The Effects of Milling and Drilling Process Parameters and Different Tool Path Strategies on the Quality of the CFRP Composites

Grigore Marian Pop(✉), Emilia Campean, Liviu Adrian Crisan, and Mihai Tripa

Technical University of Cluj-Napoca, Muncii Blvd., no. 103-105, Cluj-Napoca, Cluj, Romania
grigore.pop@muri.utcluj.ro

Abstract. Carbon fiber reinforced plastic (CFRP) composites are being used at a greater scale which is increasing the demands on automated production to improve productivity. These types of materials can be stronger than steel, about 40% lighter than aluminium, up to 80% lighter than steel and as stiff as titanium. Composite materials represent a good alternative to engineering materials, providing several important advantages in comparison to conventional materials, such as: light weight, mechanical and chemical resistance, low maintenance costs, high specific strength, higher stiffness and temperature stability, allowance of free forms modelling and specific design. Surface roughness evaluation is very important for many fundamental problems such as friction, contact deformation, heat and electric current conduction, tightness of contact joints and positional accuracy. For this reason, surface roughness, has been the subject of experimental and theoretical investigations for many decades. Also, surface roughness imposes one of the most critical constrains for the selection of machines and cutting parameters in process planning. In order to economically machine these materials with high part qualities, improvements in machining strategies must be made. This chapter presents the researches regarding different milling and drilling strategies in order to determine the best quality of the finished product. Flatness, parallelism, cylindricity, roughness and dimensional tolerances were measured using 3D CMM and the results were analysed using the Design Expert software.

Keywords: CFRP · Machining strategy · Design of experiments · Roughness · Infrared thermography · Education

1 Introduction

Composite materials represent a good alternative to conventional materials, providing several important advantages, such as: light weight, mechanical and chemical resistance, low maintenance costs, high specific strength, higher stiffness and temperature stability, allowance of free forms modelling and specific design.

Benefits from composite materials are especially important where weight control is critical, for example in the aerospace industry. They are also utilized at a greater extent

L. Wang et al. (Eds.): AMP 2020, LNME, pp. 325–344, 2020.
https://doi.org/10.1007/978-3-030-46212-3_25

due to its beneficial properties in the wind power industry, automotive, electronics and medicine (implants realized using advanced composite materials.

In industry, there are many discussions regarding the use of composite materials. The study of VDI (Association of German Engineers) shows an increased use of these type of materials from 28000 to/year in 2008 to 42000 to/year in 2012. The study expects an increase up to 130000 to/year in 2020 [7].

The challenges for automotive engineering are the reduction of gas emissions prescribed by the EU. Lightweight construction is an important lever for reducing fuel consumption. For this reason, automotive manufacturers are providing their developers and suppliers with quantitative guidelines for the continuous weight reduction of the components.

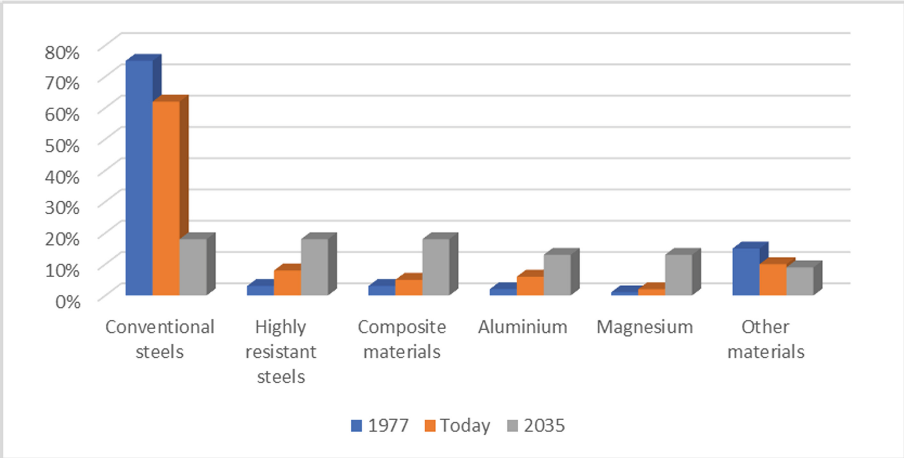

Fig. 1. Time evolution of types of materials used in a car (according to VDI)

Lightweight construction materials such as carbon fiber reinforced composites are increasingly replacing conventional steel, which thus loses its dominant role as a recent study of VDI also shows (see Fig. 1).

Nationally, for the moment at least, composite materials are not used in the manufacturing of the frames of mechanical machines, but internationally there are studies and researches regarding the replacement of classic materials of which mechanical parts of the machines are manufactured with components manufactured from carbon fiber reinforced composite materials. Analysing the published articles and the state of the art regarding the machining of composite materials, there are a few, but representative studies, in these areas [9, 15]. The researches presented in this chapter will be used in lecturers in higher education [16, 17].

The demand for high strength fiber composite components is set to increase across many industries until 2020, leading to solid market growth. According to VDMA (Verband Deutscher Maschinen und Anlagenbau, Mechanical Engineering Industry Association) the study of the demand for high-strength carbon-fiber composite components is rising by 17% a year. The results of this study present also the explicit demand of the companies to accelerate the research in this area. Another attractive aspect beside their performant mechanical properties is that the experts expect that the costs of fiber composite components will come down by around 30% by 2020. A conclusion of the studies indicates that there will be a strong growth in demand for these products, with the growing importance of lightweight construction across various industries. Challenge for engineering would be to drive down production costs through technological development, indicating a clear wish of the companies (sectors of industry, like automotive, aeronautics and wind energy), to intensify the researches in order to gain new knowledge in machining of carbon fiber reinforced composites [10].

2 Research Methodology

The methods of investigation involve solving the existing problems, such as: reduction of working times, increased productivity, cost reduction and improvement of the quality of the processed part.

First stage of this research has the role to identify and generate in working hypotheses. The existing researches were analysed and the relevant studies for the proposed theme were identified. After a detailed examination of the publications and of the knowledge existing in production, the work was focused on a step by step documentation of the information needed for identifying the machining parameters, which have influence on the quality of the machined carbon fiber reinforced composites.

Due to the variety of the machinability characteristics of different types of carbon fiber reinforced composites, an optimization of the process parameters is necessary for each type of material. Currently, the process parameters are experimental optimized by the users, which implies bigger costs.

The research was focused on three different tool paths for milling and drilling operations (Helical-Figs. 2 and 3, Zig-Zag Figs. 4 and 5 and iMachining, Figs. 6 and 7).

The three different tool paths were selected with the role of highlighting the degree of influence of the material removal method as well as of the tool trajectory on the quality of the material. The used strategies for this chapter are presented above.

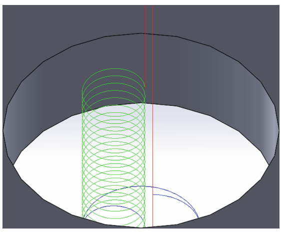

Fig. 2. Helical strategy for drilling

The Helical milling strategy uses a helical path for machining parts, while rotating around its own axis. The strategy combines the movement of the vertical z-axis with the horizontal x-y axis. The strategy has the advantage of generating low cutting forces while reducing the tool wear.

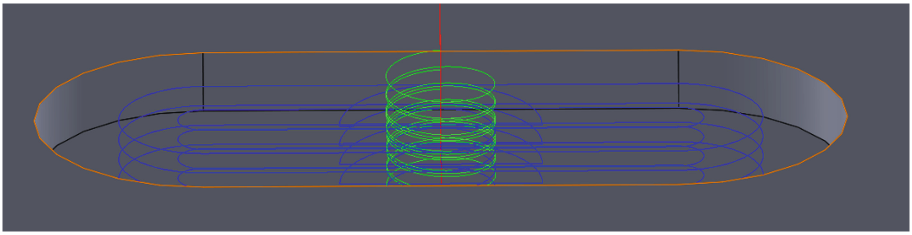

Fig. 3. Helical strategy for milling

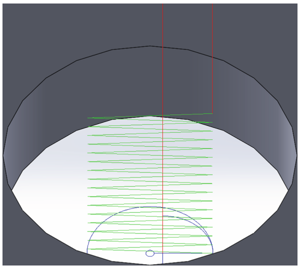

Fig. 4. Zig-Zag strategy for drilling

The Zig-Zag strategy uses parallel-linear paths for the material removal. The material is removed both in forward and backward movement, using a combination of two axis movement: the z axis with x or y axis.

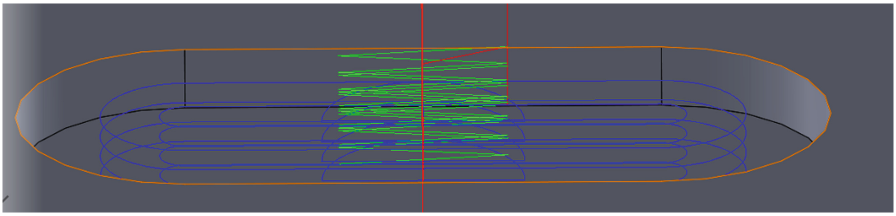

Fig. 5. Zig-Zag strategy for milling

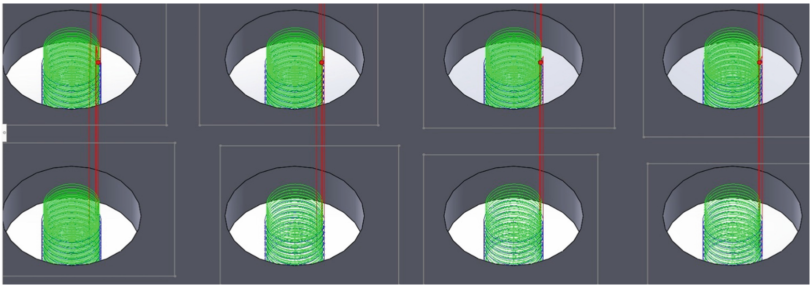

Fig. 6. iMachining strategy for drilling

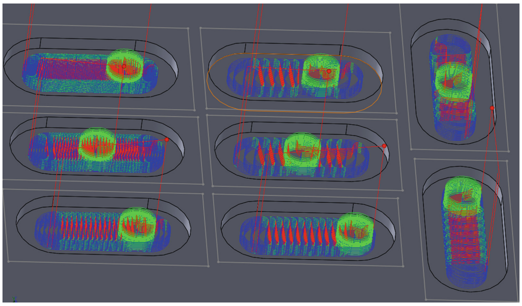

Fig. 7. iMachining strategy for milling

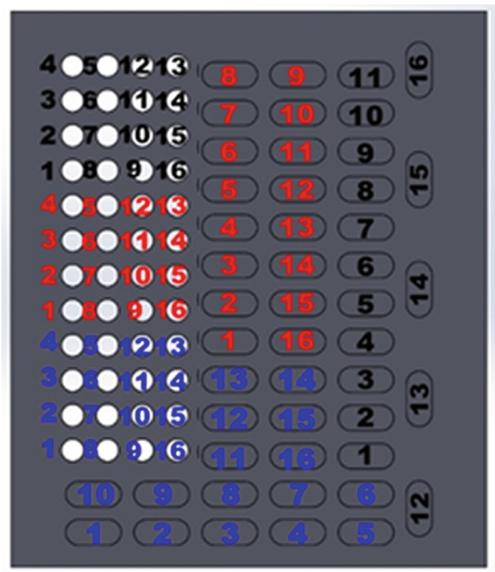

Fig. 8. Tool path strategy for each processed hole and slot (Blue-Helical, Red-Zig-Zag, Black-iMachining)

iMachining involves the establishment, by the program, of the optimal route necessary to be machined in order to remove the material with constant volume thus allowing a shorter processing time and a longer tool life (Fig. 8 and Table 1).

Table 1. Process parameters for each strategy

Operation	Helical		Zig-Zag		iMachining	
	Speed (rot/min)	Feed (mm/min)	Speed (rot/min)	Feed (mm/min)	Speed (rot/min)	Feed (mm/min)
1	11500	690	11500	690	11500	690
2	6500	390	6500	390	6500	390
3	7500	450	7500	450	7500	450
4	8500	510	8500	510	8500	510
5	7000	420	7000	420	7000	420
6	10000	600	10000	600	10000	600
7	9500	570	9500	570	9500	570
8	8000	480	8000	480	8000	480
9	10500	630	10500	630	10500	630
10	12000	720	12000	720	12000	720
11	5000	300	5000	300	5000	300
12	6000	360	6000	360	6000	360
13	5500	330	5500	330	5500	330
14	9000	540	9000	540	9000	540
15	11000	660	11000	660	11000	660
16	4500	270	4500	270	4500	270

3 Results

Surface roughness evaluation is very important for many fundamental problems such as friction, contact deformation, heat and electric current conduction, tightness of contact joints and positional accuracy. For this reason, surface roughness has been the subject of experimental and theoretical investigations for many decades. Also, surface roughness imposes one of the most critical constrains for the selection of machines and cutting parameters in process planning. Although many factors affect the surface condition of a machined part, parameters such as cutting speed, work piece condition, feed rate and depth of cut have more influences on the surface roughness for a given machine tool and work piece set-up [1].

Dimensional positioning, and geometrical tolerances such as cylindricity, parallelism and flatness [4], of each processed hole or slot was measured using the 3D measuring machine Axiom Aberlink twoo (Fig. 9), and the results were printed as shown in Fig. 10.

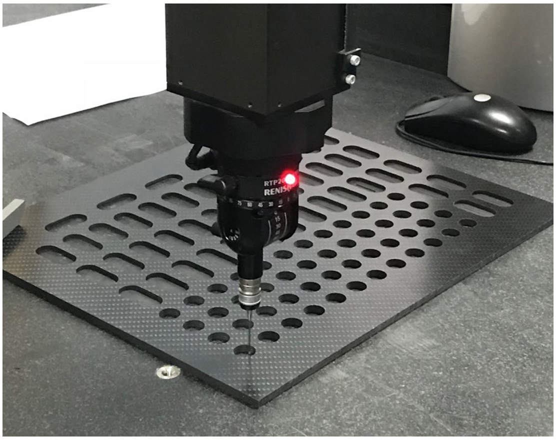

Fig. 9. 3D measurements

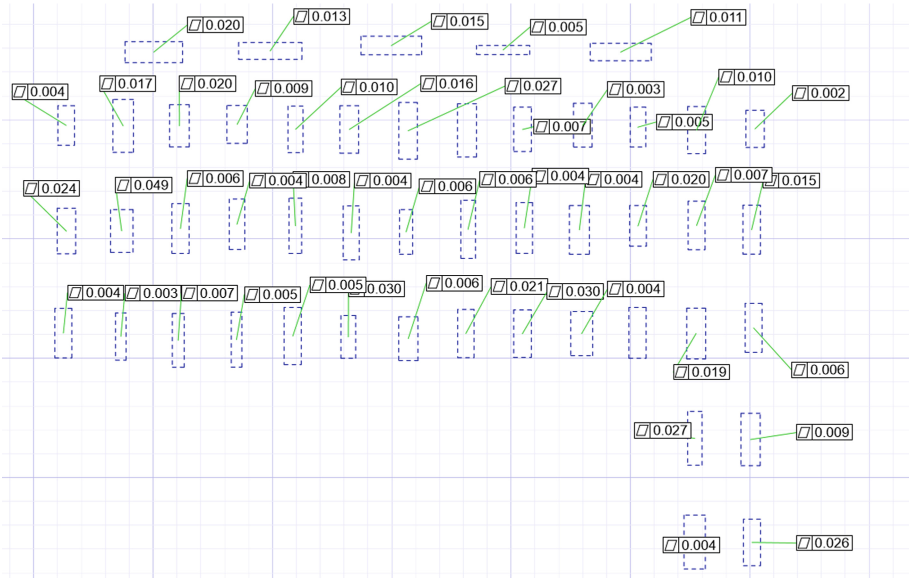

Fig. 10. Flatness deviation measurement report

Based on the results, using Design-Expert software v12 the following correlation charts were plotted in order to identify the influence of the process parameters on the obtained surface quality, for each tool path strategy (Figs. 11, 12 and 13).

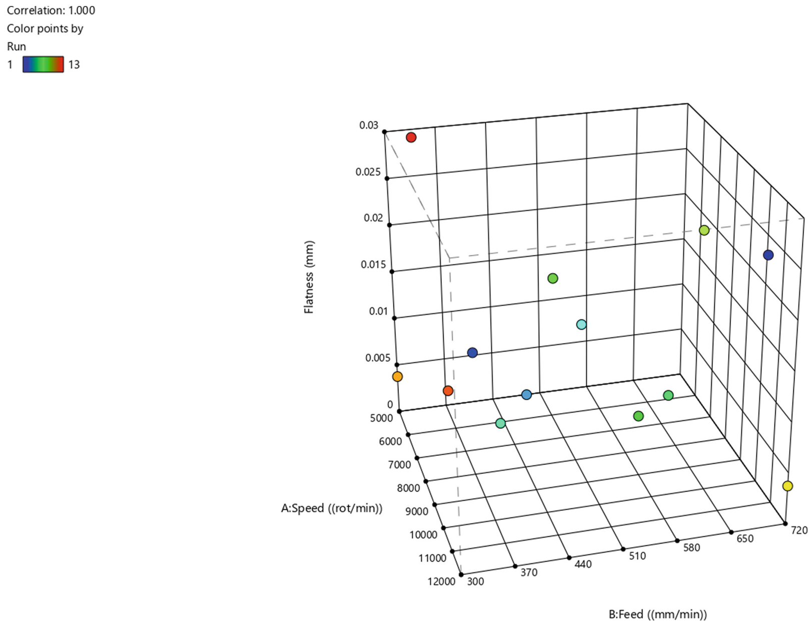

Fig. 11. Correlation chart for Helical strategy

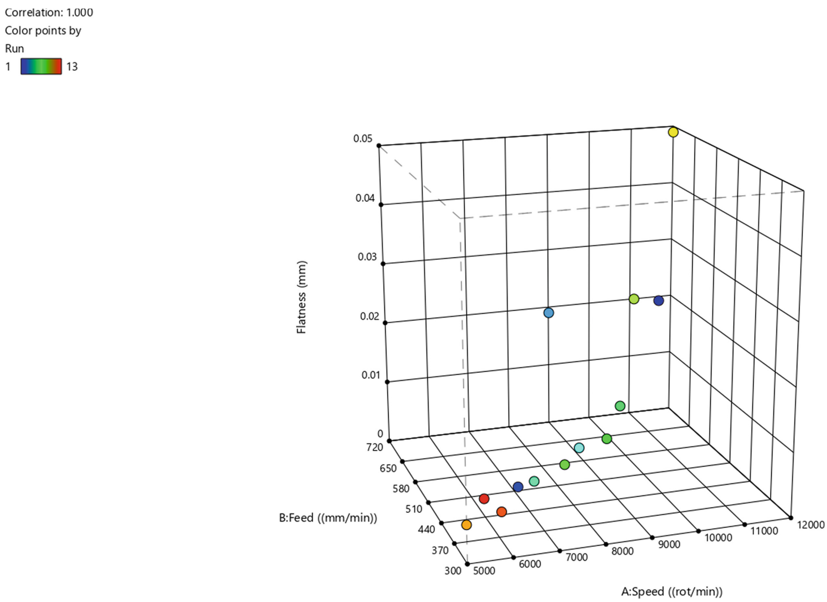

Fig. 12. Correlation chart for Zig-Zag strategy

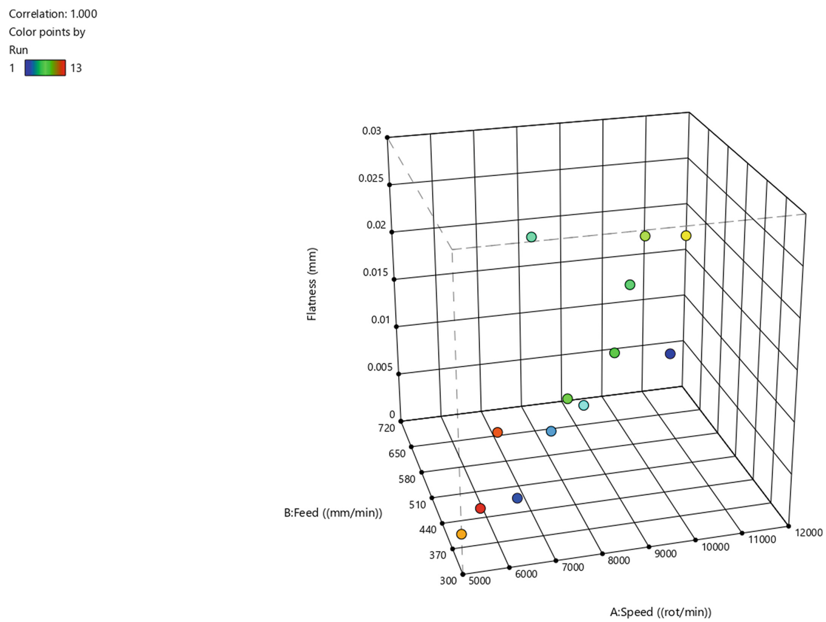

Fig. 13. Correlation chart for iMachining strategy

The best results were obtained for the iMachining method, where the values were constant for all the machining process parameters. The strategy that uses helicoidal displacements is the one for which the highest measured value of the flatness deviation was 0.027 mm. Removing material using only circular interpolation generates higher values for the flatness deviation.

Further the 3D measurement reports were plotted in order to determine the dimensional accuracy for each processed hole and the results are shown in Figs. 14 and 15.

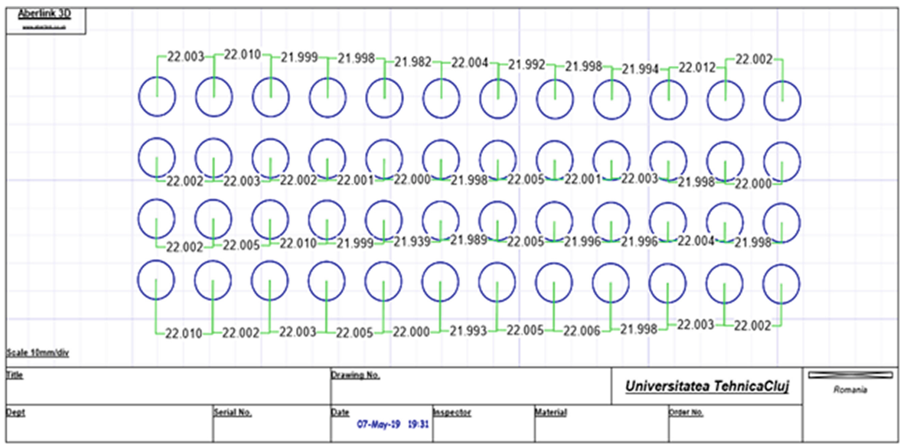

Fig. 14. Measurement report on x-axis

Fig. 15. Measurement report on y-axis

As for the milled slots the distances and parallelism between the flanks was also measured, the results were plotted in Fig. 16.

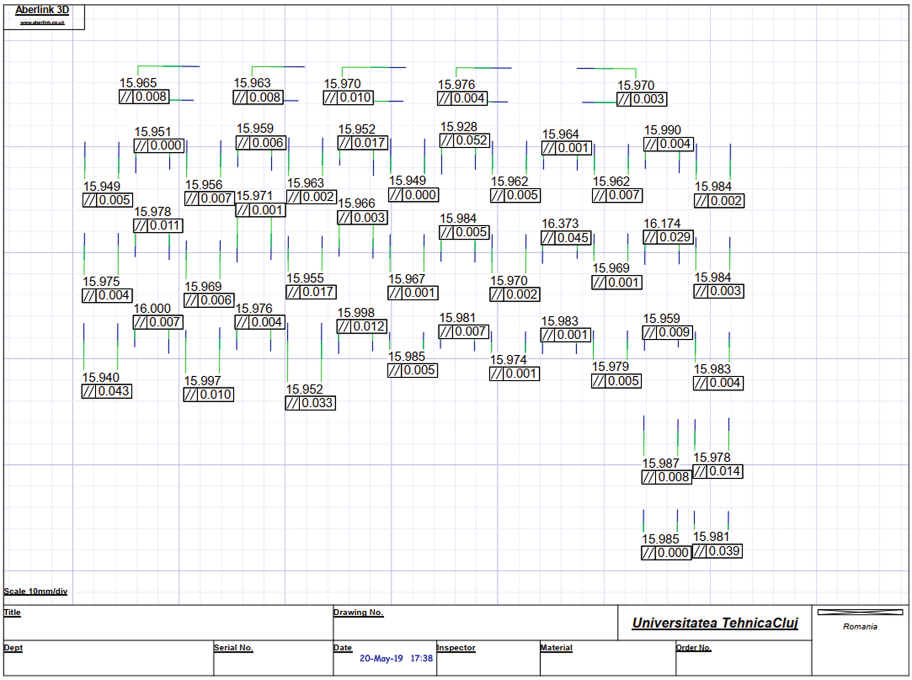

Fig. 16. Measurement report for parallelism deviation and thickness of the slots

For each processed hole the cylindricity deviation and the diameter was also measured, and the results were plotted into the correlation charts presented in Figs. 17, 18, 19 and 20.

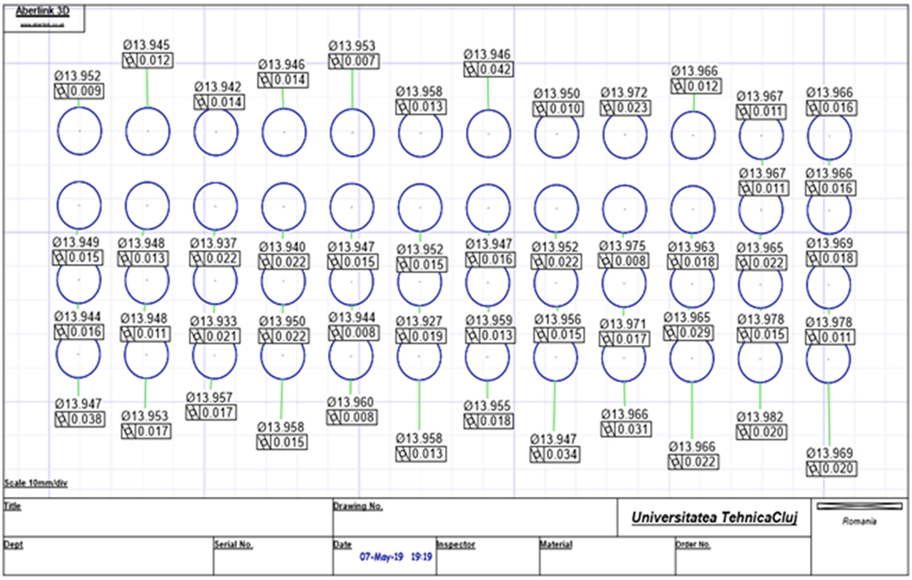

Fig. 17. Measurement report for cylindricity deviation and diameter

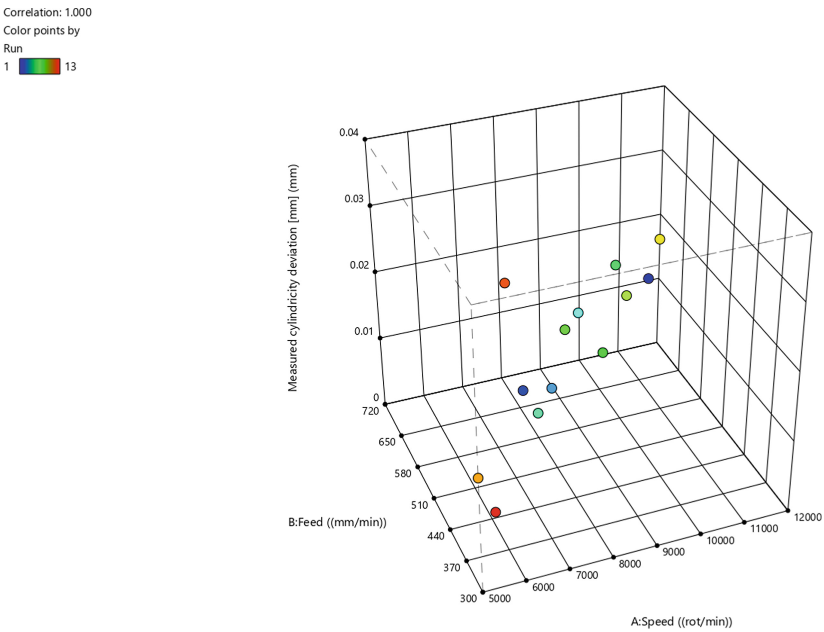

Fig. 18. Correlation chart for Helical strategy

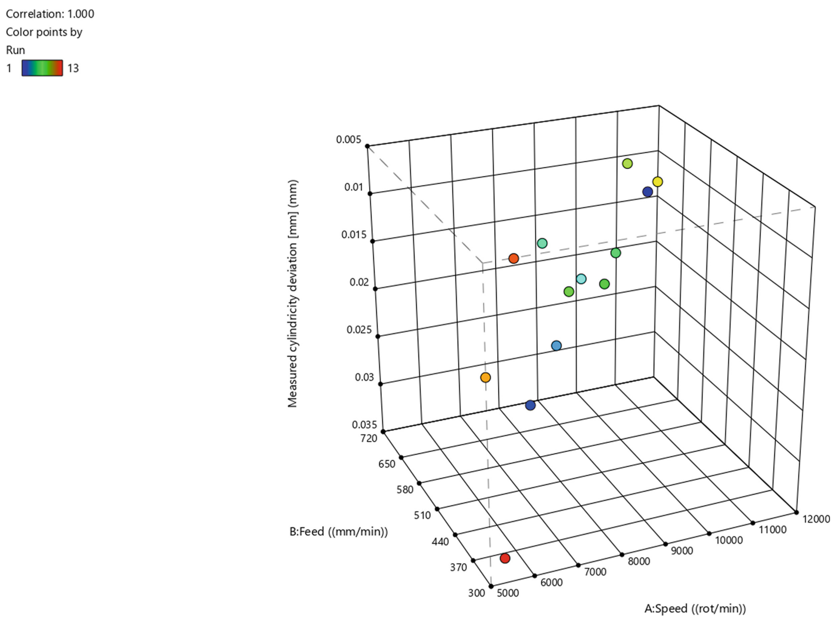

Fig. 19. Correlation chart for Zig-Zag strategy

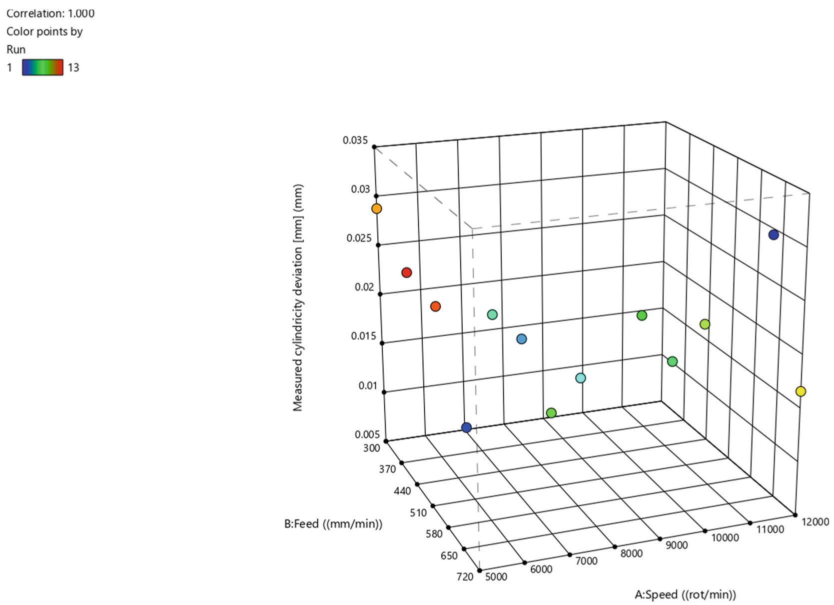

Fig. 20. Correlation chart for iMachining strategy

As in the case of the flatness analysis, the results obtained show that the iMachining strategy generates the most constant values. This strategy allows a constant machining. The biggest deviations were obtained for the Zig-Zag strategy, concluding that machining only on two axis does not lead to good result in terms of cylindricality.

Further the roughness parameters were measured using a roughness tester from Namicon, TR220. The evaluation length, ln, was set to 12.5 mm and the sampling length, lr, was set to 2.5 mm according to ISO 4288. The results are presented in Tables 2, 3 and 4.

Table 2. Measured roughness values for each processed slot

Nr op	Helical						
	Ra[μm]	Rq[μm]	Rz[μm]	Rt[μm]	Rp[μm]	Rv[μm]	Ry[μm]
1	0.67	0.902	3.667	5.722	2.101	1.566	5.722
2	1.096	1.329	5.031	6.953	2.484	2.546	6.953
3	0.682	0.873	4.273	5.82	1.789	2.484	5.82
4	1.144	1.461	6.207	10.05	2.699	3.507	10.05
5	0.985	1.235	5.21	6.894	2.402	2.808	6.894
6	0.991	1.229	5.421	7.48	2.972	2.449	7.48
7	0.594	0.79	3.316	5.722	1.265	2.05	5.722
8	1.327	1.6	6.421	8.808	2.875	3.546	8.808
9	0.953	1.203	4.835	7.91	2.531	2.304	7.91
10	0.797	1.012	4.984	8.906	2.082	2.902	8.906
11	0.871	1.13	4.976	7.089	2.292	2.683	7.089
12	0.835	1.021	4.48	6.289	1.878	2.601	6.289
13	1.195	1.459	6.269	8.261	3.074	3.195	8.261
14	1.164	1.42	5.132	7.363	2.64	2.492	7.363
15	0.833	1.08	5.171	7.148	2.488	2.683	7.148
16	0.809	1.04	4.703	7.148	2.339	2.363	7.148

For the first 13 operations, of each tool path strategy shown, correlation charts were plotted in order to establish the relation between the roughness values of Ra, Rz and the process parameters (see Figs. 21, 22, 23, 24, 25, 26, 27, 28 and 29).

The Helical strategy seems to be more constant regarding the Ra parameter, having 7 values between 0.5–1 μm. Comparing these strategies over the range of operations, iMachining optimization strategy manages to obtain the best Ra values.

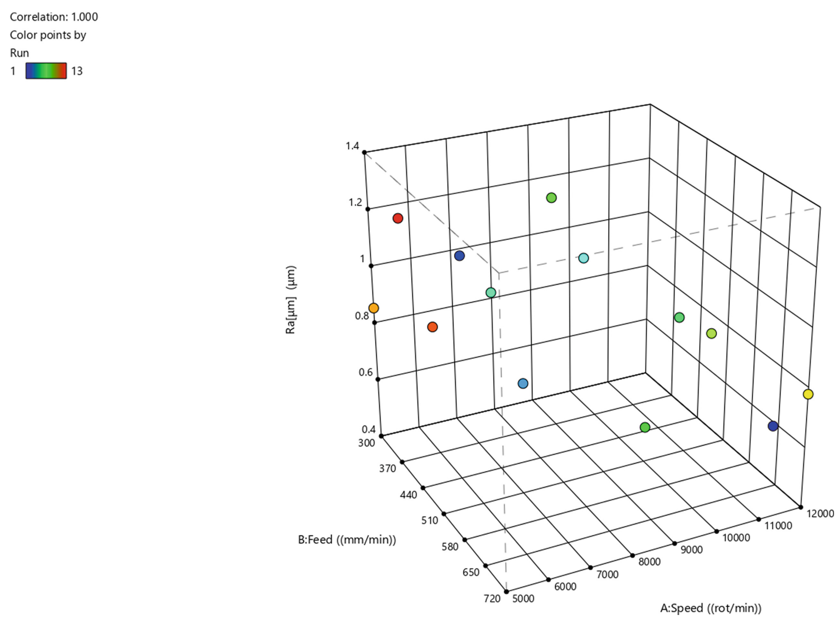

Fig. 21. Correlation chart for Helical strategy, Ra values

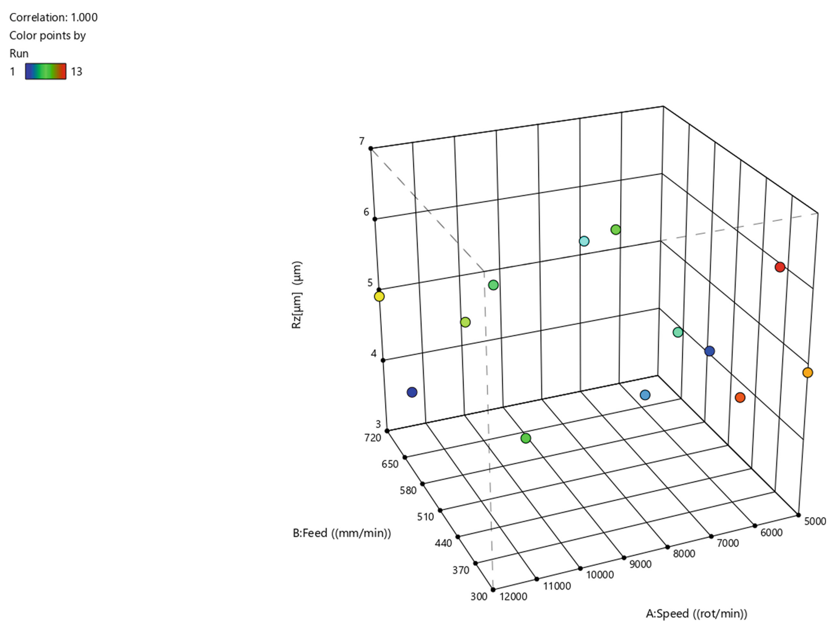

Fig. 22. Correlation chart for Helical strategy, Rz values

The Zig-Zag method involves surface machining using the maximum tool path length and maximum cycle time. For that reason, using the same tool and tool parameters, the Zig-Zag strategy generates constant values for Ra parameters, values that are higher than the one obtained for the other strategies, partly due to the large surface area to be milled in a single pass.

Table 3. Measured roughness values for each processed slot

Run	Zig-Zag						
	Ra[μm]	Rq[μm]	Rz[μm]	Rt[μm]	Rp[μm]	Rv[μm]	Ry[μm]
1	0.628	0.839	3.082	6.132	1.671	1.41	6.132
2	0.971	1.193	4.554	7.167	1.656	2.898	7.167
3	0.816	0.986	4.496	6.035	2.097	2.398	6.035
4	0.766	0.998	4.285	6.367	2.109	2.175	6.367
5	0.623	0.811	4.125	6.894	1.789	2.335	6.894
6	0.857	1.143	4.941	10.39	2.117	2.824	10.39
7	0.654	0.826	4.527	5.976	2.132	2.394	5.976
8	0.698	0.922	5.121	7.656	1.953	3.167	7.656
9	1.522	1.947	9.558	12.92	4.07	5.488	12.92
10	1.475	1.838	8.679	13.28	4.089	4.589	13.28
11	0.84	1.04	4.777	7.441	2.007	2.769	7.441
12	0.765	0.973	5.289	6.601	2.199	3.089	6.601
13	0.574	0.722	4.769	8.242	2.363	2.406	8.242
14	0.917	1.255	7.335	14.68	3.167	4.167	14.68
15	0.648	0.898	4.402	7.812	1.664	2.738	7.812
16	0.934	1.174	4.906	7.851	1.914	2.992	7.851

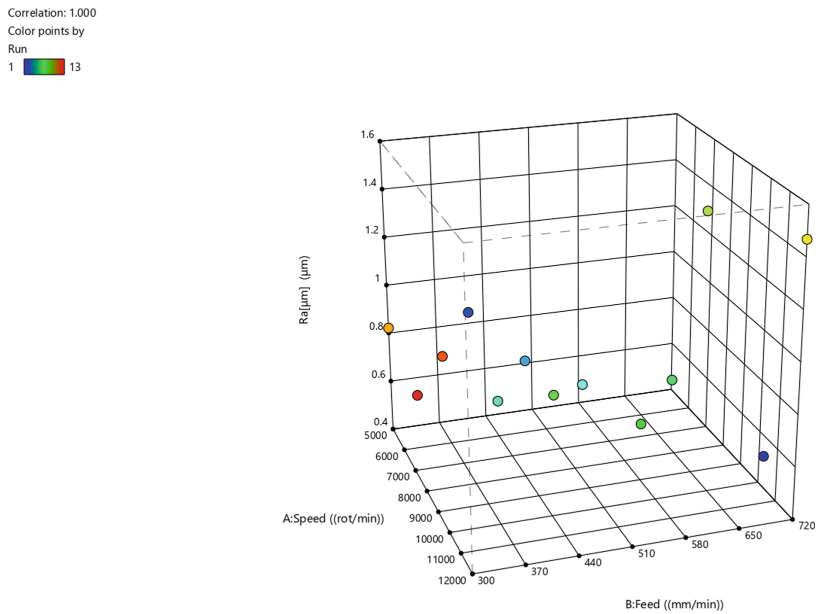

Fig. 23. Correlation chart for Zig Zag strategy, Ra values

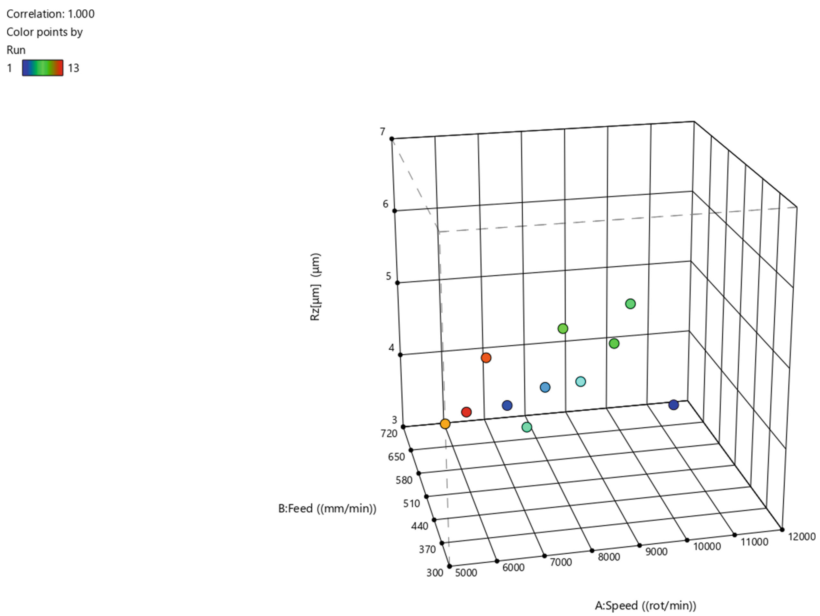

Fig. 24. Correlation chart for Zig Zag strategy, Rz values

The iMachining strategy uses constant volume removal of the material. Taking into consideration the amount of material that needs to be machined would be the reason for obtaining the smallest results. In this way, we obtain a shorter processing time and a longer tool life.

Table 4. Measured roughness values for each processed slot

Run	iMachining						
	Ra[µm]	Rq[µm]	Rz[µm]	Rt[µm]	Rp[µm]	Rv[µm]	Ry[µm]
1	0.472	0.619	2.734	4.199	1.058	1.675	4.199
2	0.635	0.787	3.382	5.253	1.507	1.875	5.253
3	0.722	0.938	3.781	6.621	1.73	2.05	6.621
4	0.541	0.683	2.945	4.707	1.21	1.734	4.707
5	0.513	0.703	3.781	6.171	1.359	2.421	6.171
6	0.664	0.868	5.425	9.863	2.605	2.82	9.863
7	0.593	0.754	2.902	5.839	1.687	1.214	5.839
8	0.636	0.792	3.945	6.132	1.925	2.019	6.132
9	2.239	2.837	13.07	28.78	6.039	7.035	28.78
10	1.773	2.214	10	15.15	4.015	5.988	15.15
11	0.458	0.665	3.425	7.421	1.562	1.863	7.421
12	1.06	1.434	8.398	10.66	2.82	5.578	10.66
13	1.216	1.598	8.304	11.52	3.039	5.265	11.52
14	1.22	1.549	7.363	9.765	3.679	3.683	9.765
15	1.026	1.29	5.703	8.769	2.867	2.835	8.769
16	1.169	1.527	7.128	12.69	4.105	3.023	12.69

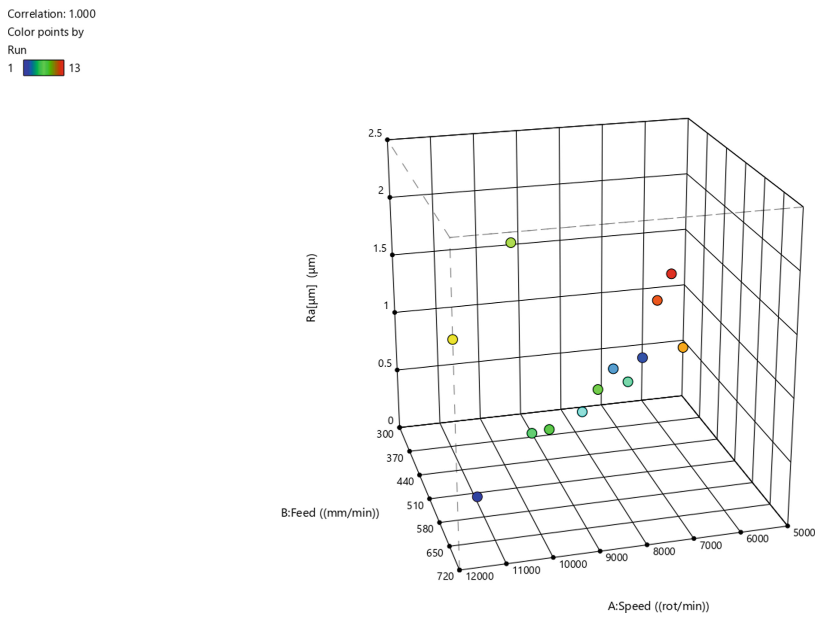

Fig. 25. Correlation chart for iMachining strategy, Ra values

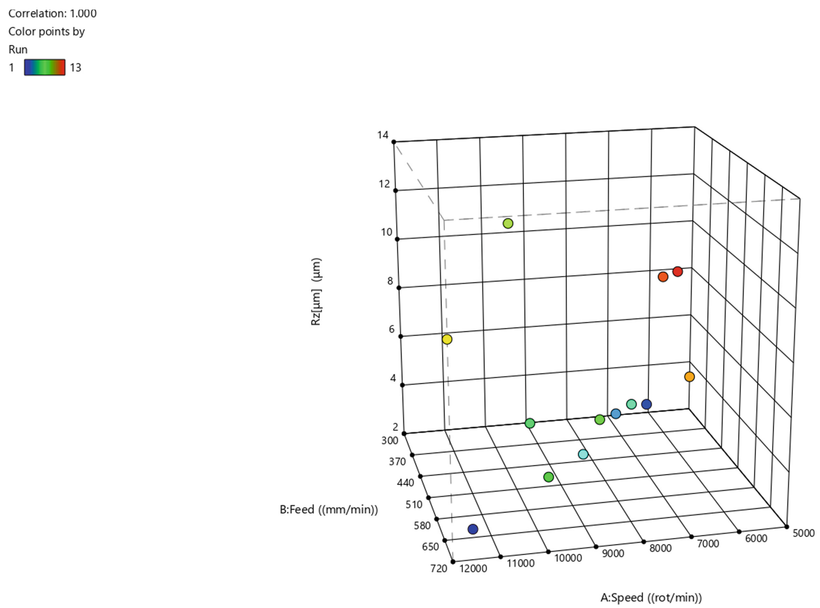

Fig. 26. Correlation chart for iMachining strategy, Rz values

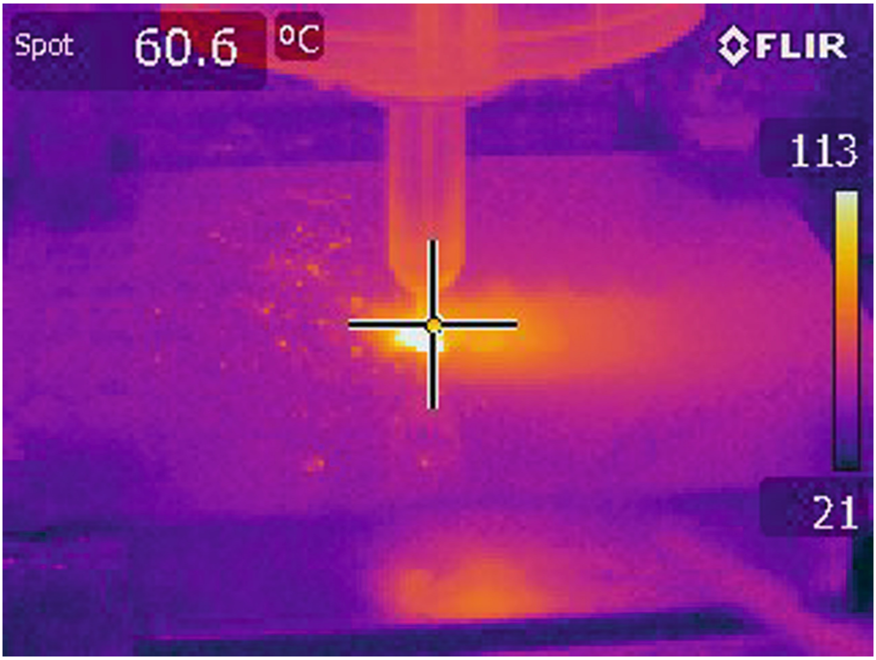

Fig. 27. Thermal image registered during the milling process

When analysing the feed and speed of the process, the surface roughness values increase whit the feed and speed rates. Therefore, all the parameter combinations and tool path strategies studied in this chapter influence the surface quality of the machined part.

Previous research show that the thermo-physical properties of the fibre reinforced polymers causes high temperatures at the tool tip when machined [13]. Another reason that must be considered is the fact that especially thermoplastic polymers have a glass transition temperature ranging from 150–250 °C, meaning that the heat formation during the milling process can lead to plasticizing of the polymer matrix [13]. The machining of fibre reinforced polymer materials presented in this chapter was performed without cooling lubricant. The coolant can imbue the plastic material and can induce chemical reactions with certain functional groups of the macromolecules [13]. Process temperatures have been recognized as an important factor influencing the tool wear rate and tool lifetime [14]. The process temperatures were also measured, for each machining operation, using a thermal camera, Flir ThermaCam E50. An example of a registered thermal image is presented in Fig. 27. During the experiments the temperatures did not exceed 113 °C.

4 Conclusions and Further Research Strategies

The researches presented in this chapter were focused on experiments to determine the process parameters that have influence on the quality of the finished product (form deviations, positional accuracy and roughness parameters).

Correlation charts were plotted using Design Expert v12 software in order to identify the best suited strategy and process parameters, to obtain the best quality of the finished products.

The measured values were linked to the process parameters used for machining and the aim was to determine the optimal process parameters and tool geometries in order to obtain the best quality of the processed parts.

The Zig-Zag strategy. generated, as expected, the lowest results of the measured parameters for all strategies.

iMachining strategy generates the best quality compared to Zig-Zag and Helical strategy, due to the constant machining of the tool.

The process temperatures were also be measured for each machining operation, using infrared thermography. The aim of these research is to further investigate if there is a relation between the process temperatures and the machined surface quality.

Testing and analysis of the proposed solutions and identifying the improved directions can give relevant results that can be used in further researches in this domain.

As for further research strategies based on the measurements presented in this chapter we can conclude:

- Mathematical models will be developed, equations that will correlate the important machining parameters with the values of the obtained roughness parameters and the measured dimensional and geometrical tolerances. These equations will be able to predict the values of the roughness parameters and the dimensional accuracy when machining these types of materials.
- Machining of different types of carbon fiber reinforced materials, having different thickness, containing different amounts of fibers, and different fiber orientation, using tools with different geometries. Afterwards, tool wear, delamination, dimensions, geometrical deviations and surface roughness parameters should be measured.
- Validating the generated equations by experimental researches. The values obtained with the developed equations will be compared with the values obtained by experimental measurements.

References

1. Palanikumar, K.: Modeling and analysis for surface roughness in machining glass fiber reinforced plastics using response surface methodology. Mater. Des. **28**(10), 2611–2618 (2007). www.elsevier.com/locate/matdes
2. Voss, R., et al.: Influence of fiber orientation, tool geometry and process parameters on surface quality in milling of CFRP. CIRP J. Manuf. Sci. Technol. (2016). https://doi.org/10.1016/j.cirpj.2016.10.002/

3. Abdul Nasir, A.A., Azmi, A.I., Khalil, A.N.M.: Measurement and optimisation of residual tensile strength and delamination damage of drilled flax fibre reinforced composites, Measurement **75**, 298–307 (2015). https://www.journals.elsevier.com/measurement
4. Dragomir, M., Popescu, S., Płowucha, W., Marxer, M.: Blended learning in the field of measurement uncertainty. experiences from the MUVOT project. In: Proceedings of the 2nd International Conference Quality and Innovation in Engineering and Management, Cluj-Napoca, Romania, 22–24 November. Published in a special issue of Quality - Access to Success, vol. 13, no. SUPPL. 5, pp. 127-130 (2012). ISSN 1582-2559
5. Uhlmann, E., Sammler, F., Richarz, S., Heitmüller, F., Bilz, M.: New production technologies in aerospace industry. In: 5th Machining Innovations Conference (MIC 2014) Machining of Carbon Fibre Reinforced Plastics, Procedia CIRP, vol. 24, pp. 19–24 (2014)
6. http://www.kfz-betrieb.vogel.de/cfk-raeder-gehen-2016-in-serie-a-505562/. Accessed 21 Dec 2016
7. http://www.ressourcedeutschland.de/fileadmin/user_upload/downloads/kurzanalysen/2014-Kurzanalyse-03-VDI-ZRE-CFK.pdf. Accessed 22 Dec 2016
8. https://www.welt.de/motor/article125550098/Auch-die-edlen-Carbon-Felgen-haben-ihre-Tuecken.html. Accessed 05 Jan 2017
9. http://www.io-journal.de/neu-auf-der-emo-hannover-steigerung-der-wirtschaftlichkeit-durch-cfk-traegerelemente-fuer-den-werkzeugmaschinenbau/. Accessed 05 Jan 2017
10. http://www.ingenieur.de/Themen/Werkstoffe/Serienfertigung-CFK-Alleine-es. Accessed 07 Jan 2017
11. http://www2.coromant.sandvik.com/coromant/eBook/Composite/eng/pdf/C-2940-155.pdf. Accessed 09 Jan 2017
12. http://www.sandvik.coromant.com/sitecollectiondocuments/downloads/global/technical%20guides/en-gb/c-2920-30.pdf. Accessed 09 Jan 2017
13. Wilfried, K., Peter, G.: Temperaturbestimung beim Bohren Faserverstaerkte Kunstoffe Hilfsmittel Thermographie. In: VDI-Z, pp. 132–138 (1990)
14. Wen-Chou, C.: Some experimental investigations in the drilling of carbon fibre-reinforced plastic (CFRP) composite laminates. Int. J. Mach. Tools Manuf **37**(8), 1097–1108 (1997)
15. http://www.cfk-maschinenbau.de/cfk-im-maschinenbau
16. Crişan, A.: Proiectarea cursurilor universitare, de la calitate la inovaţie, Editura Didactică şi Pedagogică, București, p. 218 (2016). ISBN 978-606-31-0337-7
17. Crişan, A.: Strategii curriculare în învăţământul universitar, ed. Institutul European, Iași, p. 260 (2013). ISBN 978-606-24-0006-4