE) and Escola de Engenharia de São Carlos (USP) for providing their infrastructure and technical assistance.

6. References

- Otkur M, Lazoglu I. Trochoidal milling strategies for machining of hardened steels. *Int J Mach Tools Manuf.* 2007;47(6):1324-32. <http://doi.org/10.1016/j.jmachtools.2006.08.002>.
- dos Santos AJ, de Oliveira DA, Pereira NFS, Abrão AM, Rubio JCC, Câmara MA. Effect of conventional and trochoidal milling paths on burr formation during micromilling of grade 4 commercially pure titanium. *Arab J Sci Eng.* 2024;49(2):1727-42. <http://doi.org/10.1007/s13369-023-07989-1>.
- Waszczuk M. Influence of the trochoidal tool path generation method on the milling process efficiency. *Advances in Science and Technology Research Journal.* 2020;14(3):199-203. <http://doi.org/10.12913/22998624/122198>.
- Kozový P, Šajgalík M, Holubjak J, Joch R, Drbůl M. Influence of trochoidal milling parameters on tool load. *Transp Res Procedia.* 2023;74:709-16. <http://doi.org/10.1016/j.trpro.2023.11.201>.
- Šajgalík M, Kušnerová M, Harničárová M, Valíček J, Czán A, Czánová T, et al. Analysis and prediction of the machining force depending on the parameters of trochoidal milling of hardened steel. *Appl Sci (Basel).* 2020;10(5):1788. <http://doi.org/10.3390/app10051788>.
- Sivasakthivel PS, Sudhakaran S, Sudhakaran R. Parametric optimization of trochoidal step on surface roughness and dish angle in end milling of AISI D3 steel using precise measurements. *Materials (Basel).* 2019;12(8):1335. <http://doi.org/10.3390/ma12081335>.
- Shixiong W, Wei M, Bin L, Chengyong W. Trochoidal machining for the high-speed milling of pockets. *J Mater Process Technol.* 2016;233(1):29-43. <http://doi.org/10.1016/j.jmatprotec.2016.01.033>.
- Gaitonde VN, Karnik SR, Figueira L, Davim JP. Machinability evaluation in hard milling of AISI D2 steel. *Mater Res.* 2016;19(2):361-8. <http://doi.org/10.1590/1980-5373-MR-2015-0263>.
- Niaki F, Pleta A, Mears L. Trochoidal milling: investigation of a new approach on uncut chip thickness modeling and cutting force simulation in an alternative path planning strategy. *Int J Adv Manuf Technol.* 2018;97(1-4):641-56. <http://doi.org/10.1007/s00170-018-1967-0>.
- Pleta A, Nithyanand G, Niaki F, Mears L. Identification of optimal machining parameters in trochoidal milling of Inconel 718 for minimal force and tool wear and investigation of corresponding effects on machining affected zone depth. *J Manuf Process.* 2019;43:54-62. <http://doi.org/10.1016/j.jmapro.2019.03.048>.
- Kar BC, Panda A, Kumar R, Sahoo AK, Mishra RR. Research trends in high speed milling of metal alloys: A short review. *Mater Today Proc.* 2020;26(2):2657-62. <http://doi.org/10.1016/j.matpr.2020.02.559>.
- Bergmann JA, Pothhoff N, Rickhoff T, Wiederkehr P. Modeling of cutting forces in trochoidal milling with respect to wear-dependent topographic changes. *Prod Eng.* 2021;15(6):761-9. <http://doi.org/10.1007/s11740-021-01060-4>.
- Deng Q, Chen Z, Chang Z, Shen R, Zhou Y. A model for investigating the temperature of trochoidal machining. *Journal of Industrial and Production Engineering.* 2020;37(4):194-203. <http://doi.org/10.1080/21681015.2020.1769749>.
- Li Z, Cheng L, Xu K, Gao Y, Tang K. Five-axis trochoidal flank milling of deep 3D cavities. *Comput Aided Des.* 2020;119:1-10. <http://doi.org/10.1016/j.cad.2019.102775>.
- Shahl AM, Agarwal A, Mears L. Tool wear area estimation through in-process edge force coefficient in trochoidal milling of Inconel 718. *Manuf Lett.* 2023;35:391-8. <http://doi.org/10.1016/j.mfglet.2023.08.072>.
- Yan P, Rong Y, Wang G. The effect of cutting fluids applied in metal cutting process. *Proc Inst Mech Eng, B J Eng Manuf.* 2016;230(1):19-37. <http://doi.org/10.1177/0954405415590993>.
- Kumar P, Jain AK, Chaurasiya PK, Tiwari D, Gopalan A, Dhanraj JA, et al. Sustainable machining using eco-friendly cutting fluids: a review. *Adv Mater Sci Eng.* 2022;1:1-14. <http://doi.org/10.1155/2022/5284471>.
- Nyquist H. Certain topics in telegraph transmission theory. *Trans Am Inst Electr Eng.* 1928;47(2):617-44. <http://doi.org/10.1109/T-AIEE.1928.5055024>.
- Altintas Y. *Manufacturing automation: metal cutting mechanics, machine tool vibrations, and CNC design.* Cambridge: Cambridge University Press; 2012. <http://doi.org/10.1017/CBO9780511843723>.
- Trindade KKA. *Desenvolvimento e avaliação de estratégias trocoidais para o fresamento do aço AISI 4340 temperado e revenido.* [Dissertation]. Natal: Federal University of Rio Grande do Norte; 2018.
- Uhlmann E, Reinkober S, Hoffmann M, Käpernick P. Trochoid milling with industrial robots. *Procedia Manuf.* 2020;43:447-54. <http://doi.org/10.1016/j.promfg.2020.02.189>.