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Comparison of Simulated Machining Time with Real Machining Time at Free-form Surfaces Milling

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Abstract: The presented results are part of more extensive experiments, which aim to verify the reliability of the results provided by CAM systems in the production of parts with shaped surfaces. The article deals with the comparison of production times obtained from programming and simulation systems with real production times. For production planning and organization processes, information on estimated production time is an important input. A free-form sample was designed for the experiment. Finishing of the sample surfaces was accomplished by 3-axis and 5-axis milling using three different strategies. The machining times obtained by the simulation in the CAM system, the times from the simulation mode of the machine control system and the real machining times were evaluated. Data discrepancies were shown, with in almost all cases the real machining times being longer than the times given by the simulations. The results were supplemented by outputs from software that optimizes the feed during milling thus reducing the production time. The tests proved the validity of its use.

Keywords: CNC machining; milling strategy; production time; feedrate optimization; 5-axis milling

1. Introduction

The demand for the production of increasingly complex products in high quality forces the use of efficient production processes, enabling us to remain competitive in today's market. Product diversity is growing and serial production is decreasing, which complicates process standardization and reuse of known technological settings. Therefore, knowledge of new organizational concepts and modern technologies is becoming increasingly important. This development leads to requirements that can only be met by a high level of staff expertise and a thorough knowledge of the means of production used [1].

On a growing number of engineering products, there are shaped surfaces, the production of which is realized by CNC machines either directly or indirectly. In the first case, the part is made directly on the machine, in the second case by means of a shaping tool (mould, die, press tool), also made on a CNC machine. In the production of such parts and tools, milling machines in 3-axis or 5-axis versions are most often used. Deciding to use a 3-axis or 5-axis CNC milling machine doesn't have to be easy. It determines the complexity and required accuracy of parts, operating costs of machines, their productivity and, last but not least, the knowledge and experience of programmers and machine operators [2]. For the differences between the shaped surfaces produced by 3-axis and 5-axis milling, e.g. source [3].

Attention is paid to the optimization of all activities related to the production process. During production by CNC machines, NC codes are also tuned, among

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other things. NC code tuning can consist of several steps [4]. One of the steps is the optimization of the sequence of operations, which affects, among other things, the number of tool changes, the number of rotations and tilting of the milling table, etc. The next step is the optimization of machining strategies, the main goal of which is the highest possible machining efficiency, expressed by the accuracy and quality of the machined surfaces in relation to machining time [5]. The third possible step is to optimize the code structure itself, aimed at reducing the number of lines or eliminating unnecessary (duplicate) commands. This simplifies the reading and implementation of the NC code for the machine control system. One of the main goals of NC program tuning is to reduce machining time, because it greatly affects the efficiency of the entire production process. Evidence of this is the development of specialized software for this purpose [6].

Estimated production time data is important for production planning and organization. In the case of the use of CNC machines in production, the most common source of this data are programming systems. They calculate the production time based on the process simulation. Based on experience, it can be argued that the data obtained in this way are in many cases only indicative. Compared to simulation times, real times can increase by up to tens of percent. The issue of differences in times presented by the programming system and real production times is partially addressed, e.g. at work [7].

CAM systems are the standard programming system today. Their advantage has extensive possibilities, on the other hand, there are a huge number of possible combinations of parameters [8]. This places high demands on programmers, who must have sufficient experience and appropriate sources of information. A frequently solved problem, especially in the 5-axis milling of shaped surfaces, is the maintenance of suitable cutting conditions when using hemispherical milling tools [13]. A possible solution is e.g. optimization module, implemented in the postprocessor, increasing the quality of the finished surface and optimizing the production time [9].

The design of cutting conditions is based on the tool used, the method of its clamping, the material being machined and the performance characteristics of the machine. By default, the cutting conditions are set according to the most critical section of the tool path, which leads to non-use of its possibilities in other sections. This shortcoming is addressed by various forms of adaptive control. Adaptive control can be part of the machine control system [10] or is implemented using external software, either directly by the CAM system or by specialized software. The functionality of such software is described in [11], the machine time saving in this case was 26%.

Despite the deployment of powerful software support in the form of CAM systems, the results of actual machining often differ from the results of simulations [14]. To eliminate this situation, the simulation environment of CAM systems is beginning to be supplemented by the software part of VNCK (Virtual Numerical Controller Kernel) machine control systems. The simulation, controlled by the machine control system, achieves the faithful behaviour of the virtual CNC machine, which takes into account the acceleration and deceleration of the moving elements of the machine, start and stop of the spindle speed, operation within cycles, etc. [12].

2. Experimental Section

The aim of the experimental work was to compare 3- and 5-axis milling in making free-from surfaces. The works were divided into several stages. In the first stage, the approaches in the creation of NC programs were compared, in the second stage, the conformity of virtually and really made samples in the form of shape accuracy and quality of produced surfaces was assessed. In the third stage, the reliability of the data provided by the CAM system and the machine control system was evaluated. The contribution of predicted production times with real times is evaluated in the presented paper.

For the purposes of the experiment, a sample with a freely modeled shape surface was designed - Fig. 1. The floor plan dimensions are 50 x 50 mm. The material of the sample is aluminium alloy 6061 T651, commonly used as a construction material. The height of the semi-finished product is 20 mm, the distance between the lowest and highest point of the shaped surface is 12 mm. The creation of NC programs was realized by the SolidCAM 2021 system. NC programs were generated using a postprocessor for the 5-axis continuous milling machine DMU 60 eVo, on which the samples were actually produced - Fig. 2. The machine control system is a Heidenhain TNC 640.

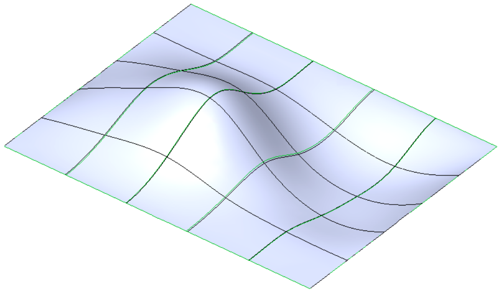

Figure 1: Designed free-form surface.

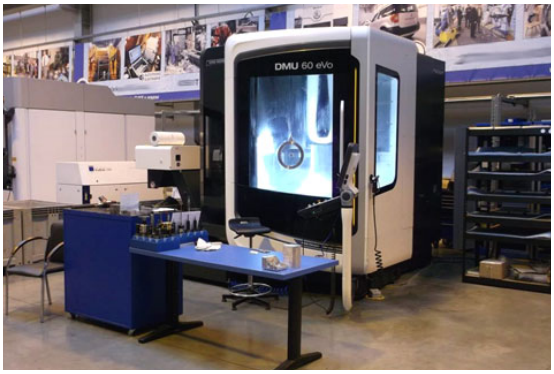

Figure 2: DMU 60 eVo milling machine.

Each sample was made in six operations. The first five operations focused on roughing and pre-finishing the shape. These operations were consistent for each sample. The last (sixth) operation was finishing, designed individually for each sample. Three types of finishing strategies were selected for comparison - Linear, Offset, and Spiral. The Linear strategy rasterizes the surface in parallel lines. The Offset creates a toolpath with the shape taken from the selected surface boundaries. In the Spiral strategy, the toolpath follows a spiral with a defined centre point. Each strategy was applied in four ways:

– *3-axis milling,*
– *3-axis milling with feed optimization,*
– *5-axis milling,*
– *5-axis milling using the Convert function (converting a 3-axis operation to a 5-axis).*

In the first method, a separate operation was designed for each strategy using tool movements in the X, Y and Z axes.

The second method used Eureka Chronos software. It is designed to optimize the feed and the expected result of its use is to reduce machine time, improve surface quality and extend tool life [6]. The feed optimization is possible according to the selected criteria or in AI (Artificial Intelligence) mode. The software allows you to choose the intensity of the tool load through the so-called performance index in five degrees. The lowest level 1 is focused on the longest possible tool life, the highest level 5 is designed to minimize production time. For sample production, the software was set to AI mode and Performance index value 3. For comparison, times were also measured at Performance index 5, but without real sample production. Fig. 3 explains the principle of operation of the software. The upper part of the image shows the adjustment of the feed rate. The lower part of the figure describes the adjustment of the material removal rate. These changes reduce the highest tool load and increase the feed rate in low load areas. The software

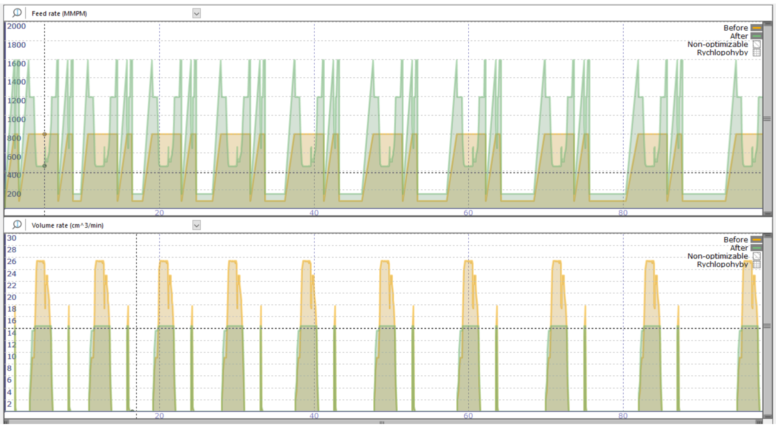

Figure 3: Adjustment of feed values and material removal rate by Eureka software

works with NC code, which was obtained by post-processing, so there was no need to design special operations. Because the software was only designed for 3-axis machines, the NC codes for 3-axis milling from the first method were used. Toolpaths have not been changed.

In the third method, a separate operation was designed for each strategy using the full kinematic capabilities of the machine, i. j. movement of the tool in the direction of the X, Y, Z axes and tilting of the table with the clamped specimen by rotary movements A and B.

The fourth method used the SolidCAM system's ability to convert 3-axis operations to 5-axis. This function respects the settings of a 3-axis operation and is therefore particularly suitable for comparison. Even in this case, the kinematic capabilities of the machine are fully utilized.

The WNT N.RD.10,0.45°.Z4.HA.K TI1000 ball nose end milling cutter with the manufacturer's recommended cutting speed in the range of 180 - 500 m.min^{-1} was chosen for finishing the shaped surface. The selected value was vc = 400 m.min^{-1} and the feed per tooth was 0.04 mm. Emulsion coolant with 8% concentration was used. The same parameters were used in the settings of all assessed strategies. The main requirement was the scallop height after machining, set to 0.0025 mm. This parameter is not compatible with standard surface roughness parameters. The relationship between the parameter Rz and the scallop height is given e.g. v [15].

An overview of the samples made is shown in Fig. 4. During the finishing of the shaped surfaces, the machine operator did not affect the cutting parameters. The tool feed and spindle speed controllers were set to 100%, which maintained the cutting parameters at the values defined in the NC program.

The time data was obtained by simulating the process in the CAM system, by simulation in the machine control system (after the post-process) and in the second method of sample production also by simulation in the Eureka software. Real production times were recorded directly by the machine control system. The measurement was started by turning the tool and ended after moving the tool and stopping its rotation.

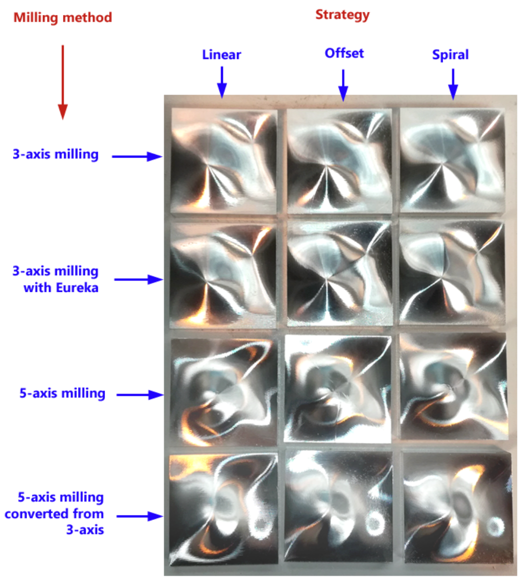

Figure 4: Overview of manufactured samples.

3. Results and Discussion

Due to the use of three software (CAM system, Eureka, machine control system) and time measurement of real processes, a large amount of data was obtained. He was e.g. the discrepancy found between the simulation time of the CAM system and the entry time of the Eureka software, determined on the basis of the NC code from the CAM system. The first of the data was obtained before the post-process, the second after the post-process. The most important results are presented in the next section.

3.1. 3-axis milling

For 3-axis milling, the time comparison in Fig. 5. With the Linear strategy, the production time was 0.96 times shorter than the time presented by the CAM system. The opposite is the Offset strategy, in which the production time was 1.07 times longer. The Spiral strategy matched the time data. The control system was more accurate in calculating time, the deviation from real times did not exceed 1%.

3.2. 3-axis milling with feed optimization

As mentioned, Eureka Chronos software was also used for the experiments to optimize the feed and shorten the machine time. For sample production, the software was set to AI mode and Performance index value 3. For comparison, times were also measured at Performance index 5, but without real sample production. Machining times from simulations and expected time savings are in Tab. 1. The graph in Fig. 6 compares times from simulations. For each strategy, the time from the CAM system and the optimization software for the two tool load levels is given.

Table 1: Machining times from simulations and estimated time savings.

Strategy	*CAM*	*Eureka PI 3*		*Eureka PI 5*	
	Simulated time [min]	*Simulated time [min]*	*Saved time [%]*	*Simulated time [min]*	*Saved time [%]*
Linear	5:09	3:38	29,5	3:16	36,6
Offset	5:47	4:03	30,0	3:41	36,3
Spiral	5:05	3:43	26,9	3:19	34,8

In Tab. 2 shows the measured machining times from the finishing of the sample area and the actual time savings. The graph in Fig. 7 compares real machining times.

Table 2: Actual machining times and real time savings.

Strategy	*CAM*	*Eureka PI 3*		*Eureka PI 5*	
	Real time [min]	*Real time [min]*	*Saved time [%]*	*Real time [min]*	*Saved time [%]*
Linear	4:58	4:36	7,4	4:24	11,4
Offset	6:10	5:42	7,6	5:27	11,6
Spiral	5:06	4:41	8,2	4:19	15,4

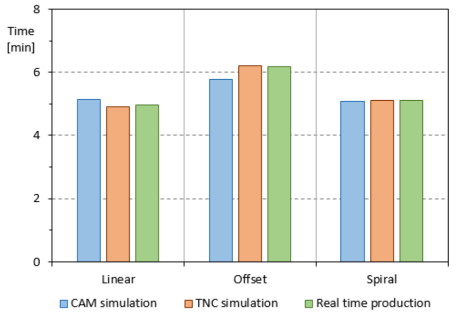

Figure 5: Comparison of times for 3-axis milling.

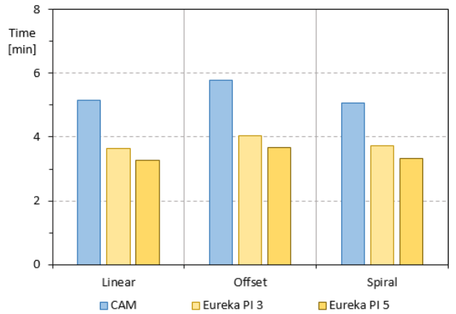

Figure 6: Comparison of simulation times.

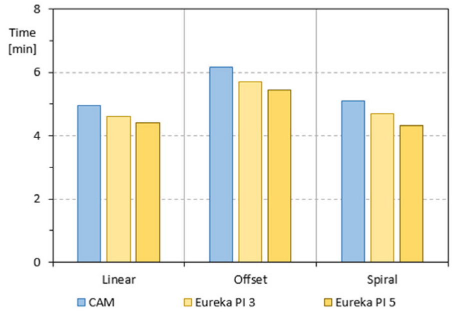

Figure 7: Comparison of real production times.

3.3. 5-axis milling

The graph in Fig. 8 compares 5-axis milling times. In all cases, the production times are longer than the times obtained by CAM simulation. With the Linear strategy, production times were 1.12 times longer, with the Offset strategy 1.25 times and the Spiral strategy 1.22 times. The simulation in the TNC 640 control system showed minor differences or compliance with the third strategy under consideration. In the first strategy, the time required to produce the area was 1.08 times longer than the time determined by the control system. In the second strategy, the real production time was 1.04 times longer.

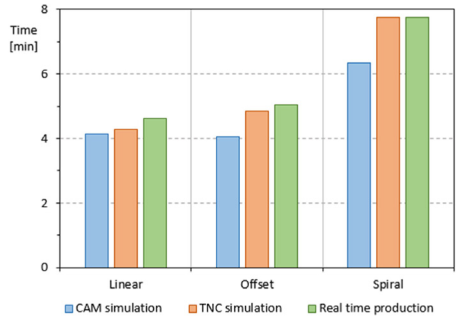

Figure 8: Comparison of times for 5-axis milling.

3.4. 5-axis milling converted from 3-axis

In 5-axis milling, converted from 3-axis operations, the real production time was in all cases longer than the times predicted by the simulations. For the Linear strategy, the real-time ratio from the CAM simulation was 1.06, for the Offset strategy 1.17 and for the Spiral 1.1. The ratio of real time and time simulated by the control system was 1.04, 1.03 and 1.03 for each strategy. The comparison of times is shown in the graph in Fig. 9.

3.5. Comparison 3-axis and 5-axis milling

The most frequently mentioned advantage of

5-axis milling in the production of shaped surfaces is better accessibility of the lower-placed surfaces for the tool and improved gripping conditions. Due to the more complex kinematics, comparable operations on the 5-axis machine are expected to take longer. The Fig. 10 compares real production times for 3-axis milling and both 5-axis milling methods. With 5-axis converted milling, a longer machining time was achieved with all three strategies than with 3-axis milling. With the newly programmed 5-axis milling, shorter machining times were achieved with the Linear and Offset strategies, and longer with the Spiral strategy than with the 3-axis milling. The assumption of the influence of kinematics was therefore not confirmed.

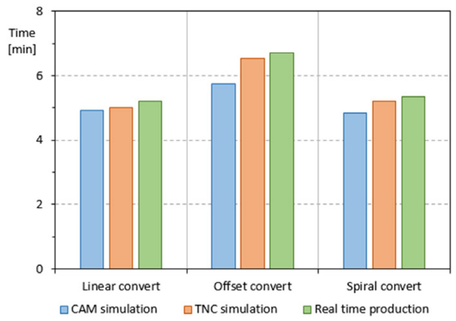

Figure 9: Time comparison for 5-axis converted milling.

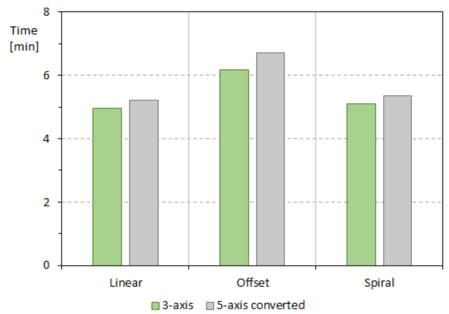

Figure 10: Comparison of real production times in 3-axis milling and both methods of 5-axis milling.

3.6. Toolpath lengths

The Fig. 11 shows a comparison of the path lengths traversed by the tool in the 3-axis and both 5-axis milling methods. In comparison with the graph in Fig. 10 it is clear that the path traversed by the tool affects the duration of the operation. However, this effect is not dominant. From a comparison of 3-axis and 5-axis converted milling e.g. it follows that even though the 5-axis milling times are longer, the paths travelled are shorter. The toolpath is created by several types of movements, which are realized at different speeds. The speed given by the working feedrate, rapid traverse and different speeds of tool approaches or departures are used. Tab. 3 shows the path lengths realized by working feed and rapid traverse for the milling methods being compared. Data for samples made with Eureka software are not provided because in this case the tool paths were not affected and were identical to 3-axis milling.

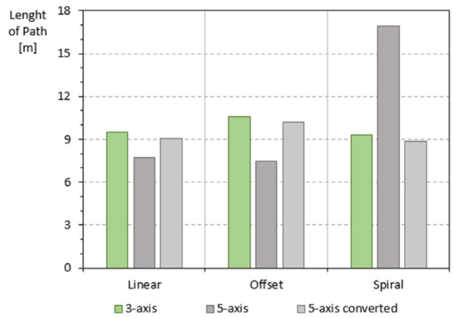

Figure 11: Comparison of toolpath lengths in 3-axis milling and both 5-axis milling methods.

With the Spiral strategy, implemented by the newly programmed 5-axis milling, a significant extreme in the length of the traversed path is noticeable. It is caused by working paths in the shape of a complete spiral even in places outside the sample - fig. 12. In 3-axis and 5-axis converted milling, these areas were skipped.

Table 3: Tool path lengths (FR - Rapid traverse).

Strategy	*Length of path [m]*								
	3-axis			*5-axis*			*5-axis converted*		
	FR	*RT*	*Total*	*FR*	*RT*	*Total*	*FR*	*RT*	*Total*
Linear	9,43	0,06	9,49	7,64	0,07	7,71	8,99	0,06	9,05
Offset	10,39	0,17	10,56	7,42	0,06	7,48	10,14	0,05	10,19
Spiral	9,16	0,14	9,30	15,25	1,65	16,90	8,72	0,14	8,86

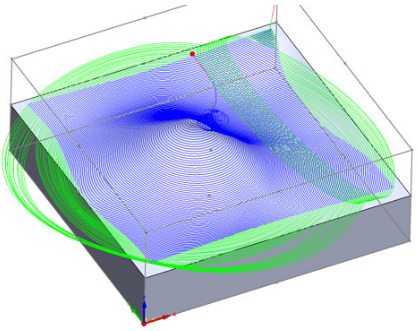

Figure 12: Toolpaths for 5-axis spiral milling.

4. Conclusions

As confirmed by the presented results, in real production in most cases there is an increase in machining time compared to the time from CAM simulation. In 3-axis milling, the difference between the actual times and the times predicted by CAM was the lowest. The largest deviation reached 7%. In 5-axis milling, the difference between predicted and real times ranged from 12 to 25%. In 5-axis milling converted from 3-axis, the differences were smaller, ranging from 6 to 17%.

The simulations in the machine control system were more accurate in determining the machining time. With 3-axis milling, a maximum deviation of 1% from real time was achieved. For 5-axis milling, the difference was in the range of 0 to 8%, for 5-axis converted milling in the range of 3 to 4%.

Differences between simulation times and real machining times have also been demonstrated using feed optimization software. The Performance Index 3 simulations assumed a time saving of 20 - 24% according to the strategy used, the real savings reached 7 - 8%. With Performance Index 5, the assumption of time savings was 29 - 31%, real savings reached 11 - 15%. Due to the fact that the production of shaped surfaces by milling is time consuming, the stated values of time savings are interesting for manufacturers.

From the point of view of direct time comparison of 3-axis and 5-axis converted milling, 3-axis milling is more preferable. The times for 5-axis milling were 5 to 9% longer. However, these values cannot be generalized. Especially with 5-axis milling, it is necessary to set a number of parameters. Each of them affects the proposed operation in some way. The combination of parameters is strongly dependent on the experience and knowledge of the programmer. This is also indicated by a comparison of 3-axis and newly programmed 5-axis milling, where it is not possible to determine the advantage of any milling method based on time.

It is clear from the results that the toolpath affects the duration of the operation, but the times are also affected by other factors. The path is realized by several types of movement, the share of which varies depending on the strategy and method of milling. In the experiments, the share of movements realized by rapid traverse reached in the range of 0.5 to 9.8% of the total length of the tool paths.

The following activities will focus on the analysis of other outputs from CAM systems, such as the comparison of virtual and real-made surfaces with a focus on shape deviations and surface roughness.

The shortcomings of current programming and simulation tools are the motivation for the development of more advanced virtual machining environments and virtual machine models. The aim is to create simulation models that allow you to predict the actual machining results, including times.

Acknowledgments

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