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Milling Strategy Design to Improve Vibration Behavior, Tool Wear and Surface Roughness in Machining

Shu Ju [1], Nico Hanenkamp [1]

[1] Institute of Resource and Energy Efficient Production Systems, Friedrich-Alexander-Universität Erlangen-Nürnberg, Fürth, Germany

Abstract. Uncontrollable vibration behavior during the milling process impairs the surface quality of the workpiece and escalate the machine damage as well as machine and tool wear. In this work, the impact of various milling strategies with control optimization for three different types of milling operations are studied. To objectively quantify the process quality, the machining time, the width of tool wear marks and the surface quality after each experiment as well as the vibration amplitude and the bending moment of the tool holder during the process have been measured and evaluated. For every milling type, three milling strategies with three iterative experiments each have been carried out. As a result, a database with vibration-related data and information for different milling strategies has been established. Thus, the machining process of workpieces with diverse geometric elements and the corresponding manipulated variables can be assessed regarding the vibration and tool wear behavior. Based on the experimental results, the potentials of the vibration-minimized milling strategies and tool path design in enhancing the process stability, the productivity and the tool life can be verified.

Keywords: milling operations; chatter suppression; process optimization

1. Introduction

Machining, due to its high shaping flexibility, is a widely implemented process for finishing and fine machining operations of primary formed or reshaped workpieces. With the constant ongoing development of machining such as high speed and high performance cutting, it has been inevitable to find process windows for new materials and the entire machining process to meet the economic and technical requirements. [1][2] As a result, the machine tool applied is subjected to increasing load during the machining process. There are many factors affecting the machining process and the machine behavior, among which the increasing machining forces have a significant impact on the machine tool, the process, as well as the workpiece quality. The resulting vibrations can lead to increased wear and tear in machine tool components and impaired surface quality of workpieces. [3] Moreover, the contact point between the tool and the workpiece hence deviates from the specified tool path, which poses a potential risk to the machining process. In addition, vibrations limit the productivity of machining processes, since intolerable vibration amplitudes and frequencies can be reached significantly prior to the performance limits of the main and auxiliary drives. [4]

The controlling of the tool path deviations and the monitoring of the machining process vibrations have been the focus of research activities for an extended period of time. In serial production processes, the minimization of vibrations can be achieved by the implementation of statistical process design, by the use of simulation tools or by similarity assessments of existing machining processes. In all cases, a high level of expertise in process planning is necessary. However, these tools reach their limits, especially in single-part and small-batch productions. The reasons for this lie in, firstly, that the experimental effort prior to production required to minimize vibrations is disproportionate to the benefits. Secondly, the short order throughput time in customized production with a batch size up to one single part does not allow this optimization. This is the prevailing situation for high-tech components from the semiconductor, aerospace and optical industries.

In order to investigate the influence of different tool paths and control strategies on process vibrations, a series of practical experiments has been conducted in this work. Different milling methods, including shape milling, groove milling and face milling, have been tested. In addition, process parameters that have a major impact on the machining process and thus also on the configuration of the tool path trajectories have been tested and optimized. The optimal tool path trajectories and control adaptions have been determined afterwards. As a result, it is possible to define the boundary conditions for the development of vibration reduced milling strategies without sacrificing process productivity.

2. State of the Art

Nowadays, there are numerous approaches to optimize the machining processes of raw workpieces with an industrial machine tool. Current research areas in this regard to be mentioned include milling strategy optimizations in tool path trajectories and control parameter configuration, as well as the reduction of vibrations and tool wear of the machining system.

2.1. Milling Strategy Optimization

To optimize the milling strategy, there exist various studies and methods focusing in particular on the process and energy efficiency as well as the process accuracy and quality improvement.

Regarding process and energy efficiency, Liu et al. [5] presented a way to improve simulation accuracy in milling operations in their article on optimizing tool paths in thin walled parts machining. The workpiece geometry was divided into individual subareas according to their dynamic properties. In particularly critical areas, test cuts were carried out to obtain the best cutting results. These results were then merged with the simulation results in the algorithm. In this way, machining time can be saved by more than 30 % compared to non-optimized process. The process efficiency and the surface quality can be improved. Other studies, such as the one from Minquiz et al. [6] compared the process output of three different part codes, self-developed and generated by two different CAM systems respectively. The cycle time, the energy consumption as well as the number of lines of the machining process of a mechanical component were measured. It was proved that reduction in cycle time and energy consumption can be achieved by designing and modifying tool path trajectories. With the same objective of reducing machining time, Senatore et al. [7] presented in their work an assistance system in choosing the suitable cutting tool, the machining direction as well as the optimal milling strategy for machining surfaces without interference. Based on the experimental results, the developed assistance tool indicated the potentials for improving machining time by optimizing machining zones and associated directions. Furthermore, Castelino et al. [8] specified in their article an algorithm in which the machining-free time was reduced, in which, for instance, the tool moves from one end of the path to the next beginning of the path. Here the tool paths were optimally connected accordingly so that the positioning time of the tool can remain as short as possible. Concentrating on production time and costs, Othmani et al. [9] carried out a series of tests to evaluate the machining time, costs and the optimal parameters for a machining process. As a result, two models were developed which are applied for machining time and costs calculation and optimum cutting parameter specification based on machine characteristics and raw workpiece surface roughness respectively.

In relation to process accuracy and quality improvement, in [10], the impact of the cutting force component on the workpiece was analyzed. Based on the results of multiple case studies of three and five axes milling, it was verified that lower deflection force leads to less deformation in the machine, the tool holder and the tool, and thus reduces the dimensional error in the workpiece. By integrating an additional utility in a commercial CAM system to predict the deflection forces, the best tool path in the high-speed milling of complex surfaces can be selected. Lazoglu et al. [11] developed an optimization process for machining free form surfaces that not only recalculated the tool path but also optimized the cutting forces and mechanics. This algorithm created a tool path with the lowest practicable average cutting forces and a specified maximum force and thus reduced both machining time and tool wear. In order to improve the surface of trochoidal milled geometries, Waszczuk et al. [12] conducted a series of experiments. Based on the chip shapes and the roughness of the bottom and side wall of the geometry, it was concluded that milling cutters with irregularly arranged and higher number of cutting edges improved the workpiece surface quality.

2.2. Vibration and Tool Wear Reducing Techniques

Demonstrating different chatter suppression techniques, Munoa et al. [13] presented a critical review of the evolution of each technique and the corresponding industrial application. One way to solve chatter problem is to modify the process parameters and spindle speed using stability lobe diagram (SLD). [14] Researchers used mathematical models with cutting coefficients or specific cutting forces to characterize the cutting force. [15] [16] To obtain the relative vibrations at the tool-workpiece contact zone resulting from the critical modes of the mechanical structure, the dynamic parameters of the system were measured. [17] [18] Consequently, with the estimation of tool-workpiece engagement [19-22] and the simulation of the tool geometry [23] [24], SLD can be constructed to predict chatter. [25] Further researches concerning process stability using SLD were conducted intensively in the last 15 years, including process damping modelling [26-30], thin wall machining [31][32], multitask operations, SLD accuracy improvement and new methods in measuring dynamic parameters. [33-36]

Another prominent method reducing chatter is the spindle speed variation techniques. Munoa et al. [13] presented in their review paper different strategies based on this method. As the modulations in the chip thickness cause the regenerative instability, these techniques focus on changing the tool cutting edge passing period to alternate the period between the modulations.

In addition, there are a large number of studies in chatter suppression using special tool geometries, increased stiffness of the machine tool structure as well as active or passive damping techniques, which will not be elaborated here in more detail.

3. Experimental Setup for Milling Operations

To cover the range of milling operation types as comprehensive as possible, a special conceptualized geometry has been established by conducting three successive series of milling operations. Hence, the trochoidal milling has been applied to mill a groove. Two dimensional shape milling with circumferential face milling is applied to mill a cuboid contour. Last but not least, the latter face milling has been applied to produce a plane surface.

3.1. Milling Machine and Measuring Devices

All experiments have been conducted in the DNM 500 vertical machining center from Doosan Machine Tools Co., Ltd., shown in Fig. 1. This is located at the Institute of Resource and Energy Efficient Production Systems at the FAU Erlangen-Nürnberg in Germany. The Sinumerik 828D machining software from Siemens AG is installed on the machine to carry out the machining processes. The milling operations have been created in the Shopmill program, generating G-codes to be executed in the machine. In this manner, manually established G-codes can also be processed by the machine control system.

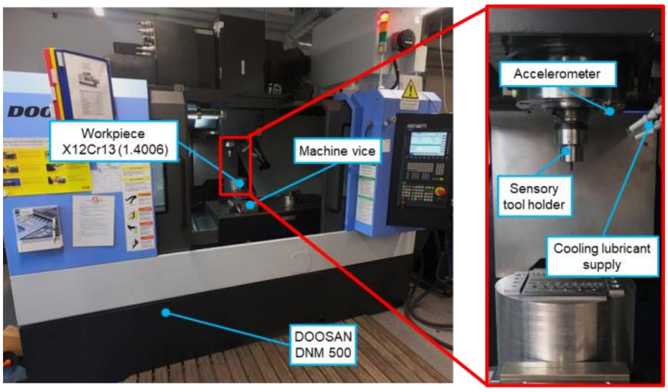

Fig. 1: Machining center DNM 500

The digital microscope VHX-5000 from the company Keyence has been utilized to determine and document the wear on the cutting edges of the installed tools (Fig. 2 a)). In order to quantify the quality of the machined surface, the roughness has been measured, using the tactile roughness measuring device W10 from Hommel etamic (Fig. 2 b), c)). The vibrations of the spindle have been recorded during the milling process with the tri-axial acceleration sensor W356B11/NC (Fig. 2 d)) and the Apollo light measuring system (Fig. 2 e)) as the interface for data transfer. In addition, during the groove milling operations, the time progressions of the magnitude and the direction of the forces acting on the spindle have been measured utilizing the tool holder Spike from promicron GmbH (Fig. 2 f)).

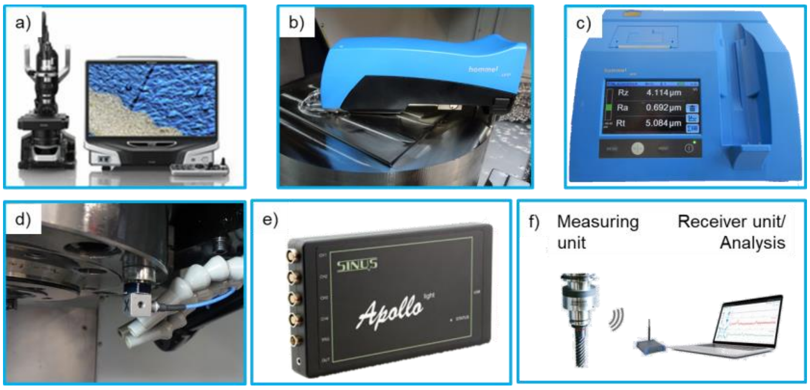

Fig. 2: Measuring devices: a) microscope; b), c) roughness tester; d) accelerometer; e) vibration measuring system; f) force measurement

3.2. Tools and Workpiece

For the groove milling operation, the end mill ”RF 100 Speed” from Gühring KG with a diameter of 8 mm has been selected. The milling head M4132-040-B16-05-09 from Walter AG with five indexable inserts has been used for the 2D shape and face milling processes.

To achieve conclusive test results, a workpiece with a specified geometry has been developed. Thus the objective is to measure and analyze critical machining situations, such as bores, grooves, overhangs and material entries and exits, in one workpiece. The geometry and the dimensions of the workpiece are shown in Fig. 3 a). In the first machining step, a square is shape-milled as a tenon from a cylindrical workpiece blank with a diameter of 200 mm (see Fig. 3 b)). Subsequently, the groove and two bores are milled into this tenon. Finally, the square is completely removed again using face milling. The geometry is clamped in the machine as oriented in Fig. 3 c). The cylinder is made of the material with the number 1.4404 and the specification X2CrNiMo17-12-2.

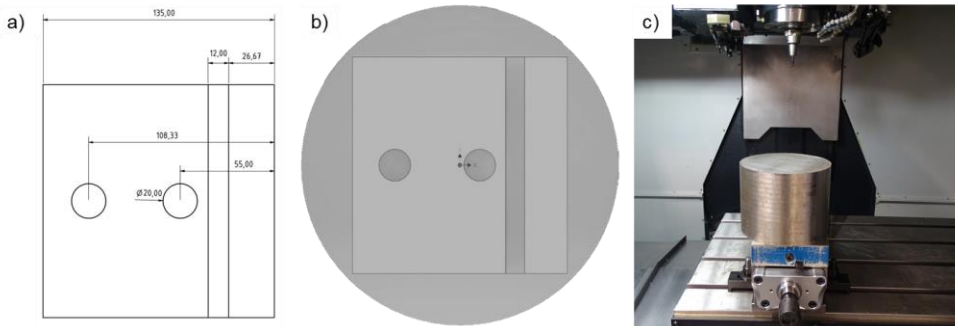

Fig. 3: Workpiece geometry and fixation in machine

3.3. Design of Experiments

To compare different milling strategies and to evaluate the influence of individual parameters on the milling process, various experiments have been carried out. In the following section, the experimental plan and the implementation of experiments are discussed. Regarding the vibration amplitude, machining time, surface quality and tool wear, optimizations have been carried out to identify the suitable boundary conditions for the milling process. In the shape milling process for creating the square tenon from the circular surface, the first strategy shown in Fig. 4 a) is generated by the NC control of Sinumerik 828D. During this strategy, the tool enters the material from the center of the side wall of the formed square tenon, with the maximal cutting width, applying the roll-in entry technique. In the corners of the contour, the tool completely exits and subsequently reenters the material. In comparison with the Sinumerik strategy, in the individually designed strategy shown in Fig. 4 b), the tool enters the material at the corner of the contour with the smallest cutting width. In addition, following an arc-form path at the corners, the tool remains in constant contact with the material until the final exit. The feed rate remains in both strategies constant at the set value without modification. The process is performed in climb milling mode.

In the groove milling process, a groove with a width of 12 mm has been machined into the material over the entire length of the created square tenon. The trochoidal groove milling strategies suggested by

Sinumerik and self-designed using Inventor are compared in Fig. 5. The tool center point path during one engagement period is shown in red respectively in both strategies. The Sinumerik strategy is operated with circular motion and constant feed. The self-designed strategy, on the other hand, follows an elliptical path with different configured feed rates for rapid motion, entry and exit as well as machining cycles.

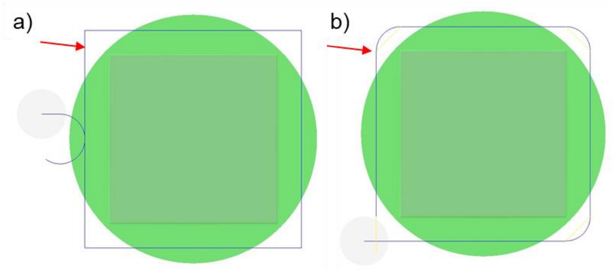

Fig. 4: Shape milling strategies with: a) Sinumerik generated tool path; b) individually designed tool path

In the face milling process, Siemens Shopmill suggests a linear lining off of the surface in climb milling (see Fig. 6 a)). In comparison, a face milling strategy regarding the vibration behavior of the milling process has been specifically developed in Inventor (see Fig. 6 b)). In this strategy, the bores are milled over without interrupted cut. The material entries and exits are carried out with the roll-in entry technique. In addition, the groove is machined in two steps instead of over milling as in the Shopmill strategy. For the face milling strategies, an additional test has been carried out with reduced feed rate at critical points during the process cycle. At material entries and exits in both strategies, the feed rate is reduced to 50 % of the original value. In the Shopmill face milling strategy, the feed rate is reduced to 50 % during the half and full over-milling of the bores and the groove. In the individually designed strategy, the feed rate is reduced to 70 % at the over-milling of bores.

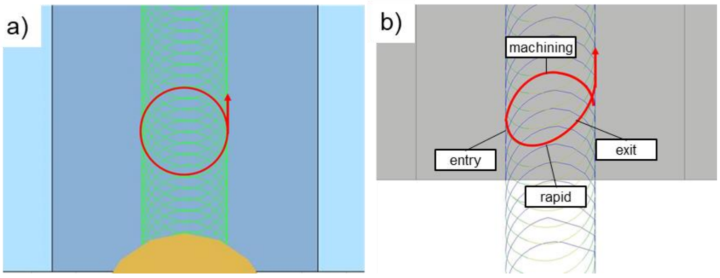

Fig. 5: Groove milling strategies with: a) Sinumerik generated tool path; b) individually designed tool path

Conducting the experiments of all three milling types, a series of milling operations combined with G-code adaption has been carried out to further investigate the influence of control strategy on the vibration behavior of the milling process. The jerk limitation, activated and deactivated by the G-code ”Soft” and ”Brisk”, has been implemented, which can reduce the occurrence of vibration excitation due to jerky accelerations in the feed. However, resulting from the reduced acceleration, this measure slightly increases the machining time. Other G-code adaptions, the continuous path mode, activated with G641, combined with ADIS = 1 or 0.5 as distance criterion, and the exact stop coarse G602, have been utilized to prevent sudden acceleration and deceleration at block change in corners of the given tool path trajectories.

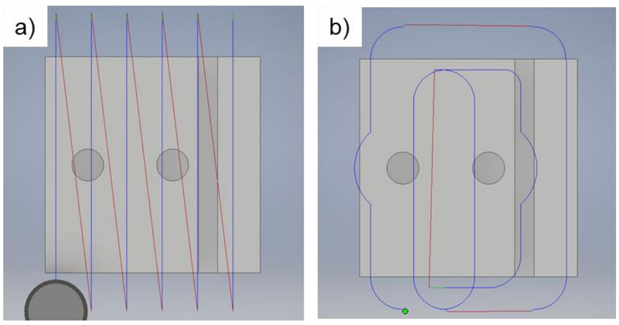

Fig. 6: Face milling strategies with: a) Shopmill generated tool path; b) individually designed tool path

The detailed experimental plan with implemented milling types and strategies is listed in Table 1. To ensure that the individual strategies are comparable with each other, the same cutting parameters are set for all shape, groove and face milling experiments. Solely the cutting width and the feed rate at specific situations vary depending on the current strategy. The cutting parameters utilized in the three milling types are listed in Table 2.

Table 1: Experimental plan

Experiment series	Experiment No.	Milling Strategy	Iteration
1	1-1	Sinumerik shape milling without G-code adaption	3
	1-2	Sinumerik groove milling without G-code adaption	3
	1-3	Shopmill face milling without G-code adaption	3
2	2-1	Designed shape milling with G-code adaption	3
	2-2	Designed groove milling with G-code adaption	3
	2-3	Shopmill face milling with feed & G-code adaption	3
3	3-1	Designed shape milling without G-code adaption	3
	3-2	Designed groove milling without G-code adaption	3
	3-3	Designed face milling with G-code adaption	3

Table 2: Cutting parameters

Cutting parameter	Shape and face milling	Groove milling	Unit
Cutting speed	125	220	m/min
Rotation speed	995	8754	rpm
Tooth feed	0.1	0.083	mm/rev
Feed rate	498	726.6	mm/min
Depth of cut	2	2	mm
Cutting width	(varies)	8	mm

4. Results

The following section presents the results of the experiments carried out to investigate the influence of different milling strategies and parameters on the milling process. These are thereby categorized into the mentioned three milling types. For each milling type, the results of the recorded data of the various strategies are compared and evaluated, including the machining time, tool wear, vibration amplitude, forces as well as the surface quality.

4.1. Shape Milling

The shortest average machining time of 78.13 s is achieved by applying the designed strategy with G-code adaption. The one without G-code adaption is slightly slower. Due to the deceleration of the tool at the contour corners, the Sinumerik strategy lasts significantly longer, with 94.63 s (see Fig. 7).

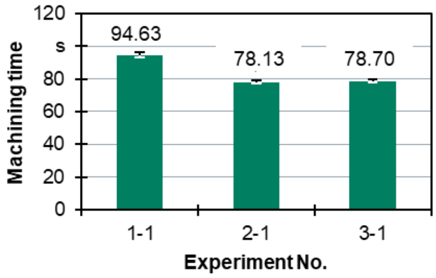

Fig. 7: Shape milling machining time

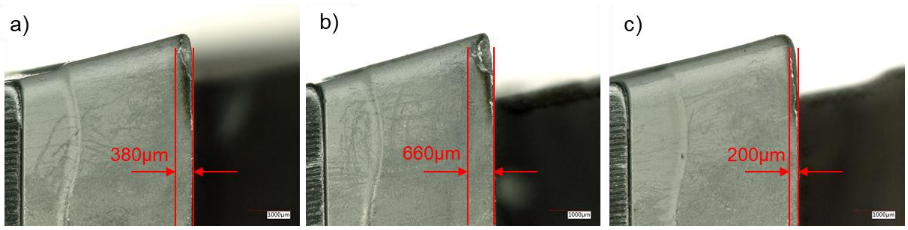

Fig. 8: Shape milling greatest tool wear on the indexable insert experiment No. a) 1-1 b) 2-1 c) 3-1

With regard to the greatest tool wear on the indexable insert after three experimental iterations, the designed strategy without G-code adaption features the best cutting conditions. As shown in Fig. 8 c), the maximum width of wear marks is approximately 200 µm, which is about 70 % less than the one with control adaption (Fig. 8 b)), with 660 µm. The Sinumerik strategy features a maximum width of wear marks of 380 µm (Fig. 8 a)), about 90 % more than the designed one without control strategy.

Respecting the vibration behavior of the Sinumerik milling strategy, the arc-shaped tool path around the geometry corners and material entries can be clearly identified as peaks in the vibration amplitudes of all three iterations (see Fig. 9 a), b), c) curves in blue). On the other hand, in the case of the two customized strategies (curves in orange and gray) where the tool entries the material with steady cutting edge loads, the vibration increment is reduced by approximately 30 % when reentering the material at the corner. Considering the mean values of all three iterations of the three strategies, only slight differences among the values can be observed (see Fig. 9 d)). Applying the designed strategies, the machining time can be saved up to 20 %, with only 1 to 3 % vibration amplitude increase.

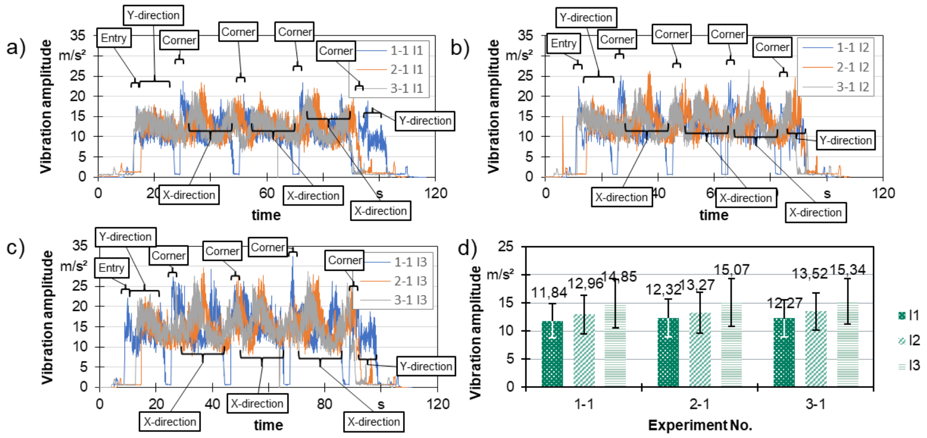

Fig. 9: Shape milling vibration amplitudes comparison a) first iteration b) second iteration c) third iteration d) mean value

4.2. Groove Milling

In the groove milling process, the machining time of the designed strategies is up to 10 % shorter (Fig. 10 a)) due to the shorter tool path lengths. Due to the severe processing delay of the machine control system, however, this time effectiveness is not as apparent in using the designed strategy with G-code adaption. The vibration mean values of the three strategies, on the other hand, deviate hardly from each other with around 2.5 to 3 %, as shown in Fig. 10 b).

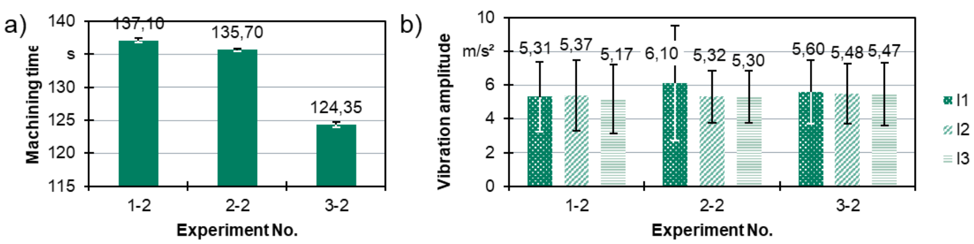

Fig. 10: Groove milling a) machining time b) vibration mean value

After the three iterations, all cutting edges of the end mills have shown almost no tool wear. Yet built-up edges have occurred in certain areas during the execution of designed strategies, where the reduced feed rates give rise to undersized chip cross-sections and thus insufficient machining temperatures.

During the groove milling process, the cutting forces acting directly on the tool and tool holder have been recorded. Parameters, including torsion, axial force, bending moment, torque and temperature have been documented. The evaluation of the results in this section is limited to the bending moment, the reason of which is that the bending moment is the most sensitive parameter with respect to process anomalies. By zooming in on the area of the cutting process, the process stability can be assessed in more detail. Fig. 11 shows selected segments of the three iterations of all three strategies. The fluctuations of the bending moments represent the cutting edge entries into the material. Hence, it can be perceived that, despite shorter machining time, the designed strategies feature a significantly more stable cutting process with more consistent bending moment, the maximum deflection of which is up to 20 % smaller than that of the Sinumerik strategy.

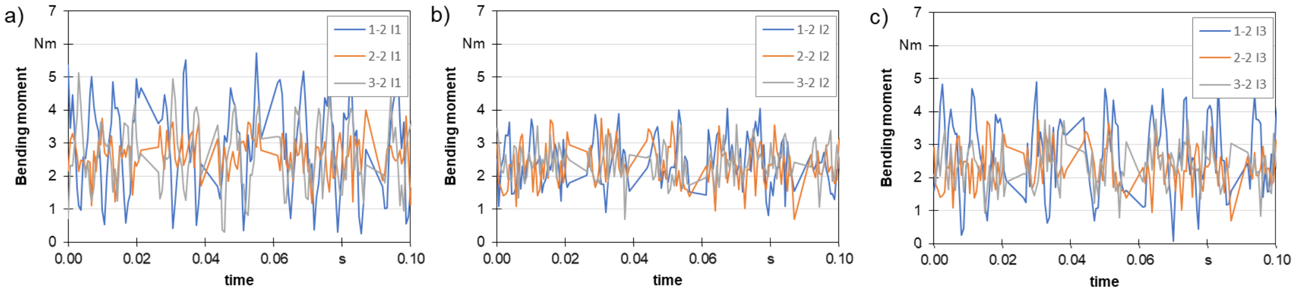

Fig. 11: Groove milling bending moment iteration 1-3

4.3. Face Milling

The last series of experiments has been carried out to compare three face milling strategies. In contrast to the previous experiment series, the G-code adaption has been especially applied to the Shopmill machining strategy. Thus, a conclusion can be drawn as to whether an individual G-code adaption or a combination of tool path optimization and G-code adaption will improve the established criteria.

The machining time of the Shopmill and designed strategy lie closely to each other. The Shopmill strategy with G-code adaption, on the other hand, lasts about 50 % longer than the other two strategies (see Fig. 12). Comparing the tool wear after the three iterations, the Shopmill strategy with G-code adaption features a 15 to 20 % larger average width of wear marks than the other strategies. The Shopmill strategy without G-code adaption and the designed strategy bring about an average width of wear marks of 223 µm and 208 µm respectively.

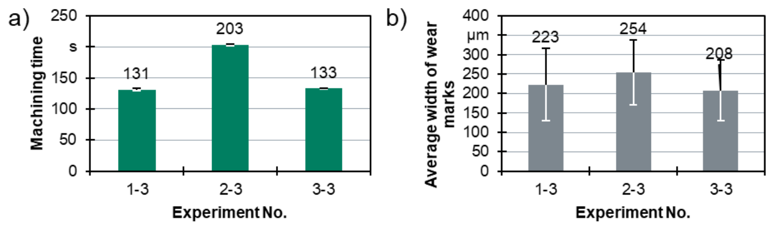

Fig. 12: Face milling a) machining time b) average width of wear marks

In order to quantify the surface quality of the workpiece, the surface roughness has been measured after each face milling iteration, which is characterized by three parameters, i.e. the average distance between the highest peak and lowest valley R_z, the arithmetic mean deviation of the assessed profile R_a and the maximum height of the profile R_t. The results are shown in Fig. 13. It can be observed that the Shopmill strategy with G-code adaption has the lowest R_z on the workpiece surface. With 20 % higher than the lowest R_z, the designed strategy has yet better performed in comparison to the Shopmill strategy without G-code adaption. Accordingly, the other two parameters R_a and R_t also demonstrate the similar tendency.

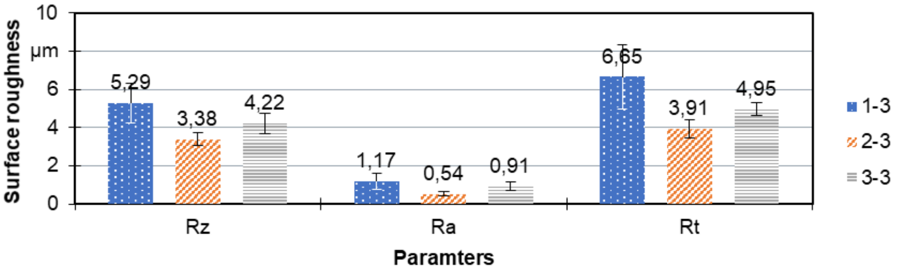

Fig. 13: Face milling surface roughness

For a sufficiently detailed comparison of the vibration behavior of all three strategies, six critical situations during the milling process, numbered respectively on the Shopmill and the designed tool path (see Fig. 14), are discussed below. The three diagrams in Fig. 15 show the process vibration amplitude progression of time of the three experimental iterations. In each diagram, the course of vibration of the Shopmill strategy without G-code adaption, the Shopmill strategy with G-code adaption and the designed strategy are illustrated in blue, orange and grey respectively. Because of the unequal machining time and various tool paths of the three strategies, the six critical situations take place at different moment and even in different order in the milling process with various strategies. The exact moment of the six situations, occurring within the milling process, are identified with numbered boxes in matching colors according to the milling strategies respectively.

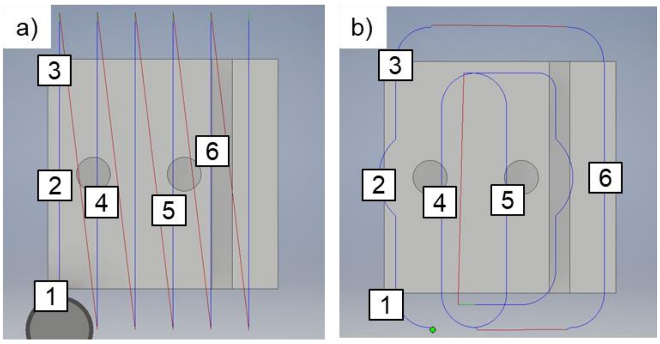

Fig. 14: Face milling critical situations a) Shopmill b) designed tool path

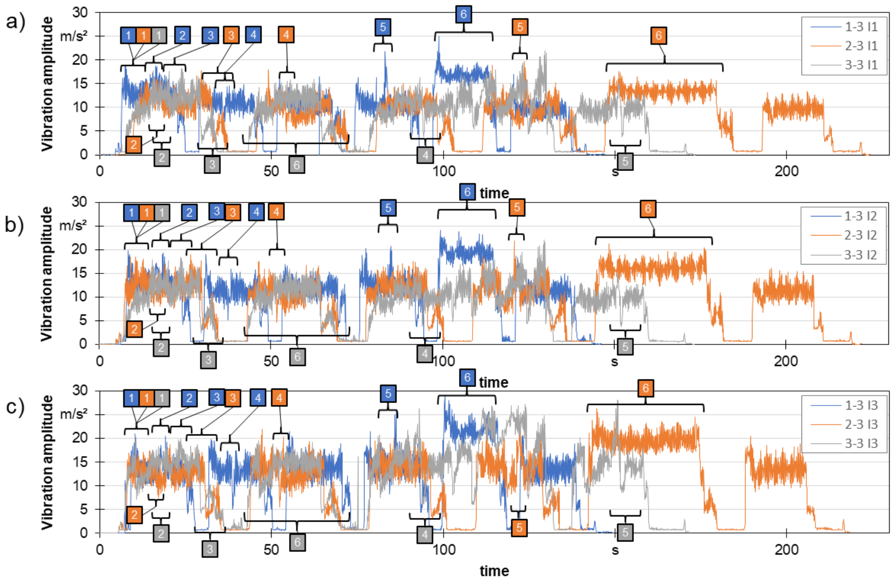

Fig. 15: Face milling vibration amplitude iteration 1-3

In the first situation, the vibration amplitudes of the three milling strategies are compared at the time of the first material entry. It can be observed that with the assistance of a reduced feed rate in combination with roll-in entry technique, the vibration amplitude increases significantly slower and more evenly to its maximum value which is also notably lower. As shown in Fig. 15, the maximum amplitude deflection of the designed strategy in three iterations are up to 17 % lower than the Shopmill strategy with G-code adaption, and 54 % lower than the one without G-code adaption.

The milling operation in the second situation is performed in two different ways depending on the strategy. With the designed strategy, the bore is milled around in an arc-shaped tool path at the edge of the bore. In contrary, with both Shopmill strategies, the bore is milled over in a half section. Plotting the mean values of the vibration amplitude over the time span from entry to exit of the bore, it is found that a feed rate reduction in the Shopmill strategy with G-code adaption, adjusted by direct intervention in the feed rate control, as well as indirectly by the activated jerk limitation, leads to an average reduction in vibration amplitude by 25 % over all iterations, compared to the Shopmill strategy with the same tool path but no G-code adaption. The designed strategy features in this situation only a minimal improvement of approximately 1.5 % lower mean vibration value compared to the Shopmill strategy without G-code adaption.

The material exits in the third situation show a high similarity in the vibration amplitudes. For all three strategies, as the cutter exits the material, the vibration amplitude decreases to a lower value. Equivalently in the fourth situation, where the left bore is milled over for a second time and the remaining material around the hole is face milled, the course of the vibration amplitude deviates only insignificantly from each other.

In the fifth situation, the Shopmill strategies mill over the right bore in a full cut in only one pass. This results in an interrupted cut across the bore, which creates large chip cross sections and in turn cause the deflections of the vibration amplitude. The designed strategy, on the other hand, processes the right bore in two passes, analogous to the first bore. The bore is firstly milled around and subsequently milled over. In order to establish an easy comparison, the mean values of each strategy are calculated from the first entry into the bore to the last exit from it. With a mean value of 12.8 m/s^2, the designed strategy brings about up to 20 % lower vibration amplitude than the Shopmill strategy without G-code adaption and 5 % lower than the one with G-code adaption.

Last but not least, in the sixth situation, the groove is milled over with large chip cross sections and interrupted cut in both Shopmill strategies. In the designed strategy, however, the groove is taken into account in the tool path planning, where an interrupted cut is thus prevented. The mean value of the vibration amplitude is thereupon reduced by around 36 % compared to the Shopmill strategy with reduced feed rate and by 60 % compared to the one with the same feed rate.

A concluding evaluation of the three different strategies can be achieved by averaging the vibration amplitudes over the entire experiment. The Shopmill strategy without G-code adaption features a mean value of 11.35 m/s^2, which is about 15.8 % higher than the designed strategy, with 9.80 m/s^2. In the Shopmill strategy with G-code adaption, with 9.72 m/s^2, the vibration mean value is negligibly lower than that of the designed strategy.

5. Discussion

After analyzing the experimental results of three different milling types in separate aspects, namely machining time, tool wear, vibration behavior, bending moments and surface quality, a summary evaluation of each milling type applying different strategies is presented in the Table 3.

Table 3: Summary comparison of process criteria

Milling type	Milling strategy	Machining time		Tool wear		Vibration behavior		Cutting forces		Surface quality	
		in s		width of wear marks in µm		mean vibration amplitude in m/s²		mean value bending moment in Nm		R_z in µm	
Shape milling	Sinumerik	95	(ref.)	380	(ref.)	13.2	(ref.)	--	--	--	--
	G-code adaption	78	↓	660	↑	13.6	→	--	--	--	--
	Designed	79	↓	200	↓	13.7	→	--	--	--	--
Groove milling	Sinumerik	137	(ref.)	≈ 0	--	5.3	(ref.)	4.0	(ref.)	--	--
	G-code adaption	136	→	≈ 0	--	5.6	→	4.3	→	--	--
	Designed	124	↓	≈ 0	--	5.5	→	4.5	→	--	--
Face milling	Shopmill	131	(ref.)	223	(ref.)	11.4	(ref.)	--	--	5.3	(ref.)
	G-code adaption	203	↑	254	↗	9.7	↘	--	--	3.4	↘
	Designed	133	→	208	↘	9.8	↘	--	--	4.2	↘

In the shape milling process, the milling strategy for material entry and exit has been examined. By saving up to 20 % machining time, despite comparable mean vibration amplitude, the designed strategies yet feature about 30 % lower vibration deflection amplitude, in comparison to the Sinumerik strategy. Additionally, due to the unfavorable cutting conditions, the Sinumerik strategy causes significantly more tool wear than the designed strategy with G-code adaption.

Regarding the groove milling process, despite a shorter machining time, the designed strategies exhibit a much more stable cutting process with reduced deflections in the course of the bending moment at material entries. By utilizing the designed optimization method, the deflection in the vibration amplitude can also be decreased by up to 20 %. The mean value of the vibration amplitude and the bending moment, however, only differs slightly.

Just as importantly, in the final face milling process, a reduction of 54 % in the mean value of vibration amplitude during the material entry can be achieved by applying the designed strategy. The vibration behavior of the designed strategy shows a smooth and slowly increasing tendency compared to the significantly faster and more abruptly rising tendency of the Shopmill strategy. The milling around and over milling of the bores have ensured a mean value reduction of the vibration amplitude by up to 25 %. Moreover, by avoiding the interrupted cut over the groove, the mean value is lowered up to 60 %. Respecting the width of wear marks and the surface roughness parameters, it can be concluded, that the higher vibration amplitude has a negative effect on the tool wear and the surface quality of the workpiece. Here, the average wear mark width of the inserts of 223 µm and the average roughness depth R_z of 5.3 µm are measured to be approximately 7 % and 26 % higher, respectively, comparing the Shopmill strategy with the designed strategy.

6. Summary and Outlook

To establish the negative effects of excessive vibration behavior on the resulting cutting forces, the surface quality and the tool wear, experiments on three milling types with respectively three different milling strategies have been conducted. In this work, CAM and CNC strategies automatically generated by common programming tools, which do not explicitly take vibration minimization into consideration, have been compared with specifically designed tool path with optimized tool engagement behaviors and parameters. As a conclusion, it can be stated that in particular the feed rate, the acceleration of the milling cutter, tool path trajectory and the cutting width have a considerable influence on the milling process. Through the experimental tests, it can be determined that depending on the milling situation, a reduction of the feed rate in combination with a tool path modification exhibits a great potential in the process optimization. However, an optimization with regard to the defined criteria by intervening in the machine control merely with G-code adaption could not be clearly verified.

Further research should be conducted in the field of determining the influence of the interaction between CNC-machine control system and the manipulated variables on the process as well as effective variables. Especially, the control parameters of the cascaded control system of the machine drives, which define the accuracy of the tool path trajectory and the robustness of the machine control system, should be taken into consideration. Moreover, integrating the obtained experiential knowledge into a simulation model that enables the optimization progress of the milling processes on existing machining tools without additional appliances or complex add-on will also be highly beneficial.

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8. References

[1] J. Dietrich, Praxis der Zerspantechnik: Verfahren, Werkzeuge, Berechnung, 12th ed., Springer Fachmedien Wiesbaden GmbH, Wiesbaden, 2016. URL: https://ebookcentral.proquest.com/lib/kxp/detail. action?docID=4749231.

[2] A. Risse, Fertigungsverfahren der Mechatronik, Feinwerk- und Präzisionsgerätetechnik, 1st ed., Springer Vieweg. in Springer Fachmedien Wiesbaden GmbH, Wiesbaden, 2012. URL: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=993954.

[3] C. Brecher, M. Weck, Werkzeugmaschinen Fertigungssysteme 2: Konstruktion, Berechnung und messtechnische Beurteilung, VDI-Buch, 9. aufl. 2017 ed., Springer Berlin Heidelberg, Berlin, Heidelberg, 2017. URL: http://nbn-resolving.org/urn:nbn:de:bsz:31-epflicht-1559429.

[4] C. Brecher, M. Weck, Werkzeugmaschinen Fertigungssysteme 3: Mechatronische Systeme, Steuerungstechnik und Automatisierung, 9. aufl. 2021 ed., Springer Berlin Heidelberg, Berlin, Heidelberg, 2021. URL: http://nbn-resolving.org/urn:nbn:de:bsz:31-epflicht-1867107.

[5] Y. Liu, B. Wu, M. Luo, D. Zhang, Modeling and cutting path optimization of shallow shell considering its varying dynamics during machining, Procedia CIRP 31 (2015) 521–526. doi:10.1016/j.procir.2015. 03.059.

[6] G. M. Minquiz, V. Borja, M. López-Parra, A. C. Ramírez-Reivich, M. A. Domínguez, A. Alcaide, A comparative study of cnc part programming addressing energy consumption and productivity, Procedia CIRP 14 (2014) 581–586. doi:10.1016/j.procir.2014.03.009.

[7] J. Senatore, S. Segonds, W. Rubio, G. Dessein, Correlation between machining direction, cutter geometry and step-over distance in 3-axis milling: Application to milling by zones, Computer-Aided Design 44 (2012) 1151–1160. doi:10.1016/j.cad.2012.06.008.

[8] K. Castelino, R. D'Souza, P. K. Wright, Toolpath optimization for minimizing airtime during machining, Journal of Manufacturing Systems 22 (2003) 173–180. doi:10.1016/S0278-6125(03)90018-5.

[9] R. Othmani, M. Hbaieb, W. Bouzid, Cutting parameter optimization in nc milling, The International Journal of Advanced Manufacturing Technology 54 (2011) 1023–1032. doi:10.1007/s00170-010-3017-4.

[10] L. N. López de Lacalle, A. Lamikiz, J. A. Sánchez, M. A. Salgado, Toolpath selection based on the minimum deflection cutting forces in the programming of complex surfaces milling, International Journal of Machine Tools and Manufacture 47 (2007) 388–400. doi:10.1016/j. ijmachtools.2006.03.010.

[11] I. Lazoglu, C. Manav, Y. Murtezaoglu, Tool path optimization for free form surface machining, CIRP Annals 58 (2009) 101–104. doi:10.1016/j.cirp.2009.03.054.

[12] K. Waszczuk, P. Karolczak, M. Wisniewska, M. Kowalski, Influence of the path type on selected technological effects in the trochoidal milling, Advances in Science and Technology Research Journal 11 (2017) 147–153. doi:10.12913/22998624/66501.

[13] J. Munoa, X. Beudaert, Z. Dombovari, Y. Altintas, E. Budak, C. Brecher, G. Stepan, Chatter suppression techniques in metal cutting, CIRP Annals 65 (2016) 785–808. doi:10.1016/j.cirp.2016.06.004.

[14] S. A. Tobias, W. Fishwick, Theory of regenerative machine tool chatter, The Engineer (1958).

[15] Y. Altintas, Manufacturing automation: Metal cutting mechanics, machine tool vibrations, and CNC design, 1. publ ed., Cambridge Univ. Press, Cambridge, 2000. URL: http://www.loc.gov/catdir/samples/cam032/99030935.html.

[16] E. Budak, Y. Altintas¸, E. J. A. Armarego, Prediction of milling force coefficients from orthogonal cutting data, Journal of Manufacturing Science and Engineering 118 (1996) 216–224. doi:10.1115/1.2831014.

[17] H. van Brussel, J. Peters, Comparative assessment of harmonic, random, swept sine and shock excitation methods for the identification of machine tool structures with rotating spindles. Ann CIRP 24 (1975) 291–296. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0016444948&partnerID=40&md5=f3a4f0b21c5daa9ff1ffb9a0755aad66, cited By 7.

[18] D. J. Ewins, Modal testing: Theory, practice and application, volume 10 of Mechanical engineering research studies Engineering dynamics series, 2. ed. ed., Research Studies Press, Baldock, 2000. URL: http://www.loc.gov/catdir/enhancements/fy0745/97043590-d.html.

[19] W. Ferry, Y. Altintas, J Manuf Sci. Eng 130 (2008) 1. Cited By 1.

[20] A. Lamikiz, L. N. López de Lacalle, J. A. Sánchez, M. A. Salgado, Cutting force estimation in sculptured surface milling, International Journal of Machine Tools and Manufacture 44 (2004) 1511–1526. doi:10. 1016/j.ijmachtools.2004.05.004.

[21] Y. Altintas, P. Kersting, D. Biermann, E. Budak, B. Denkena, I. Lazoglu, Virtual process systems for part machining operations, CIRP Annals 63 (2014) 585–605. doi:10.1016/j.cirp.2014.05.007.

[22] B. Tukora, T. Szalay, Real-time cutting force prediction and cutting force coefficient determination during machining processes, Advanced Materials Research 223 (2011) 85–92. doi:10.4028/www.scientific.net/AMR.223.85.

[23] S. Engin, Y. Altintas, Mechanics and dynamics of general milling cutters, International Journal of Machine Tools and Manufacture 41 (2001) 2195–2212. doi:10.1016/S0890-6955(01)00045-1.

[24] Z. Dombovari, Y. Altintas, G. Stepan, The effect of serration on mechanics and stability of milling cutters, International Journal of Machine Tools and Manufacture 50 (2010) 511–520. doi:10.1016/j.ijmachtools.2010.03.006.

[25] Y. Altintas, M. Weck, Chatter stability of metal cutting and grinding, CIRP Annals 53 (2004) 619–642. doi:10.1016/S0007-8506(07)60032-8.

[26] Y. Altintas, M. Eynian, H. Onozuka, Identification of dynamic cutting force coefficients and chatter stability with process damping, CIRP Annals 57 (2008) 371–374. doi:10.1016/j.cirp.2008.03.048.

[27] M. Eynian, Y. Altintas, Chatter stability of general turning operations with process damping, Journal of Manufacturing Science and Engineering 131 (2009). doi:10.1115/1.3159047.

[28] K. Ahmadi, F. Ismail, Analytical stability lobes including nonlinear process damping effect on machining chatter, International Journal of Machine Tools and Manufacture 51 (2011) 296–308. doi:10.1016/j.ijmachtools.2010.12.008.

[29] L. T. Tunc, E. Budak, Identification and modeling of process damping in milling, Journal of Manufacturing Science and Engineering 135 (2013). doi:10.1115/1.4023708.

[30] K. Ahmadi, Y. Altintas, Identification of machining process damping using output-only modal analysis, Journal of Manufacturing Science and Engineering 136 (2014). doi:10.1115/1.4027676.

[31] B. Denkena, C. Schmidt, Experimental investigation and simulation of machining thin-walled workpieces, Production Engineering 1 (2007) 343–350. doi:10.1007/s11740-007-0017-9.

[32] D. Biermann, P. Kersting, T. Surmann, A general approach to simulating workpiece vibrations during five-axis milling of turbine blades, CIRP Annals 59 (2010) 125–128. doi:10.1016/j.cirp.2010.03.057.

[33] C. Brecher, Y. Trofimov, S. Bäumler, Holistic modelling of process machine interactions in parallel milling, CIRP Annals 60 (2011) 387–390. doi:10.1016/j.cirp.2011.03.025.

[34] C. Brecher, A. Epple, S. Neus, M. Fey, Optimal process parameters for parallel turning operations on shared cutting surfaces, International Journal of Machine Tools and Manufacture 95 (2015) 13–19. doi:10.1016/j.ijmachtools.2015.05.003.

[35] E. Shamoto, T. Mori, K. Nishimura, T. Hiramatsu, Y. Kurata, Suppression of regenerative chatter vibration in simultaneous double-sided milling of flexible plates by speed difference, CIRP Annals 59 (2010) 387–390. doi:10.1016/j.cirp.2010.03.028.

[36] E. Budak, E. Ozturk, Dynamics and stability of parallel turning operations, CIRP Annals 60 (2011) 383–386. doi:10.1016/j.cirp.2011.03. 028.