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Production quality of shaped surfaces during milling

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Abstract[1]

In the context of the development of continuous improvement, increasing the level of quality, safety and protection of the ecological environment, it is necessary to deal with the sensitive phases of the production process and to evaluate the efficiency in terms of time and cost. In the paper, the quality of production in milling (method that is using rotary cutters to remove material) of shaped surfaces is pursued. The quality of the production process leads to the satisfaction of customer needs, and it is essential to focus on the quality/price ratio due to non-conformities. In the paper, the authors use the quality method to provide effective solutions and improve production activities, processes, and systems. This approach stands for a quality management system applied as a perpetual improve-ment tool, where individual activities consist of four steps: Plan, Do, Check, and

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Action, with returned stages developing a cycle. This cycle starts with minor to examine potential effects on systems and progresses to more extensive and precise improvements. The results of the implementation of effective solution method can be practiced for constant improvement and as a working model in developing a process or system in an organization. The different stages of the method are applied to set the path tolerance in relation to precision in 3-axis milling. The paper describes area computer numeric control milling center programming during 3-axis finishing milling. The article is focusing on setting the tolerance of tool paths during finishing milling in Computer Aided Manufacturing systems to recommend specific tolerance settings in computer aided Manufacturing systems concerning achieved accuracy, machining time, surface roughness, and quantity of blocks of machine tool control program. Finding suitable tool paths during finishing is very time-consuming and can be expensive. The aim is also to compare the practical results of machining with predicted simulation. The methodology for evaluating this problem is based on the following steps: experimental sample design for production, accuracy prediction of machined samples, production of samples using Computer Numeric Control milling center, analysis of accuracy, and surface roughness for the shape of the workpiece. The result is the variance of the shape accuracy deviations from the specified computer-aided design model of the workpiece, focusing on individual areas of its shape. The workpiece (aluminium alloy), focusing on individual areas of its shape. The research results show milled surface errors depending on the tool path tolerances. Using the effective solution method, it is possible to efficiently set up individual processes to improve the quality of production processes for time and cost.

Keywords: *Tool Path, Tolerance, Computer Aided Manufacturing System, Accurancy, 3axis Milling, Quality Management*

1. Introduction

Machining accuracy is critical for the quality of a mechanical product and is an important consideration for any manufacturer (Mital et al., 2018; Stahl, 2012; Drbúl, Czán, Šajgalík, Piešová & Stepien, 2017; Krolczyk, Legutko & Gajek, 2013). And what quality means? The very term of quality is commonly described as the standard of something as ranked against other articles of a similar kind; the degree of perfection of something (Reeves & Bednar, 1994). In the case of mechanical products, the quality explains more specific forms offered by norm of International Organization for Standardization (ISO, 2019). This system is understood as quality management standards to help work more efficiently and reduce product failures. It describes quality as the level to which a set of inherent characteristics of an object meets requirements. With reference to the constant development of the quality, security, and assurance of the ecological environment, it is unavoidable to deal with the subtle phases of the production process and appraise the time and cost-efficiency (Slivkova, Brumarova, Kluckova, Pokorny & Tomanova, 2021).

The level of production quality drives the settlement of customer demands, and it is crucial to focus on the quality/price proportion due to non-conformities. It is necessary to find and use one of the methods that enables increasing improvements in the process at the organizational level. Quality evaluation based on this method can be used in all areas, but the focus of this article will be on the area of milling.

In the literature (Sadílek, Čepová & Čep, 2018; Lim & Menq, 1997; Wei, Wang, Cai, Zhu & Wang, 2013) can be found milling errors caused by cutter deflection when machining a sculptured part using a ball-end milling tool. Due to this reason, the topic of the article is concentrating on setting the tolerance of tool paths during finishing milling in Computer Aided Manufacturing systems to prescribe particular tolerance settings in computer aided Manufacturing systems regarding obtained accuracy, machining time, surface roughness, and quantity of blocks of machine tool control program. The aim is also to contrast the practical results of machining with predicted simulation. For setting the path tolerance concerning precision in 3-axis milling, the authors used the quality management approach applied as a perpetual improvement tool. This method, known as PDCA cycle, for managing and developing the processes or the organization habits within the company consist of repeating four steps: Plan, Do, Check, and Action, with returned stages developing a cycle (Rajagopalan, 2021). This cycle was at first utilized as a mechanism to control the quality of products. However, later it was identified as a method to generate improvements in the processes. It means constant growth philosophy imported into the organization's culture, containing these sequences (Azzemou & Noureddine, 2021).

Plan. In this period, opportunities are recognized, and the following preferences are attached to them. The current condition of the process is described using appropriate data, the problem origins are confirmed, and potential solutions are introduced.

Do. This period is meant for the implementation of the performance plan, choosing and documenting the data. Additionally, unanticipated features, gained knowledge, and the best practice must be considered.

Check. The effects of the performed actions in the second section are analyzed. A prior-to comparison is performed, expressing whether there were increases and achievement of the settled objectives. Often particular graphic support instruments, such as the Pareto chart or Ishikawa diagram, can be applied.

Act. This phase consists of growing methods intended to normalize the improvements (in the case objectives had been reached). Additionally, the evidence is repeated to collect new data and re-test (only if data are deficient or circumstances changed), or the project is rejected, and a new one starts from the first stage (in the case the implemented actions did not generate productive improvements). This cycle approves two types of corrective motion – temporary and permanent. The temporary action points as results by realistically undertaking and fixing the problem. The permanent corrective action consists of examination and reducing the root causes and consequently targets the sustainability of the revised process. The most significant character of this method prevails in the "act" step after the fulfillment of a project when the cycle starts again for additional development (Milosevic, Djapan, D'Amato, Ungureanu & Ruggiero, 2021).

During the implementation of the above cycle, the quality management department should ask the following question (Aichouni, Ramlie & Abdullah, 2021) What is the company trying to achieve? How will company management understand that a change means an improvement? What modifications should be make to develop? In practice, exists several conditions under which the method implementation is sufficient:

1. When the sustainable development programs are performed.
2. A process's carried out repeatedly, will be capable to recognize new resolutions.
3. New solutions can be explored to solve the number of problems and improve solutions while testing with control implementation.
4. Implementation without first testing can withdraw spending large numbers of resources (Taufik, 2020).

The combination of these conditions and flexible model for estimating for the form error in three-axis ball-end milling of sculptured surface is shown in literature (Chen, Huang & Chen, 2005; Kim, Kim & Chu, 2003; Imania, Sadeghib & Elbestawia, 1998).

Figure 1 displays tool path tolerance when linear interpolation is used. This research was carried out e.g. in Figure 1 describes one toolpath during 3axis operation. This toolpath creates a consistent scallop motion relative to stepover distance. Computer Aided Manufacturing systems offer to set tool path tolerance.

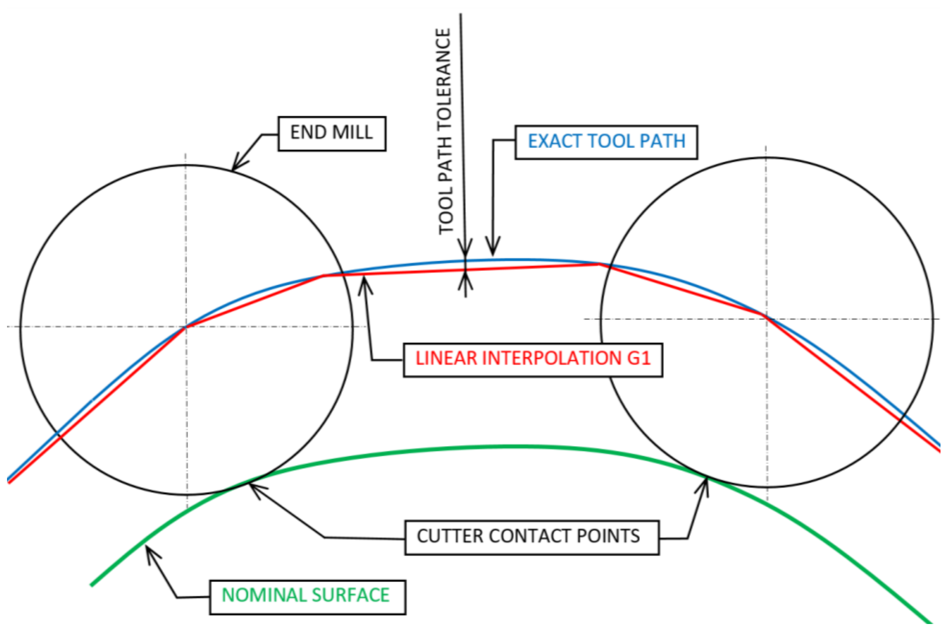


Figure 1 : Tool path tolerance in front view

2. Experimental Work

This article is focusing on the analysis of geometrical accuracies during milling which is part of section one, the fist step of PDCA cycle, the Plan. In the context of planning, it is essential to understand the current set-up of the process, only based on an in-depth analysis does the space emerge for identifying areas for improvement and thus setting their parameters. Milling of samples (see Figure 2) has been realized on 5axis Computer Numeric Control milling center, with condition in Table 1 and Table 2. Part of the method for improving the quality of the Plan is therefore based on these values. On Figure 3 is displayed schematic diagram of the experimental work. Section Model for machining stands for Plan part, together with part Tool paths simulation. Here also belongs a part Surface errors prediction as an essential component of the target's comparison with reality. Sections Real workpiece, Scan, and finally Actually measured belongs to part Do, where the process (based on the data and facts from the previous section) is implemented. Graph arrow with comparison stands for action Check, the third of used method. It should be noted that the division into individual levels of tool path tolerance then falls into the last section of the applied method, Action. When, based on the differences found and the evaluation of the results and errors (predicted and measured) the whole process is performed again under three different settings.

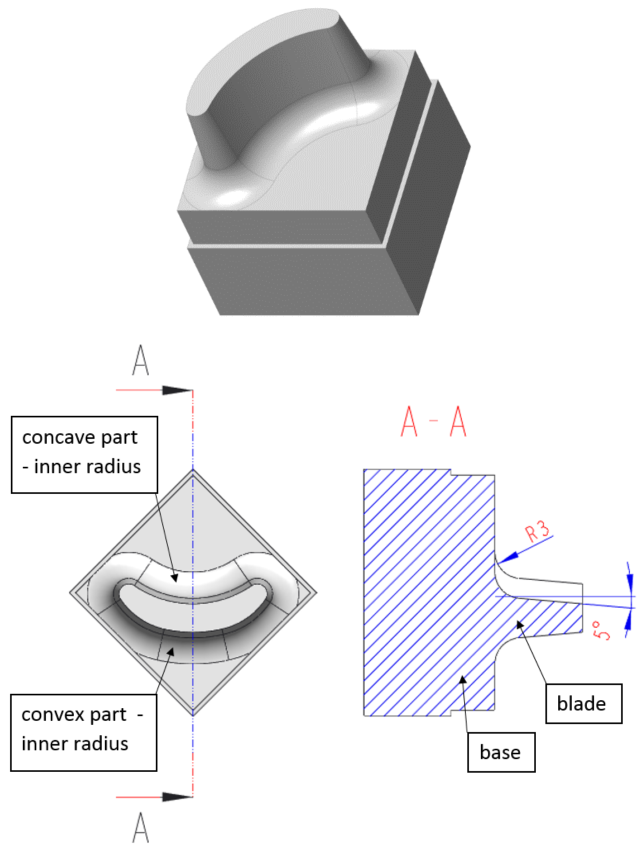


Figure 2 : Design of samples (Plan - process analysis)

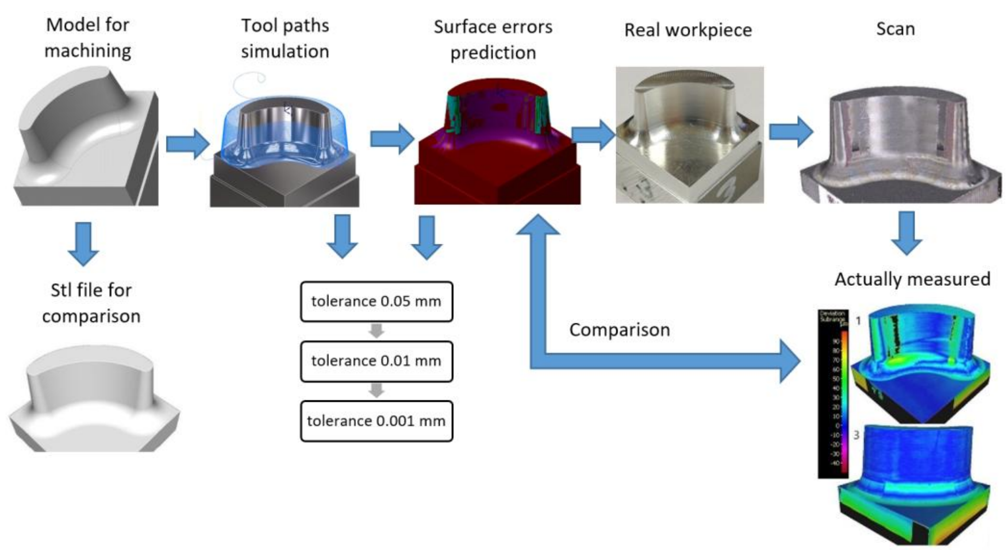


Figure 3 : Scheme of the experimental work

Table 1. Technological parameters of the cutting process (Plan – process settings)

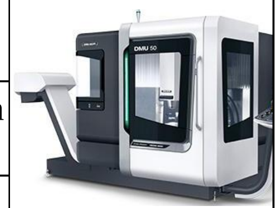
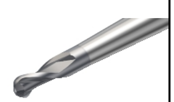
Machine	DMG MORI DMU 50	
Control system	Heidenhain iTNC 530	
CAM system	Mastercam 2017	
Material of workpiece	Aluminium alloy EN AW-6060 – AlMgSi0,5 F19	
Workpiece	20x20-26 mm	
Clamping	vice KSX-L 125 (SCHUNK)	
Tool	Solid carbide ball end mill, D6 mm (R216.42-06030-AP06G 1620)	
Tool holder	High-precision hydraulic chuck - CoroChuck 930	
Tool overhang	60 mm	

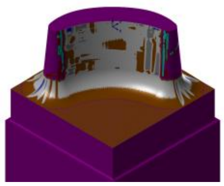
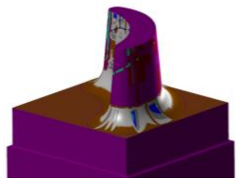
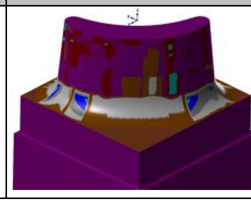
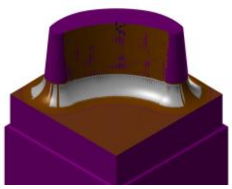
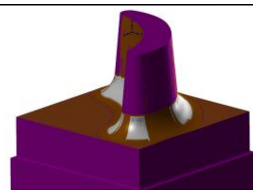
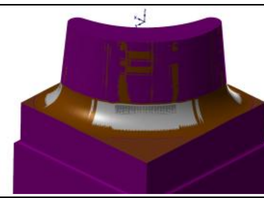
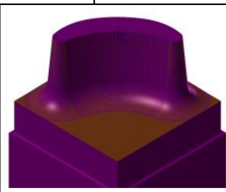
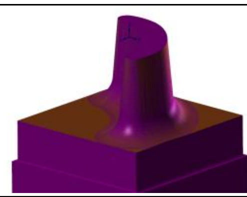
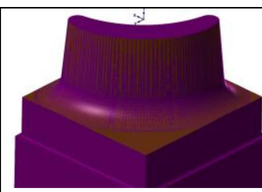
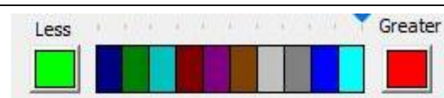
Table 2. Cutting conditions of finishing 3axis milling operation (Plan – process settings)

Endmill diameter	d	[mm]	6
Spindle rev.	n	[min^{-1}]	17500
Cutting speed	v_c	[$m \cdot min^{-1}$]	330
Axial cutting depth	a_p	[mm]	0.15
Radial cutting depth	a_e	[mm]	0.15
Feed per tooth	f_t	[mm]	0.1
Feed	f	[$mm \cdot min^{-1}$]	3713
Coolant	Blasocut 2000 CF, Art. 875-12		
Milling strategy	Climb milling		

2.1. Milled Surface Errors Prediction

The Computer Aided Manufacturing systems allow to compare the Computer-Aided Design model with the prediction of milled surfaces. This prediction allows to determine the size of errors of the calculated surfaces before machining. Tolerance of the model and tool shape was set at 1 μm. The predicted errors (residual material) are in the range -40 to 50 μm during tool path tolerance 50 μm shows Table 3, the last part of the Plan section, as an estimate of the values of the required parameters.

Table 3 Predicted surface errors (Plan - parameter estimation)

Tool path tolerance [µm]	View 1	View 2	View 3
50			
Predicted errors	-40 to 50 [µm]		
10			
Predicted errors	-15 to 15 [µm]		
1			
Predicted errors	-2 to 2 [µm]		
Offsets and colors			

The Table 4 shows tool path tolerance and their influence on machining time and number of Numerical Control codes.

With more precise toleralnce the number of Numerical Control codes increases. Thanks to the time then required to process Numerical Control code by Computer Numeric Control machine, increase also machining time. Computer Aided

Manufacturing simulation does not include this time for processing Numerical Control code, therefore it remains the same (with minimal deviation during calculation when set very precise tolerance).

Table 4 Machining time – (settings for Action)

Tool path tolerance [mm]	Number of NC blocks [-]	CAM simulation time [min:sec]	Machining time [min:sec]	Time increasing [%]
0,050	5625	01:17	01:58	-
0,010	9315	01:17	01:58	0
0,001	21944	01:19	02:08	8.5

Legend: Computer Aided Manufacturing (CAM); Numerical Control (NC).

2.2. Accuracy Measurement

Machined samples measurements were carried out with an optical three - dimensional microscope Alicona Infinite Focus G5, see Figure 4. The optical 3D micro coordinate measurement system is suitable for accuracy and surface roughness measurements. The measurement itself belongs to the section Do.

Figure 4 : Real scan by Alicona Infinite Focus G5 (Do section)

The measured samples were compared with the model created in the Computer-Aided Design system Inventor, which means navigate to the Check section of the used quality improvement method. The models were saved with the input format necessary for Alicona Infinite Focus G5 (software IF MeasureSuite) in the format *. stl with a tolerance of 0,1µm for the comparison. A range of the variance scale was selected from -50 to +100 µm for all samples. Machined surfaces colored dark blue has minimal deviations (range of -10 to 10 µm) and it shows Figure 5,6,7.

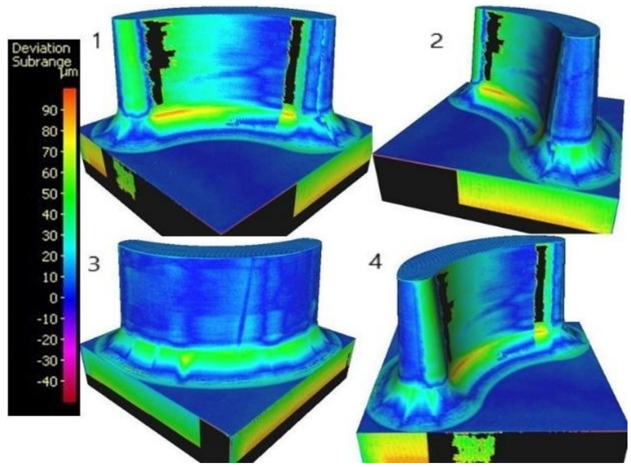


Figure 5 : Comparison of the original model with the workpiece after milling (tool path tolerance 50µm - Check section)

During decreasing tool path tolerance in Computer Aided Manufacturing system is decreasing surface errors.

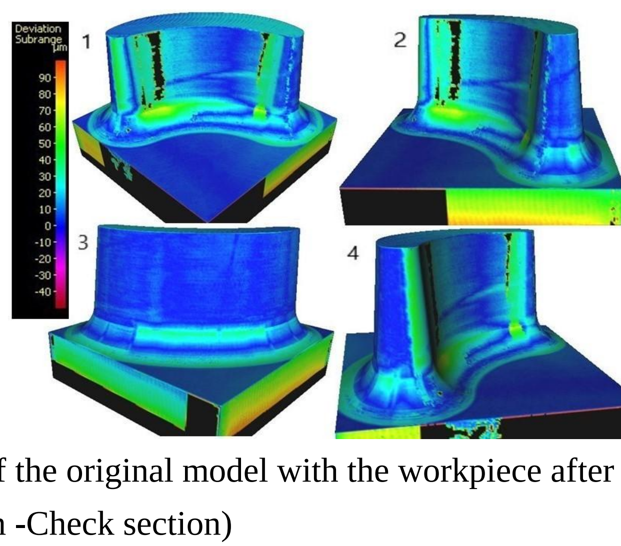


Figure 6 : Comparison of the original model with the workpiece after 3axis milling (tool path tolerance 10µm -Check section)

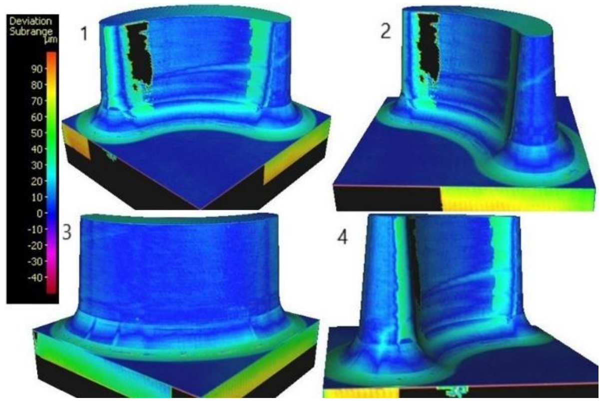


Figure 7 : Comparison of the original model with the workpiece after milling (tool path tolerance 1µm – Check section)

Displayed black color on the scan means wrong part of workpiece scan, but this do not influence comparison results.
Problematic area of cutting is inner radius of convex and concave part of bladeThe largest (surface errors) are placed in concaved part – inner radius of blade according to colored deviation subrange. The maximum surface errors are 89 µm there.

Figure 8 represents values of surface errors acording tool path tolerance setting in Computer Aided Manufacturing system. Shape of blades, out of inner radius, have smallest surface errors up to 48 µm. Errors mentioned above are acceptable for production.

These real surfaces were also compared with the predicted surfaces calculated in the Computer Aided Manufacturing system Mastercam, see Table 5, Which means the last phase of the cycle, Action, where the whole quality improvement process starts again based on setting different tool path tolerance values in an effort to keep predicted and also measured errors as low as possible.

Table 5 Range of surface errors

Range of surface errors			
	Tool path tolerance [µm]		
	50	10	1
Predicted errors [µm]	-30 to 30	-15 to 15	-2 to 2
Measured errors [µm]	1 to 89	0 to 71	1 to 77

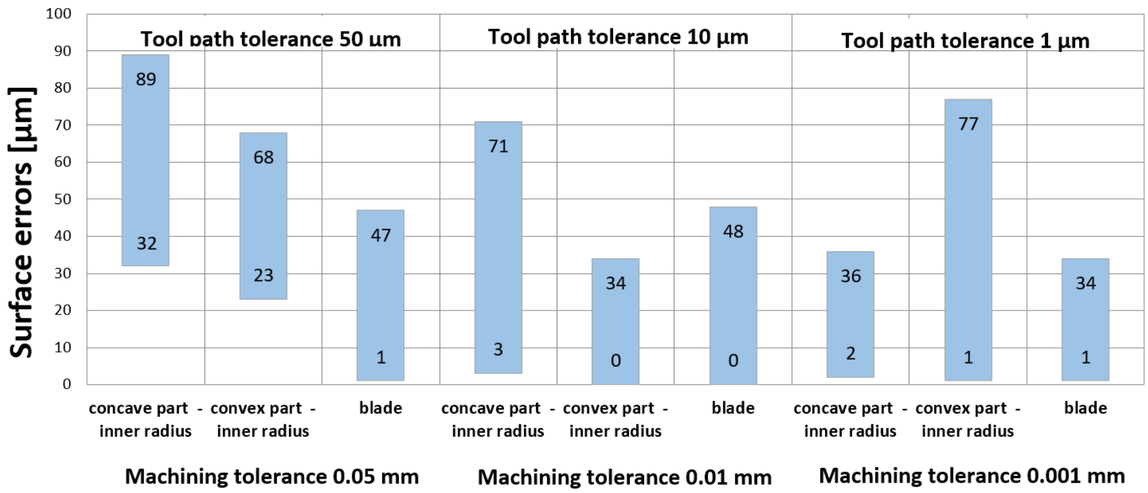


Figure 8 : Surface errors according tool path tolerances

2.3. Surface Roughness

Surface roughness is often classified in two directions: pick feed direction and feed direction during milling.

The feed direction surface roughness is theoretically formed by copying the roughness of the cutting edge and practically formed by friction of the tool back and the machined surface (Beudaert, Lavernhe & Tournier, 2014; Sadílek, Fojtík, Sadílková, Kolařík & Petrů, 2015).

Pick feed direction roughness is created by copying the rounded edge onto machined surface with effect of plastic deformation and tool wear (Mizugaki et al., 2001; Adamczak, Miko & Čus, 2009; Sadílek, Kousal, Naprstková, Szotkowsky & Hajnys, 2018).

Figure 9 displays surface roughness (parameter Ra - the arithmetical mean deviation of the assessed profile and Rz the maximum height of the profile) according to tool path tolerances setting in Computer Aided Manufacturing system measured in pick feed direction and feed direction. Lower tolerance cause decreasing surface roughness. Again, this part of the experiment falls under the Action section.

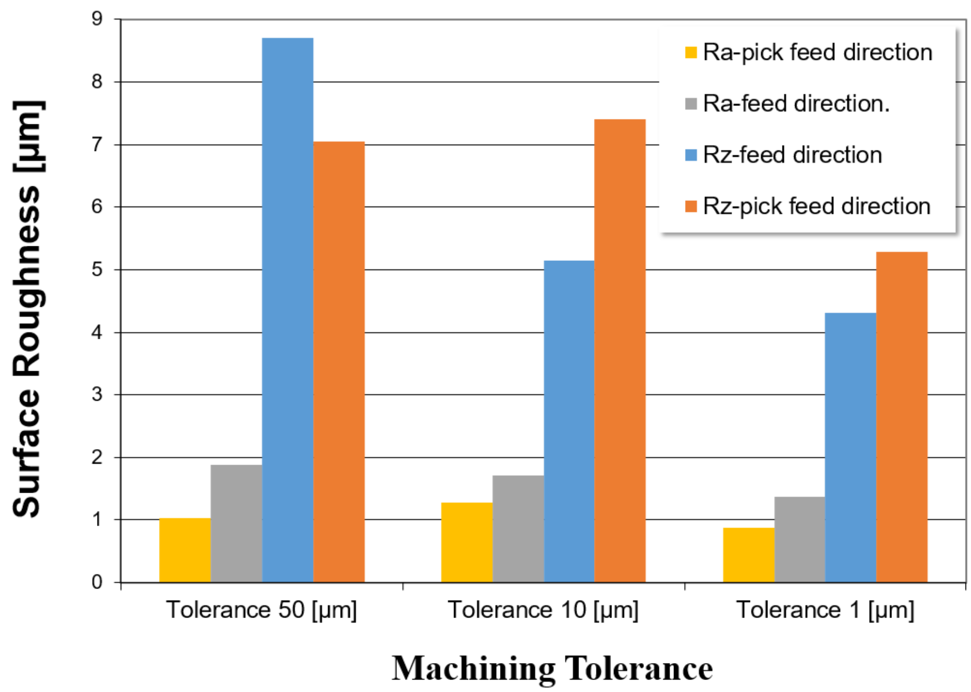


Figure 9 : Surface roughness according tool path tolerances (Action)

3. Discussion and Conclusions

Quality is crucial in all aspects and all industries. It is essential to address the various stages of production preparation and feedback to ensure that products are at the best possible price/quality ratio. This statement has been demonstrated here in this case when appropriate tool path tolerances are set. In that case, the quality is not reduced, but at the same time, the products are not so overpriced because the cost of production is reduced by retooling the machine used.

Research results confirm the assumption that decreasing tool path tolerance increases machining accuracy. Tool path tolerance 1 µm increases machining time (8.5 %), but the accuracy and surface roughness are very similar to tolerance 10 µm. Recommendation is using tool path tolerance 10 µm in Computer Aided Manufacturing system.

The prediction (calculation) of residual material in the Computer Aided Manufacturing system is the most consistent with the real-measured residual material. The results show the quality of the computational algorithm used in the Computer Aided Manufacturing system.

Within the chosen method of continuous, cyclical quality improvement, it is possible to use quality adjustment of preparation and all steps in different sectors from engineering to manufacturing, healthcare, food, even in services. It is advisable to understand the essence of the quality concept and incorporate it in all preparatory productive and post-productive parts of the process in the sub-sector.

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