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A Comparative Analysis of Milling Strategies of Complex Geometry Surfaces

This paper analyses the influence of machining strategies and cutting parameters on the milling of aluminium complex geometry parts. In the first experimental phase, parts were machined with a combination of two roughing strategies and three finishing strategies, with recommended machining parameters. The machining time, machining surface roughness, and the surface geometric accuracy were measured. In the second phase, a new sample was machined with corrected cutting parameters using the best strategy adopted from the first phase. The results have shown that the selection of machining strategy and cutting parameters significantly affects the productivity, quality, and accuracy when machining complex geometry parts.

Keywords: *milling strategies, complex geometry, productivity, accuracy, surface roughness*

1. INTRODUCTION

The very rapid development of complex geometry products, which was a technological challenge in the development of the automotive and aviation industries, as well as the propeller, turbine, and machine tool industries, required the acceleration and improvement of CAD systems [1]. Although modern CAD systems have enabled users to model shapes with very complex geometry, a new problem has emerged - how to make those parts and meet the following requirements at the same time: accuracy, quality, and cost of machining [2].

Many authors point out that the selection of a toolpath is critical in the technological process planning. Typically, tool paths are selected from standard toolpath libraries in commercial CAM software [3, 4]. When machining complex geometry models, milling is the most problematic, especially when making complex molds for plastic injection molding and plastic blow molding [4, 5].

Izol et al. l [4] indicate that applying standard tool paths from a toolpath file significantly complicates the machining process. Then, it is necessary to choose an appropriate strategy for each surface to be machined in each specific case. This further complicates and prolongs the process of planning. In many cases, additional topographical analysis of surfaces is also required [6,7]. In paper [4] a methodology is proposed for checking the validity of the machining strategy where the first machining strategy is selected in CAM and where not all the problems that occur during machining are taken into account. The authors suggest an overview of the machining strategy in virtual machining, which requires a relatively short time. Thus, if certain problems are observed, this strategy is unsuitable for the entire surface. The authors suggest that in that case, the surface should be divided into groups or regions (vertical, curved, horizontal, etc.) and different strategies for each region should be used. This significantly increases programming time, which is the problem in this proposal. However, this shortcoming is partially compensated for by reducing the number of machining errors and the time needed to eliminate them. Optimization of a machining strategy is particularly obvious in manufacturing objects with minimum surface roughness and minimum machining cost [11, 13, 14]. After machining, it is often necessary to leave an extra surface for grinding and polishing so that the machined surface is according to the tolerance limits on the drawing. Choosing the appropriate strategy can minimize or eliminate finishing and significantly reduce machining time, i.e., machining costs. The analysis of different finishing milling strategies of a complex geometry part containing concave and convex surfaces and the machining quality can be evaluated through the comparison of surface roughness, surface texture, and dimensional control parameters [11].

Products with complex geometry place strict demands on modern machining in terms of achieving adequate productivity rate, machined surface quality, dimensional accuracy of a part, and reduction of machining costs. A large percentage of these products are made of aluminum and its alloys due to well-known properties such as good tensile strength and specific weight ratio, and machinability at least. Tightening the mentioned requirements requires complex and fast research on the influence of machining conditions, machining strategies, and cutting process parameters on machinability indicators [15, 16].

Over the last three decades, different sensing elements such as milling force, spindle and cutting power, and noise/ sound measurement sensors have been commonly used to determine cutter life, wear, deflection and chatter, etc. [17, 18]. Some researchers have used machining acoustic measurement approaches to observe cutting parameters or cutting tool wear [19, 20]. For

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example, acoustic methods were used to detect the stability lobe in a machining process using sound mapping techniques [21]. Some authors used acoustic signals and compared the tool life's cumulative sound spectrum and roughness [22]. Others investigated the possibility of using acoustic signals to observe the complex surface machining and to evaluate the effect of cutting parameters and tool path strategies. Machining forces, tool deflection, sound pressure levels, and surface errors were measured and analyzed [23]. Recent research about Artificial Neural Networks (ANN) can help predict the milling toolpath strategy to establish which milling path strategy or sequence will show the best results [24].

Analysis of previous works showed that free-form surfaces must be commonly machined with traditional processes until a certain degree of surface finishing, and the toolpath must be generated with computer-aided applications. The authors [25] indicate the importance of implementing new theoretical strategy operations to control toolpath and trajectories in traditional strategies. In addition to the existing processing strategies, what is needed now is a validation of new strategies in computer-aided applications regarding time minimizing and how the cutting parameters affect the final surface result. The authors simulated two case studies with a commercial CAx application (3DEXPERIENCE), and they only analyzed machining strategies but not the quality of the machined surface. The authors suggested that all the machine tool features must be defined – geometry and kinematics, but also the dynamics of different elements - speeds, and the acceleration and deceleration of a model in each axis. This implies a correct definition of the digital twin model is needed [25].

This paper analyses the influence of machining strategies and cutting parameters on machinability indicators. The machining time, surface roughness, and part shape accuracy were chosen and measured as a machinability indicator.

The paper proposed an approach to defining the optimal machining strategy and optimal machining parameters when milling a part of complex geometry with concave and convex surfaces. The point is to select an optimal roughing and finishing strategy through the first phase of testing. In the second phase, optimal processing parameters were chosen for the adopted machining strategy. The advantage of the offered methodology is reflected in the implementation of CAD inspection of a part with complex geometry in certain stages of testing. Namely, after the first phase of testing, using the CAD inspection, regions with the largest deviations are located on concave and convex surfaces, which are minimized in the next phase. In the second phase, based on the adopted most favorable roughing and finishing strategy and detected deviations using the CAD inspection, machining parameters are adapted, whereby satisfactory results are achieved according to all tested machinability indicators: processing time, surface roughness, and accuracy of the shape of the part. Such testing methodology through these two phases takes longer, but, as a result, it satisfies all the machinability requirements and the production of parts without deviations in the shape of the part and surface roughness beyond the permitted limits. In this way, longer production preparation time is compensated.

2. EXPERIMENTAL RESEARCH

Experimental research was divided into two phases. In the first experiment phase, workpieces were machined with combinations of two roughing strategies, noted Hatch and Contour, and three finishing strategies, noted Constant step over, Spiral, and Linear [26]. In this phase, the literature recommended cutting parameters such as depth of cut, radial depth, feed rate, and cutting speed [27, 28]. After analyzing the first phase results, in the second experiment phase, a new workpiece was machined with corrected and adapted cutting process parameters using the best strategy combination from the first experimental phase.

The tests were performed on an Emco Concept MILL 450 three-axis milling machining center with a Sinumerik 810D / 840D control unit with a Windows platform (Figure 1.) located in the Laboratory at the Faculty of Mechanical Engineering in Banja Luka. The working space of the machining center in the x, y, and z-axis directions was 700x520x500, respectively. The machining center has a magazine for 20 tools and a tool holder ISO-40.

In the experimental tests for 3D milling, a Dormer carbide two flute ball mill, type S501, body length 83 mm, and diameter d_c = 12 mm was used. This milling tool was used for roughing and finishing. The cutting length was l_2 = 22 mm, radius r = 6 mm, the angle of the helix was ω = 30°, and the rake angle of the cutting wedge was γ = 10°. Coolant and lubricant were used during the machining (oil emulsion - Castrol Hysol T15 in the ratio 1/10), supplied from the tank system of the machine with a capacity of 60 liters, under a pressure of 2 bar, by two nozzles, directly into the machining zone.

Figure 1. Experimental setup

The samples for experimental tests were prepared using aluminum alloy Al 5083, known for its exceptional performance when working in extreme condi–

tions. In addition, it is highly resistant to the influence of water and the industrial chemical environment. Due to its strength and corrosion resistance, Al 5083 is widely used in marine applications, soil containers, transport equipment, communications, etc. The specific mass of this material is ρ_{spec} = 2660 kg/m³, tensile strength ranges from R_m = 270-345 MPa, while Brinell hardness is 75HB. The dimensions of the raw material were 80x60x40mm. This aluminum alloy is soft, so it tends to form a built-up edge (BUE) during machining, which is especially pronounced when milling with a ball mill, Figure 2.

Table 1. Workpiece material alloyed elements

Chemical composition (%)							
Mn	**Fe**	**Cu**	**Mg**	**Si**	**Zn**	**Cr**	**Ti**
0.4 - 1	0.4	0.1	4 – 4.9	0 – 0.4	0 – 0.1	0.05 – 0.25	0.15

The process planning for different machining strategies for a specific part with a complex surface was done in the SolidCAM program. SolidCAM provides support in programming all types of CNC machines. It is integrated with the SolidWorks CAD package, and together they represent a concept whose advantage is reflected in toolpath associativity and the geometry of the machined object.

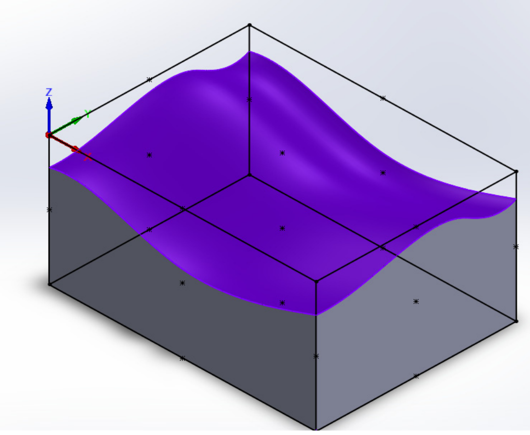


Figure 2. CAD model of the workpiece

The machining time, machining surface roughness, and the surface geometric accuracy were analyzed. Machined surface roughness was measured in three characteristic points on the workpiece by a Mitutoyo SJ-301 device. Dimensional and shape accuracy was inspected by a MCAx20+ multisensory measuring system arm with an MMDx100 integrated laser scanner, Figure 3.

A classic digital stopwatch was used to measure the main machining time (roughing and finishing), while the MITUTOYO SJ-301 roughness measuring device with PC software for processing measurement results was used to measure the roughness of machined surfaces. The operation of this device and the performing of measurements comply with the ISO 4287 standard. Two parameters describing the roughness of the machined surface were measured and analyzed, Ra and Rz. In addition to the numerical display of the parameters set, the device also provides a visual image of the recorded surface in a specific resolution, and a printed version is possible that shows an image of the machined surface with selected parameters for measurement.

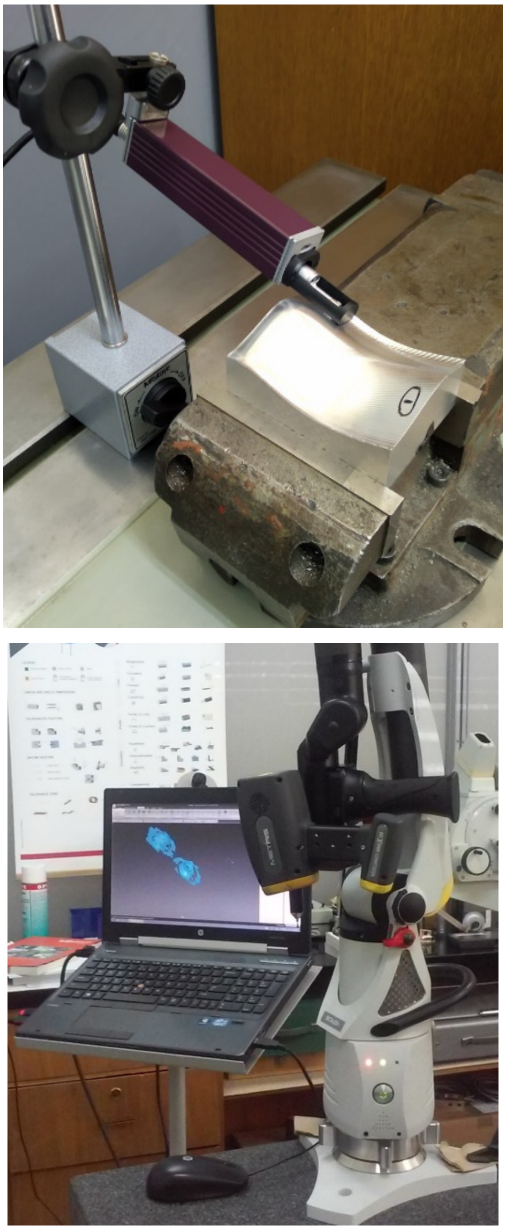


Figure 3. Measuring equipment for surface roughness (above) and dimensional accuracy (below)

When machining was completed, the geometric accuracy of machined surfaces was analyzed using the CAD inspection method, which is based on comparing the digitalized model of the machined surface and the CAD model [29]. To perform this procedure, it is necessary to obtain all geometric and dimensional information about tested parts quickly and efficiently [30, 31]. Geometric accuracy was analyzed using a manual coordinate measuring arm (MCAx20+) with an MMDx100 integrated laser scanner, and a multisensory measuring system, Figure 3.

2.1 The first phase of experimental research

In the first phase, three samples were processed with combinations of two roughing strategies (Hatch and

Contour), and three finishing strategies (Constant step over, Spiral, and Linear) with the recommended cutting parameters. In Table 2, combinations of roughing and finishing machining strategies are presented. All three workpieces were machined with the same parameters to analyze the impact of selected machining strategies on the main roughing and finishing times, machined surface roughness, and the geometric accuracy of machined surfaces using the technique of Reversible engineering (RE).

Table 2. Roughing and finishing strategies in the first phase

Exp. no.	Roughing strategy		Finishing strategy	
EXP1	SR1	Contour	SF1	Constant step over
EXP2	SR 2	Hatch	SF2	Spiral
EXP3	SR 1	Contour	SF3	Linear

Cutting process parameters have been adopted according to the recommendations of the Dormer cutting tool manufacturer. Rough machining parameters included radial depth of cut ae = 2 mm; depth of cut ap = 1.5 mm; feed rate vf = 400 mm/min; number of revolutions n = 4000 o/min; cutting speed vc = 150.72 m/min. Finishing parameters amounted to radial depth of cut ae = 1 mm; depth of cut ap = 0,5 mm; feed rate vf = 300 mm/min; number of revolutions n = 6000 o/min; cutting speed vc = 226.08 m/min.

When determining roughing parameters for selected machining strategies, one has defined cutting depth (Step field) of 1.5 mm and 83% toolpath overlap (overlapped field). This was set based on the radial depth of cut of 2 mm and milling diameter of 12 mm, Figure 4. In finishing, the depth of cut equals the defined residuum after roughing, i.e., 0.5 mm, whilst the radial depth of cut was determined in the step field, and it was 1 mm. Tool approaching was set on linear by a safety distance of 2 mm, and lead in/out was in a linear direction. In the finishing strategy, constant step-over machining went one way, and milling was in one direction (Conventional) starting from the outside. In the spiral finishing strategy, the linear type of spiral machining was chosen on the model pick center of the helical toolpath. The linear toolpath was selected for the finishing strategy noted as linear, with a one-way machining direction and radial depth of cut of 1 mm, Figure 5. Profile error was set to the standard value of 0.01 for finishing strategies.

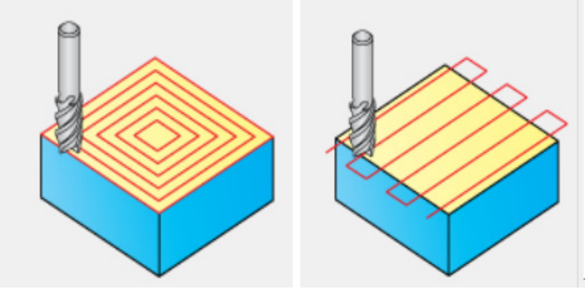


Figure 4. Roughing strategies: Contour (left) and Hatch (right) [12]

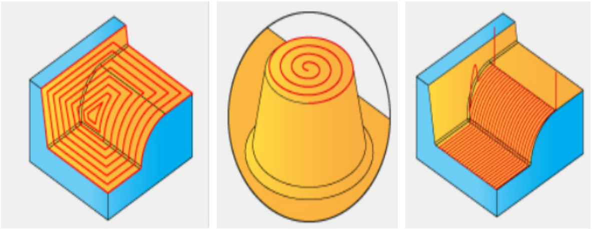


Figure 5. Finishing strategies: Constant step over (left), Spiral (middle), and Linear (right) [12]

2.2 The second phase of experimental research

Based on the results of the first experimentation phase, it can be concluded that the most favorable was EXP1, which consisted of roughing contour path, and finishing was a constant step-over path. EXP1 from the first experimentation phase gave the most favorable results. It was used as a strategy combination in the second experimentation phase and machining of a new workpiece. A new second phase of the experiment run, noted as EXP4, was machined with a combination of roughing and finishing strategies and the same milling tool as in EXP1 but with different cutting parameters. This combination was chosen to observe the influence of cutting parameters on cutting process output parameters: the machining time, surface roughness, and workpiece geometric accuracy. Previously used cutting parameters for EXP1 and newly adopted cutting parameters for EXP4 are shown in Table 3.

Table 3. Roughing and finishing strategies and cutting parameters in the second phase

Exp. no.	Roughing	Finishing
EXP1	SR1 - Contour ae = 2 mm ap = 1.5 mm vf = 400 mm/min n = 4000 o/min	SF1 - Constant step over ae = 1 mm ap = 0,5 mm vf = 300 mm/min n = 6000 o/min
EXP4	SR 1- Contour ae = 2 mm ap = 1.0 mm vf = 500 mm/min n = 5000 o/min	SF1 - Constant step over ae =1 mm ap = 0,5 mm vf = 200 mm/min n = 6500 o/min

3. RESULTS AND DISCUSSION

3.1 The analysis of the first phase of experimental research

The main roughing and finishing times measured with a digital stopwatch were analyzed in Table 4. Based on the presented results, the contour milling roughing strategy achieved a slightly better result regarding the main machining time. It certainly indicates the advantage of applying this strategy in mass production. The contour milling roughing strategy has a shorter production time due to its characteristic path, i.e., the layout of passages, compared to the hatch roughing strategy.

The finishing strategy with the best results in terms of machining time is the constant step-over, which is also the result of characteristic tool paths, i.e., the layout of passages. The third finishing strategy, spiral fini–

shing, has the longest machining time due to its specific layout of tool paths, in which the initial machining zone for this strategy was machined longer than in the other finishing strategies, i.e., most of the finishing time was spent on the machining of this zone.

Table 4. Roughing and finishing times for different machining strategies

Exp. no.	Strategy comb.	Rough. time (h)	Finish. time (h)	Machining time (h)
EXP1	SR1-SF1	0.510	1.014	1.524
EXP2	SR2-SF2	0.600	1.380	1.980
EXP3	SR1-SF3	0.510	1.230	1.740

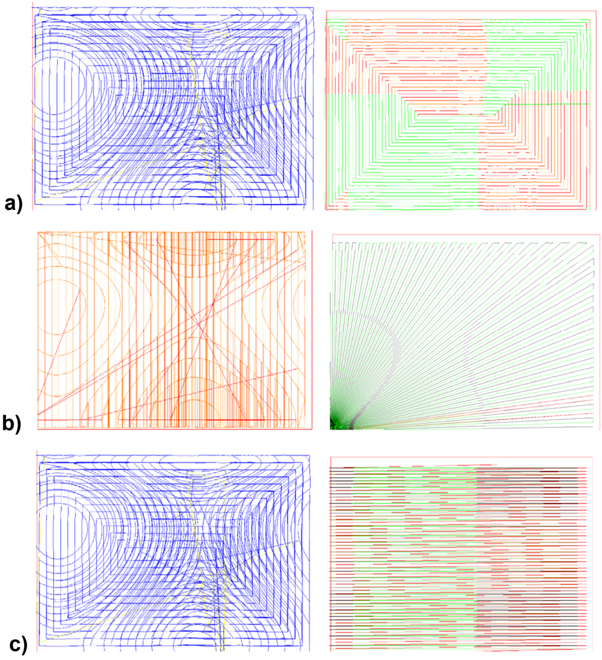


Figure 6. Toolpaths: (a) EXP1 (contour + constant), (b) EXP2 (hatch + spiral), and EXP3 (contour + linear) [12]

The roughness of the workpiece machined surface was measured for each machining strategy in three machined zones marked I, II, and III in Figure 7. These zones represent characteristic machining spots for which we can expect different measurement results; therefore, they have been selected accordingly for each workpiece.

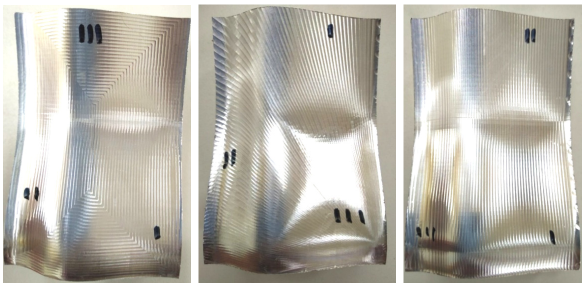

a) b) c)

Figure 7. Machined workpiece and surface with marked zones: (a) EXP1, (b) EXP2, and (c) EXP3

Based on the presented results of machined surface roughness, it can be concluded that EXP1 gave the best results and is very similar to the results for EXP3, Figure 8. But EXP1 also provided the best results in terms of total machining time, which puts it in first place in the machining strategy selection. EXP3 gave acceptable results, while EXP2 was rejected as the worst, Table 4.

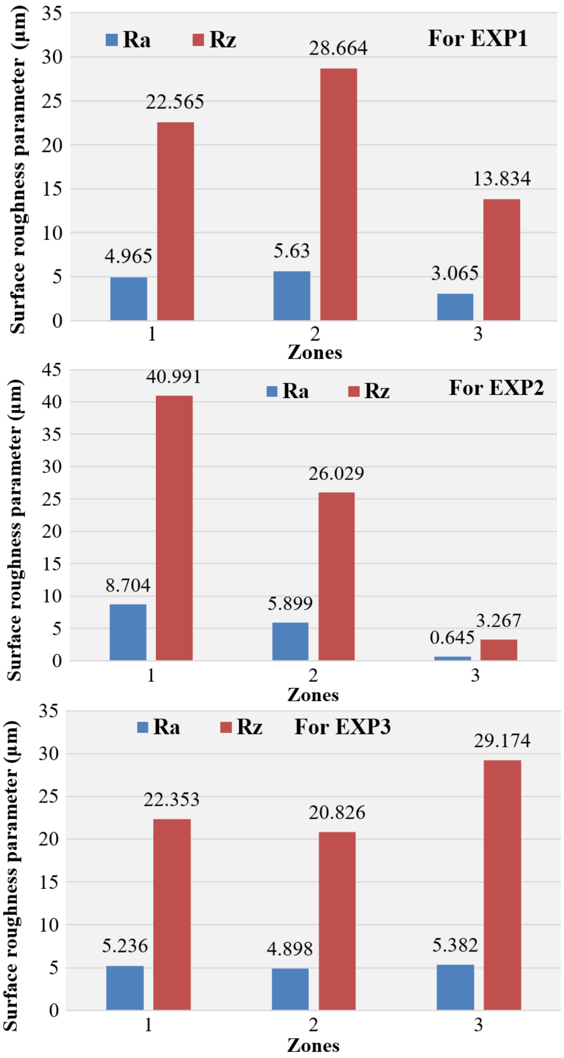


Figure 8. Measured values of parameters Ra and Rz for different machining strategies

The workpiece in EXP2 resulted in extremely high roughness in zone 1; similar values were obtained in zone 2, while zone 3 had extremely low roughness. The reason was the selected strategy in which the tool moved from the center (beginning of the strategy), marked by zone 3. This zone was machined as the tool starting position zone, and most of the total finishing time was spent on it. Therefore, it gave the obvious result, while zone 1 and zone 2 had extremely poor roughness due to the characteristics of the path along which the tool moved, i.e., moved away from the starting position (zone 3) towards the endpoints of the manufactured surface. For this reason, zones 1 and 2 had a much worse quality of the machined surface compared to zone 3; therefore this strategy was rejected because of the machined surface roughness, too (Figure 9).

When comparing samples from EXP1 and EXP3, significant deviations from the nominal (CAD) geometry have been observed. Simultaneous comparison of the complex surface with the CAD model was performed. A coordinate system was used as the basis for the real and nominal geometry overlap.

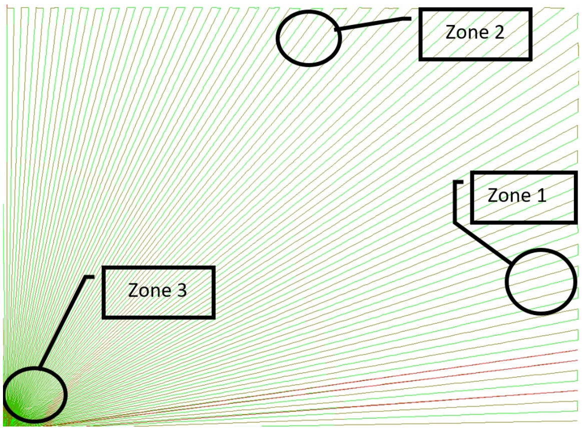


Figure 9. Measurement zones for machined surface roughness for EXP 2 (SR2+SF2)

The aim of the first phase of experimental research was to select the best strategy for roughing and finishing when it comes to the machining time and treated surface roughness aspects. The first phase of the experimental research concludes that the EXP1 (SR1+SF1) has shown the best results in terms of the said aspects. EXP3 (SR1+SF3) has given acceptable results regarding the said aspects, while EXP2 (SR2+SF2) has been rejected as the worst and has not been further considered in the second phase of experimental research.

3.2 The analysis of the second phase of experimental research

The measured machining time for the two experiments mentioned above is shown in Table 5. Based on the results shown in the previous table, it can be concluded that during the machining of the workpiece in EXP1 (SR1+SF1), the shortest machining time was achieved. The workpiece in EXP4 has been machined with the same machining strategies as the workpiece in EXP1 but with modified cutting parameters –the roughing being performed with higher values of feed rate and cutting speed and less cutting depth; and the finishing has been performed with lower feed rate and higher cutting speed resulting in longer machining time.

Table 5. Roughing and finishing time for machining strategies in the second phase of experimental research

Exp. no.	Roughing time (h)	Finishng time (h)	Machining time (h)
EXP1	0.51	1.101	1.52
EXP4	0.53	1.46	1.99

The roughness of the machined surface was measured for each experimentation run in the second phase in workpiece zones marked with numbers (1, 2, 3, 4), Figure 10.

Compared to the first experimentation phase, a larger number of measuring zones have been examined in order to analyze more detailed results.

Based on the results presented for measuring machined surface roughness, it can be concluded that EXP4 (SR1+SF1) with changed cutting process parameters yields better results. EXP1 machined using the same roughing and finishing strategies but with enhanced cutting process parameters produced poorer results in terms of machining quality. When analyzing roughness parameters Ra per four measurement zones EXP1 and EXP4 that were machined using the same pre-treatment machining and finishing strategies but different cutting process parameters, it can be seen that the Ra parameter has the highest values in measurement zone 1, resulting from the toolpath of the ball mill and geometry of the sample itself, Figure 11.

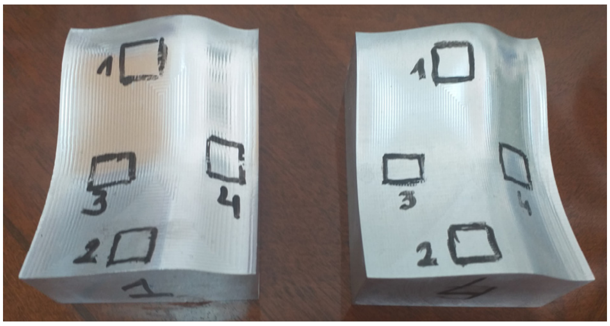


Figure 10. Machined surface with marked zones for EXP and EXP4

Considering the workpieces in EXP1 and EXP4 machined by the same roughing and finishing strategies but different cutting parameters, it can be noted that the roughness parameter Ra has the highest values in measuring zone 1 due to the simple ball milling path and flatness geometry. The values measured for the parameter Ra and the workpiece in EXP1 are 1.5 to 2 times higher than for the workpiece in EXP4. This indicates that, with the same roughing and finishing strategy, the selected cutting parameters significantly impact the machined surface quality.

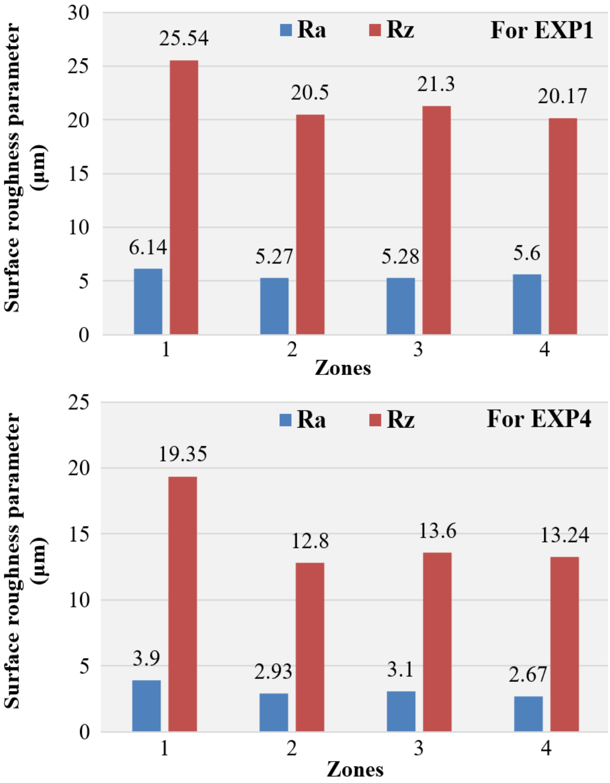


Figure 11. Measured values of parameters Ra and Rz for different machining strategies in the second phase

As the geometric accuracy of machined parts with complex geometry significantly affects their functionality, it is very important to inspect the geometry of surfaces and check whether accuracy requirements are met [16].

To perform this procedure, it is necessary to acquire all the geometrical and dimensional information on the parts quickly. The analysis of the geometric accuracy of freeform surfaces using the CAD inspection technique is based on selecting a specific point on the machined surface and comparing it with a corresponding point on the CAD model. Deviations of the analyzed point include deviations in the position and orientation of the point compared with the CAD model. Geometric accuracy of machined surfaces was analyzed by using the CAD inspection method based on a systematic approach to geometry analysis. Geometric accuracy was analyzed using an articulated coordinate measuring arm (MCAx20+) with an MMDx100 integrated laser scanner, a multisensory measuring system.

The results of deviation can be presented in numerical and graphical form [30, 31, 32]. The main advantage of this method is fast and simple control over the geometric accuracy and surface quality of machined parts and of complex geometry parts in particular. Form deviation of samples from the second phase of experimental research is shown below, Figures 13-18. A graphical representation of deviations implies maps of form deviations with color-marked areas with the greatest deviations, Figures 12 and 13.

As mentioned above, the analysis of EXP1 shows the greatest deviations of geometry in zone 4. In this area, the high roughness of the machined surface was measured on the workpiece from EXP1. Approximately the same roughness Ra was measured in zones 2 and 3 on this sample, and geometry deviations in the zones were approximately the same. It has to do with the toolpath of the ball mill during finishing. Changed cutting parameters in EXP4, which was machined with the same combination of roughing and finishing strategies as in EXP1, resulted in smaller form deviations in general, Figure 13.

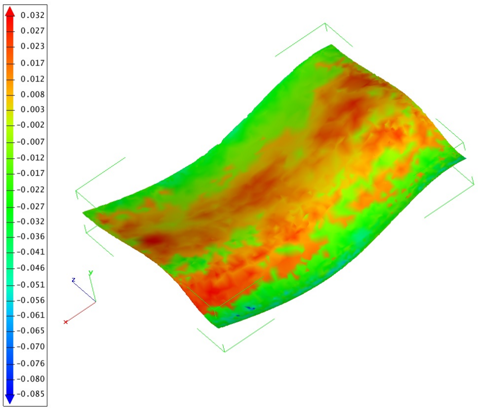


Figure 12. Global compare EXP1

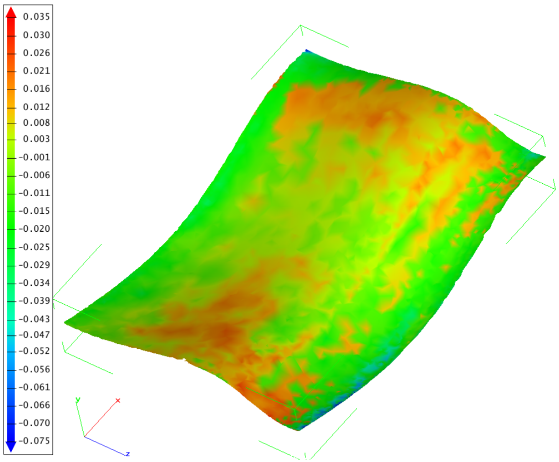
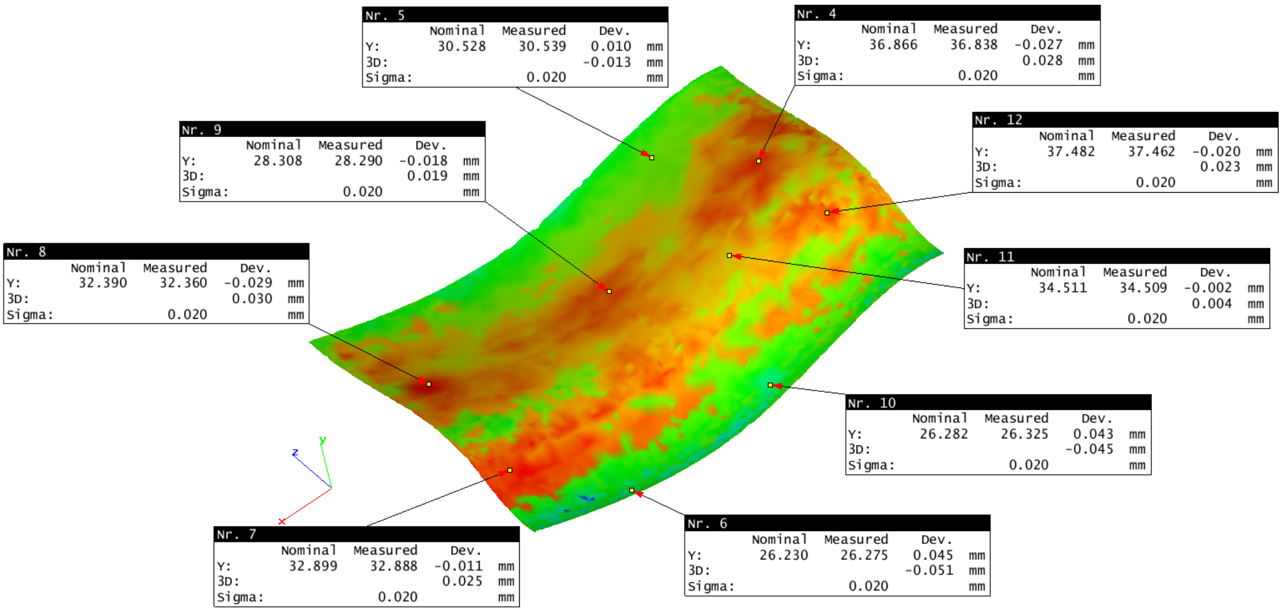


Figure 13. Global compare EXP4

Numerical form deviations of randomly selected points at the machining surface are shown in Figures 14 and 16. Estimating cross-sectional deviation includes determining a deviation vector whose intensity corresponds to deviation levels 15 and 17. This way of displaying deviation is visually less clear but gives a better insight into deviation values in specific areas.


```
Nr. 5
          Nominal  Measured    Dev.
Y:         30.528    30.539   0.010  mm
3D:                          -0.013  mm
Sigma:                0.020          mm
```

```
Nr. 4
          Nominal  Measured    Dev.
Y:         36.866    36.838  -0.027  mm
3D:                           0.028  mm
Sigma:                0.020          mm
```

```
Nr. 9
          Nominal  Measured    Dev.
Y:         28.308    28.290  -0.018  mm
3D:                           0.019  mm
Sigma:                0.020          mm
```

```
Nr. 12
          Nominal  Measured    Dev.
Y:         37.482    37.462  -0.020  mm
3D:                           0.023  mm
Sigma:                0.020          mm
```

```
Nr. 8
          Nominal  Measured    Dev.
Y:         32.390    32.360  -0.029  mm
3D:                           0.030  mm
Sigma:                0.020          mm
```

```
Nr. 11
          Nominal  Measured    Dev.
Y:         34.511    34.509  -0.002  mm
3D:                           0.004  mm
Sigma:                0.020          mm
```

```
Nr. 10
          Nominal  Measured    Dev.
Y:         26.282    26.325   0.043  mm
3D:                          -0.045  mm
Sigma:                0.020          mm
```

```
Nr. 7
          Nominal  Measured    Dev.
Y:         32.899    32.888  -0.011  mm
3D:                           0.025  mm
Sigma:                0.020          mm
```

```
Nr. 6
          Nominal  Measured    Dev.
Y:         26.230    26.275   0.045  mm
3D:                          -0.051  mm
Sigma:                0.020          mm
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Figure 14. Numerical form deviation of randomly selected points for EXP1

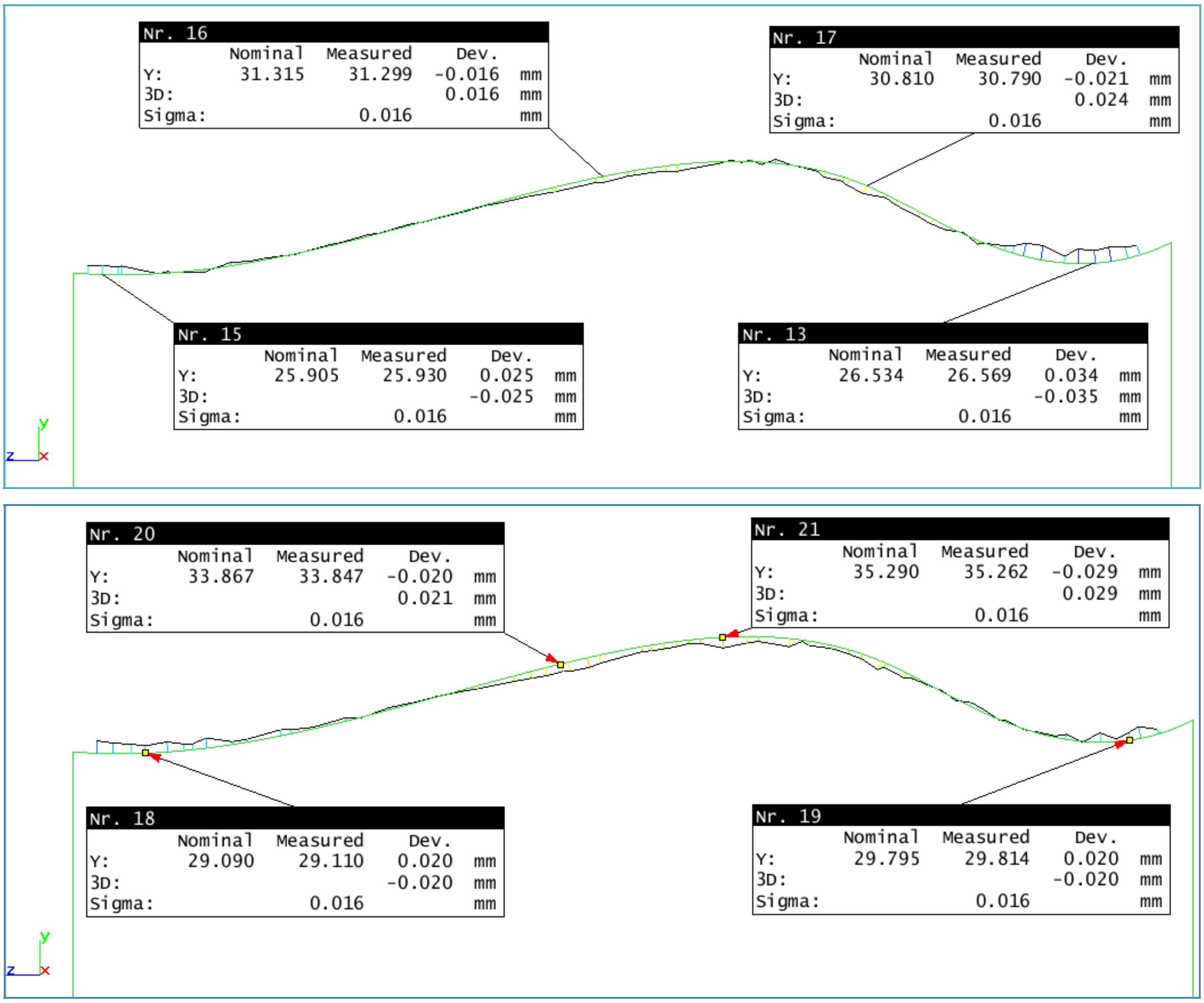

Figure 15. Evaluation of the deviations in the cross-section X=18 mm (above) and cross-section X=58 mm (below) EXP1

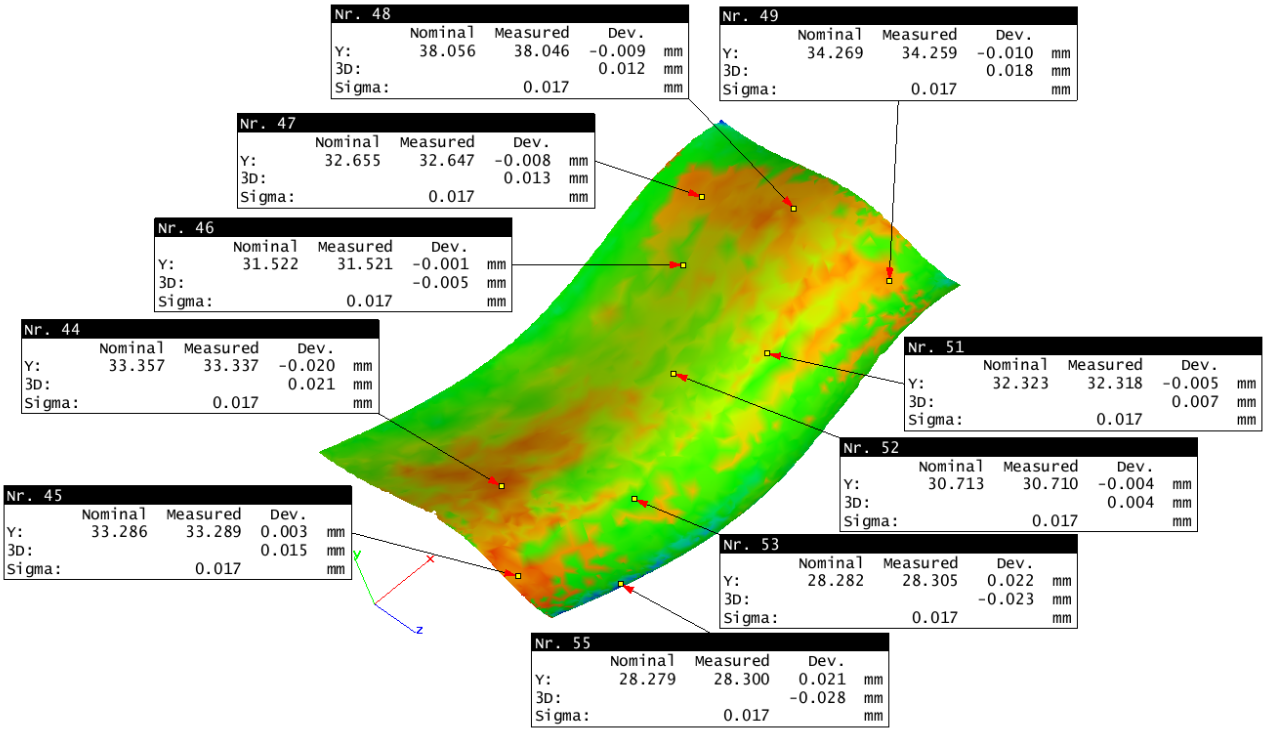

Figure 16. Numerical form deviation of randomly selected points EXP4

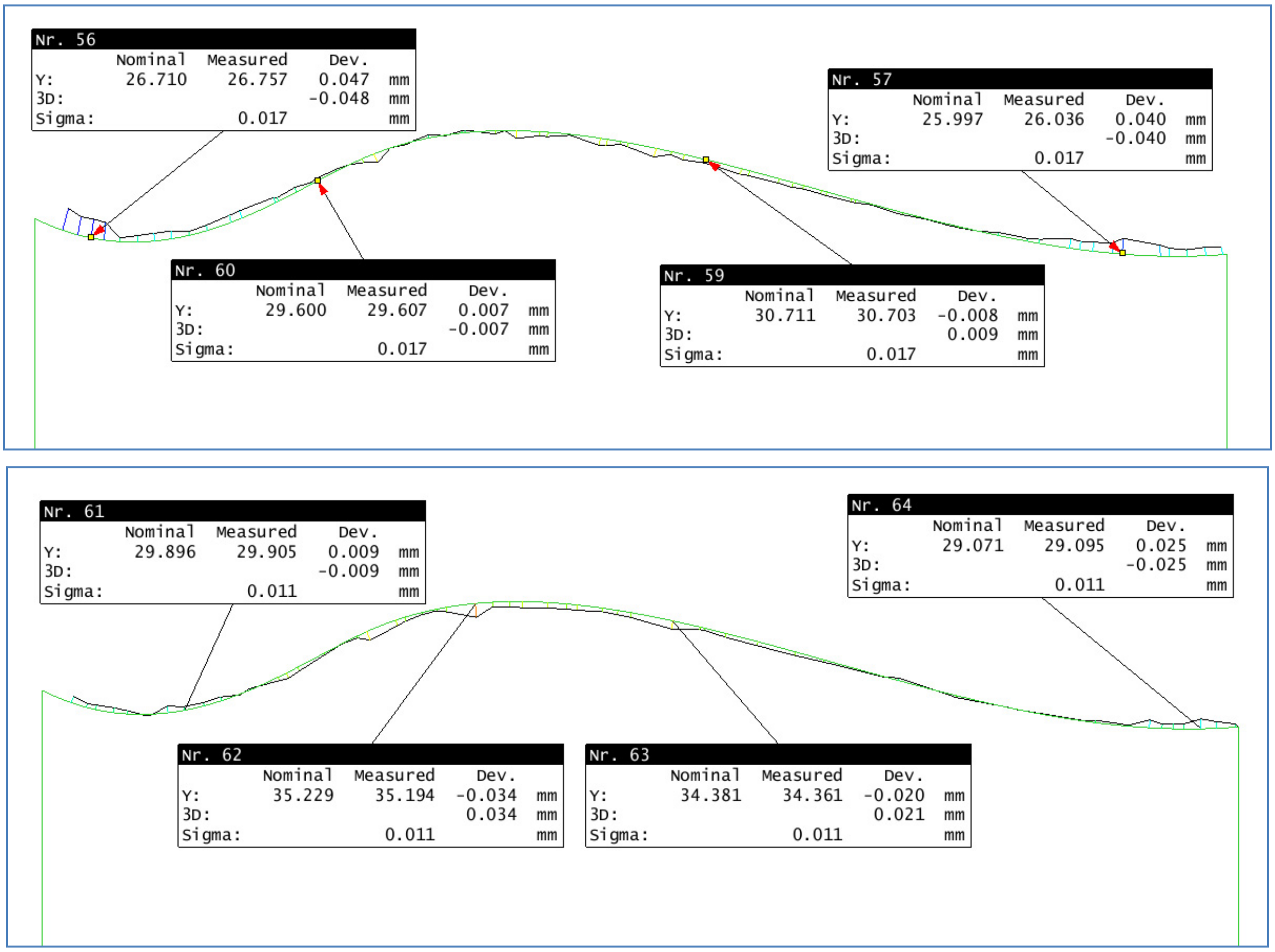

Figure 17. Evaluation of the deviations in the cross-section X=18 mm (above) and cross-section X=58 mm (below) for EXP4

The analysis of figures 14-17 shows that geometric deviations are significantly smaller on the workpiece sample in EXP4 (SR1+SF1) with changed cutting parameters compared to EXP1 (SR1+SF1). The cross-sectional analysis for experiment 4 in x=58 mm indicates that the largest deviations of geometric accuracy are in zones 2 and 3, where the higher roughness parameters Ra and Rz value was measured. Compared to the highest values of the geometric deviations in EXP1, it can be concluded that deviations in EXP4 are significantly smaller.

Therefore, the results of this analysis show that, together with the choice of roughing and finishing strategies, the choice of cutting process parameters significantly impacts output parameters, i.e., machining quality and geometric accuracy. A detailed analysis of the main machining time, machined surface roughness parameters, and complex machined surfaces' geometric accuracy on the tested samples in the second experimental phase has shown that with the same roughing and finishing strategies and selecting the most favorable cutting process parameters, can significantly increase the productivity, accuracy, and machining quality when milling complex surface parts.

4. CONCLUSION AND PROPOSAL FOR FUTURE RESEARCH

In this paper, experimental research was performed to study the influence of machining strategies and cut parameters on machining time, machined surface quality, and dimensional accuracy. Experimental work and analysis was performed in two phases: first, the influence of machining strategies analysis, and second, cutting parameters influence analysis. The first experimentation phase aimed to select the best strategy for roughing and finishing due to machining time and machined surface roughness. It can be concluded that EXP1 (SR1+SF1) has given the best results. EXP3 (SR1+SF3) has led to acceptable results according to the mentioned aspects, while EXP2 (SR2+SF2) has the worst results. EXP1 from the first experimentation phase has provided the most favorable results.

A new second-phase experiment run noted as EXP4 was machined with a combination of roughing and finishing strategies and with the same milling tool as in EXP1 but with different cutting parameters. The point was to examine the influence of machining parameters on the productivity and quality of machined surfaces, but also on the accuracy of machining because the largest deviations in shape were measured in the places where the roughness was the greatest, that is, at the transitions from concave to convex regions and vice versa.

For workpieces in EXP1 and EXP4, it can be noted that the roughness parameter Ra has the highest values in measuring zone 1 due to a simple ball milling path and surface geometry. The measured values of the parameter Ra for the workpiece in EXP1 are from 1.5 to 2 times higher than in the workpiece in EXP4. This indicates that, with the same roughing and finishing strategy, the selected cutting parameters have a significant impact on the machined surface quality.

The geometric accuracy of machined surfaces was analyzed by using the CAD inspection method based on a systematic approach to geometry analysis. The results of deviation have been presented in numerical and graphical form. Comparing results for the digitalized model of complex surfaces and the CAD model shows that smaller surface form deviations are generated in EXP4. The main advantage of this method is fast and simple control over the geometric accuracy and surface quality of machined parts and of complex geometry parts in particular.

Detailed analysis of the machining time, roughness parameters, and geometric accuracy of complex machined surfaces has shown that the choice of roughing and finishing strategy and the choice of the most favorable cutting parameters significantly increases productivity and accuracy, and surface quality. This analysis showed that, in the examined conditions, the most favorable results according to all three considered processing aspects (productivity, accuracy, and quality) are obtained by EXP4, with roughing strategy contour and finishing strategy constant step over with adopted cutting parameters). The importance of selecting cutting parameters in the conditions of the same machining strategies applied, according to all considered aspects of measured output parameters (productivity, quality of processing, and geometric accuracy) was also pointed out.

By analyzing numerous papers dealing with the issue of choosing the optimal machining strategy to achieve the required quality of machined surfaces and machining accuracy, as well as based on our representative research, it is possible to propose a methodology for future research:

1. Based on the geometry of a part, choose the most acceptable strategies from the existing library of standard machining strategies in commercial CAM software and perform an overview of the selected strategy in virtual machining, which requires spending relatively little time.
2. Choose the most favorable roughing and finishing strategy based on the best simulation results. In the case of significant deviations from the simulation, it is clear that the same strategy cannot be successfully applied to all surfaces, so it would be advantageous to sequence a complex surface into regions and select the most favorable strategy for each region [4].
3. Perform workpiece machining according to the adopted roughing and finishing strategies. Also, an appropriate milling strategy can be adopted for machining the observed workpiece complex surface region.
4. Perform a CAD inspection and detect the biggest deviations in the accuracy of the shape and roughness of the surfaces.

Correct the machining parameters and create a new sample on which the CAD inspection will be performed. Longer programming time and the time needed for the CAD inspection of a workpiece extend the total preparation time needed to produce complex geometry parts. However, compensation for the lost time is certainly obtained by producing parts where the number of machining errors and the time for their elimination is reduced to a minimum or eliminated, which is the main advantage of the proposed methodology.

REFERENCES

[1] Misevic, M., Dihovicni, D.: Application of Robotics and CNC Machines in Production, Applied Engineering Letters: Journal of Engineering and Applied Sciences, Vol. 5, No. 4, pp. 135-141, 2020.

[2] Lukić, D., Milošević, M., Vukman, J., Đurđev, M., Antić A.: Applying precedence relationships and CAD/CAM 1. simulation in time-based optimization of process planning, Applied Engineering Letters, Vol. 2, No. 4, pp. 130-138, 2017.

[3] Altintas Y., Kersting P., Biermann D., Budak E., Denkena B., Lazoglu I.: Virtual process systems for part machining operations, CIRP Annals – Manufacturing Technology, Vol. 63, pp. 585–605, 2014.

[4] Ižol P., Vrabeľ M., Maňková I.: Comparison of Milling Strategies when Machining Freeform Surfaces, Materials Science Forum, Vol. 862, pp. 18-25, 2016.

[5] Janák, M.: Manufacturing Strategies in CAM Systems, in: *Proc. of 7th International Multidisciplinary Conference*, May 2007, Baia Mare pp. 291-295.

[6] Yao Z., Gupta S.K.: Cutter path generation for 2.5D milling by combining multiple different cutter path patterns, International Journal of Production Research, Vol. 42, No. 11, pp. 2141–2161, 2014.

[7] Mawussi K.B., Tapie L.: A knowledge base model for complex forging die machining, Computers & Industrial Engineering, Vol. 61, No. 1, pp. 84–97, 2011.

[8] Novák-Marcinčin, J., Janák, M.: Software Support for Selection of Suitable Milling Strategy, Scientific Bulletin, Serie C, Fascicle: Mechanics, Tribology, Machine Manufacturing Technology, Vol. 23, pp. 119-122, 2011.

[9] Liua, N., Loftusa, M., Whitten, A.: Surface finish visualisation in high speed, ball nose milling applications, International Journal of Machine Tools & Manufacture, Vol. 45, pp. 1152 - 1161, 2005.

[10] Mlađenović, C., Kalentić, N., Zeljković,M., Tabaković, S.: The influence of milling strategies on roughness of complex surfaces, Journal of Production Engineering, Vol 17, No. 1, pp. 51 – 54, 2014.

[11] Ramos, A. M., Relvas, C., Simões, J. A.: The influence of finishing milling strategies on texture, roughness and dimensional deviations on the

machining of complex surfaces, Journal of Materials Processing Technology, Vol. 136, pp. 209–216, 2003.

[12] Grzesik, W.: *Advanced machining processes of metallic materials: theory, modelling and application*, Elsevier B. V., Amsterdam, 2008.

[13] Česáková, I., Zetek, M., Švarc, V.: Evaluation of cutting tool parameters, Procedia Engineering, Vol. 69, pp. 1105 – 1114, 2014.

[14] Kokotovic, B., Vorkapic, N.: Feedrate optimization for 2.5D milling operations, FME Transactions, Vol. 47, No. 3, pp. 613-623, 2019.

[15] Mladenovic, G., Tanovic, T., Ehmann, K. F.: Tool path generation for milling of free form surfaces with feedrate scheduling, FME Transactions, Vol. 43, No. 1, pp. 9 - 15, 2015.

[16] Quinsat, Y., Sabourin, L.: Optimal selection of machining direction for three-axis milling of sculptured parts, International Journal of Advanced Manufacturing Technology, Vol. 33, pp. 684 - 692, 2007.

[17] Okafor C., Adetona O.: Predicting quality characteristics of end-milled parts based on multi-sensor integration using neural networks, individual effects of learning parameters and rules, Journal of Intelligent Manufacturing, Vol. 6, Issue 6, pp. 389-400, 1995.

[18] Dornfeld D. A.: Monitoring of machining process-literature review, CIRP Annals-Manufacturing Technology, Vol. 41, Issue 1, pp. 93-96, 1992.

[19] Nagatomi K., Yoshida K., Banshoya K., Murase Y.: Recognition of wood cutting conditions through cutting sounds I. Effects of tool system's stiffness and tool wear on the generation of sound in cutting parallel to the grain. Journal of the Japan Wood Research Society, Vol. 39, Issue 5, pp. 521-528, 1996.

[20] Banshoya K., Ohsaki H., Nagatomi K., Murase Y.: Relationship between cutting sound and tool wear in machine boring of wood and wood based materials, Mokuzai Gakkaishi, Vol. 40, Issue 4, pp. 521-528, 1994.

[21] Quintana G., Ciurana J., Ferrer I., Rodriguez C. A.: Sound mapping for identification of stability lobe diagrams in milling processes, International Journal of Machine Tools and Manufacture, Vol. 49, Issues 3-4, pp. 203 - 211, 2009.

[22] Downey J., O'Leary P., Raghavendra R.: Comparison and analysis of audible sound energy emissions during single point machining of HSTS with PVD TiCN cutter insert across full tool life. Wear, Vol. 313, Issues 1-2, pp. 53-62, 2014.

[23] Bağci E.: Experimental investigation of effect of tool path strategies and cutting parameters using acoustic signal in complex surface machining, Journal of Vibroengineering, Vol. 19, Issue 7, pp. 5571-5588, 2017.

[24] Balic J., Korosec M.: Intelligent tool path generation for milling of free surfaces using neural networks, International Journal of Machine Tools and Manufacture, Vol. 42, No. 10, pp. 1171-1179, 2002.

[25] Vilaa C., Ayabacaa C., Torresa R., Gutiérreza S. C., Meseguera A., Yanga X.: Analysis of Different Tool Path Strategies for Free Form Machining with Computer Aided Surface Milling Operations, Procedia Manufacturing, Vol. 41, pp. 843 - 850, 2019.

[26] Web SolidCAM tutorials, www.solidcam.com, Headquarter, Scharamberg, Germany

[27] Vakondios, D., Kyratsis, P. Yaldiz, S., Antoniadis, A.: Influence of milling strategy on the surface roughness in ball end milling of the aluminum alloy Al7075-T6, Measurement, Vol. 45, No. 6, pp. 1480-1488, 2012.

[28] Pillaiet, J. U., Sanghrajka, I., Shunnmugavel, M., Muthuramalingam, T., Goldberg, M., Littlefair, G.: Optimisation of multiple response characteristics on end milling of aluminium alloy using Taguchi-Grey relational approach, Measurement, Vol. 124, No. 1, pp. 291-298, 2018.

[29] Feng, L., Longstaff, A., Myers, A.: Rapid and accurate reverse engineering of geometry based on a multi-sensor system. The International Journal of Advanced Manufacturing Technology, Vol. 74, No. 1-4, pp. 369-382, 2014.

[30] Mingrang, Y., Yingjie, Z., Yunlong L., Ding Z.: Adaptive, sampling method for inspection planning on CMM for free-form surfaces, International Journal of Advanced Manufacturing Technology, Vol. 67, pp. 1967-1975, 2013.

[31] Jotić, G., Tešić, S. Čiča, Đ., Jokanović, S.: Quality inspection of free-form surface parts, in: *Proc. of 14th International Conference on Accomplishments in Mechanical and Industrial Engineering DEMI 2019*, May 24 - 25 2019, Banja Luka, pp. 623 - 630.

[32] Budak, I., Hodolič, J., Bešić, I.: *Koordinatne merne mašine i CAD inspekcija*, Fakultet tehničkih nauka Novi Sad, Novi Sad, 2009.

NOMENCLATURE

a_e	radial depth of cut
a_p	depth of cut
d_c	diameter of cutting tool
HB	Brinell hardness
l_2	length of tool cutting part
n	number of revolutions
r	radius of cutting tool
R_m	tensile strength
R_a	mean roughness value
R_z	ten-point mean roughness
v_f	feed rate
v_c	cutting speed

Greek symbols

γ	rake angle of cuttung wedge
ω	angle of helix

ρ_{spec} specific mass of material

ABBREVATIONS

CAD	Computer Aided Design
CAM	Compiter Aided Manufacturing
BUE	Built Up Edge

КОМПАРАТИВНА АНАЛИЗА СТРАТЕГИЈА ГЛОДАЊА ПОВРШИНА СЛОЖЕНЕ ГЕОМЕТРИЈЕ

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У раду се анализира утицај стратегија машинске обраде и параметара резања при обради глодањем алуминијских дијелова сложене геометрије. У првој фази експеримента дијелови су обрађени ком–бинацијама двије стратегије грубе и три стратегије завршне обраде, уз примјену препоручених пара–метра обраде. Мјерено је вријеме обраде, храпавост обрађене површине и геометријска тачност површине. У другој фази, нови дио (узорак) је обрађен са коригованим параметарима резања примјеном најбољих стратегија обраде усвојених из прве фазе. Резултати су показали да одабир стратегије обраде и параметара резања значајно утиче на продуктивност, квалитет и тачност при обради дијелова сложене геометрије.