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Lead time reduction by high precision 5-axis milling of a prototype gear

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Abstract

Gearbox development is significantly delayed due to the long lead times associated with the manufacturing of functional prototype gears by means of classical methods such as hobbing and grinding. This paper presents a novel method to machine a prototype gear using high precision 5-axis milling with the same geometrical and surface properties associated with aforementioned technologies, only reducing lead times from 10 weeks to less than 24 hours. Different milling strategies and tools are shown to have an influence on the achieved geometrical properties such as roundness, pitch error and flank quality. A ground quality gear has been manufactured using an alternating milling strategy combined with tool wear compensation.

Keywords: Precision milling, lead time reduction, gear manufacturing, prototyping

1. Introduction

The automotive industry, among others, is constantly evolving towards a shorter time-to-market for its new products. New cars and trucks need to be designed, tested and released for production in a much shorter period of time. While at the moment 48 months is standard, there is an evolution towards 36 months and it is expected that further in the 21st century this can be reduced even further to 13-15 months. This shorter time-to-market evolution also has an influence on the gearbox manufacturers which have to design and test their products in a much shorter period of time. Critical in this process is the lead time to create new prototype gears, which is currently around 10 weeks. This is mostly caused by the need to create custom hobbing and grinding tools, a process which is time consuming and costly [1]. This long lead time limits the amount of configurations which can be tested and makes it difficult to achieve the best possible result concerning tribological and acoustic performance. For this reason, gearbox manufacturers need a faster production technology to create precision gears for prototyping purposes.

Comparisons between different machining methods [2] showed that the geometrical and surface quality requirements for prototype gear cannot be met with state of the art EDM, SLM and milling technologies. SLM was not sufficiently accurate to produce a part within the geometrical and surface quality constraints, while EDM is inherently not flexible enough to tackle the wide array of prototyping needs. Milling had the highest degree of flexibility since it is no problem to add micro flank corrections such as tip relief, root relief, angular profile variance, profile crowning, angular lead variance, end relief and lead crowning using this technology. This makes it suitable for a wide array of gear types. However, in the author’s previous work [2] it was shown that milling did not meet the geometrical requirements for prototype gears according to DIN 3960. In particular, profile variation, run out and pitch errors remained.

Considering the increased flexibility, 5-axis high precision milling is chosen as a method to create high quality gears.

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Schmitz et al. [3] proved that high speed milling can provide a dramatic reduction in lead time compared to classical methods and already outlined the main areas of investigation for the future, namely tool wear compensation, strategy and appropriate path generation. Other research on the 5-axis milling of gears, and in particularly bevel gears, mainly focused on the simulation of the cutting process [4,5]. In this research, the machining of a prototype gear up to ground quality is explained with a total machining time of less than 24h. In particular, the focus will be the compensation of the excessive run out and pitch error reported in the previous work by means of milling strategy and wear compensation.

2. Experimental

The samples were made of cylindrical cast 16MnCr5 steel parts, pre-machined to the outer gear diameter of 82,75 mm, an inner diameter of 51,5mm and a height of 41,75 mm by means of turning on a Mazak Integrex 200-IV integrated machining center. The part was clamped on a mandrel (Rohm KFS-06) and machined on a Fehlmann Picomax Versa 850 high precision milling machine in order to create a involute gear with a total of 36 gear teeth, a normal module of 2.120 mm and a helix angle of 0˚. The specifications which the gear should meet are shown in Table 2 (DIN 3960). Two types of tools were used for the finishing process: (a) a 2 mm diameter ball nose cutter (WNT VHM 52 256 206, WC-Ti coating) and (b) a 2 mm diameter end mill (Union Tool CSS 2020-0500, L=5 mm). The milling strategy is outlined in Table 1 for both tools. In the final finishing regime, the ball nose cutter applied 150 passes over a flank length of 4.5 mm, resulting in an ap of 0.03 mm, while the end mill operation featured 40 or 120 passes over the same length. However, due to the nature of the end mill operation, it is not possible to define a true ap value. In both cases, the residual stock that has to be removed after pre-finishing is 0.1 mm (radial cutting depth ae). Surface roughness measurements were performed on a contact profilometer (Mahr Perthometer PGK Plus) and measured on individual flanks removed from the gear by means of EDM. Tool wear measurements were performed both optically (Leica MZ 125) and on an integrated tool measurement system (BLUM Lasercontrol NT). Gear profile measurements were performed on a Klingelnberg Gear Measurement Center PNC 65 and a Mitutoyo Crysta Apex-S coordinate measurement system.

Table 1: Gear milling strategy.

Operation	Tool	Feed Rate [mm/min]	Spindle Speed [rpm]	Time [min]
Rough Profile Machining	End Mill 3 mm	260	8000	67
Rough Profile Machining	End Mill 2 mm	200	12000	60
Rough Root Profile Machining	Ball Nose 2 mm	230	11500	25
Semi-Finishing	End Mill 2 mm	860	16000	110
Finishing	Ball Nose 2 mm	640	16000	280
Finishing	End Mill/Ball Nose 2 mm	640	16000	360 or 1080

3. Results & Discussion

3.1. Alternating flank machining

Based upon the results from the past [2] the milling strategy outlined in Table 1 is used to create a gear using a 2 mm ball nose cutter to apply the last finishing operation. The advantage of the ball nose cutter compared to a straight end mill is that using this tool, a 3 + 2 axis milling strategy is sufficient, significantly reducing the CAM programming effort, which is substantial for prototype gears. When machining this gear it was noticed that a strategy in which every tooth and tooth flank is machined consecutively clockwise, the pull and push movement created by this strategy significantly deteriorated the flank quality, in particular, the flanks machined by a push movement. To solve this, a new alternating strategy was employed in which first all the left flanks are machined, and then the right flanks, using a pull movement. The results of this strategy are shown in Table 2 (Sample 2). It can be seen that in particularly the profile variations (F_α and ff_α) are significantly reduced, indicating a better profile quality, caused by the absence of a push milling strategy. In addition, the run out Fr and pitch errors F_p, f_p and f_u are significantly lower as well. The reason for this is that the error resulting from tool wear is now distributed more evenly over the gear. However, for the right flanks, the flanks that we machined the last, a higher profile variation is visible, due to the fact that there the error from the tool wear is the highest.

Table 2: Comparison between Sample 1 (sequential milling) and Sample 2 (alternating milling) for the left and right flanks.

Parameter	Limit	Sample 1		Sample 2	
		L	R	L	R
Profile Angle Variation $f_{h\alpha}$ [µm]	6	**-25,2**	**- 26,1**	**-6,6**	**-8,5**
Profile Form variation ff_α [µm]	8	**9,2**	7,7	4,6	8
Total profile variation F_α [µm]	10	**22,3**	**24,7**	9,3	**12,3**
Tooth trace Angle Variation $f_{h\beta}$ [µm]	12	-2,5	2,8	-3,7	-2,3
Total tooth trace variation F_β [µm]	15	**24**	**20,2**	**15,5**	14,5
Tooth trace form variation ff_β [µm]	9	0,9	4,5	0,4	0,4
Run out F_r [µm]	24	**67,7**		24	
Cumulative Pitch Error F_p [µm]	32	**37,1**	**36,4**	19,1	21,3
Single Pitch Error f_p [µm]	7	**22,5**	**20,5**	5,5	6,3
Pitch to Pitch error f_u [µm]	9	**33,5**	**20**	**9,9**	5
Total Milling Time [min]	1440	1196		1196	

While the numbers shown in Table 2 (Sample 2) are averages, the individual numbers for the last right flank were higher with an F_α and ff_α of respectively 14 and 9.7 µm, significantly above the limit values. Because that this right flank is machined last, with a worn tool, and is next to the first machined left flank where a new tool was used, a considerable pitch error f_u was present. This indicated that an even higher degree of wear distribution to avoid pitch errors is required.

3.2. Tool wear distribution

To increase the distribution of tool wear a new strategy was used. Instead of machining every left and then right flank, a single tooth cavity (a left and right flank, including top edge and root) was now machined in its entirety, in a sequence as shown in Figure 1 using a pull-pull strategy. This method insured that the pitch errors, and in particular the single pitch error and pitch to pitch errors do not become too large by placing a tooth flank with little or no deviation due to tool wear next to a tooth flank with a lot of error caused by tool wear. The results of this strategy is shown in Table 3 (Sample 3).While an excellent profile quality has been achieved, a significantly higher run out F_r is also observed. Due to this strategy, the tool wear error differences between two adjacent teeth are minimalized, however, the reduction in tool radius is noticed to follow the strategy with the gear teeth machined the last, contributing the most to the F_r. The reason for this can be twofold. First, the cutting forces and associated tool deflections are proportional to the wear of the tool, increasing with increasing tool wear. Using a simplified cutting model[6] it was possible to calculate the cutting forces and corresponding tool deflections. With an ae of 0.1 mm and a ap of 0.03 mm, the cutting forces were maximum 1 N and the tool deflection 0.25 µm, which is too low to be significant. The second option is the decrease in tool radius due to tool flank wear. A tool flank wear of 80 µm has been observed accompanied with a tool ball nose radius decrease of around 40 µm. The dimensional errors caused by this is significant enough to cause the excessive run out.

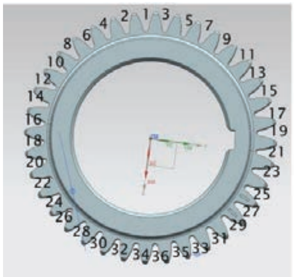

Fig. 1: Milling strategy for wear compensation.

To lower the run out, a second tool has been introduced to this strategy in order to avoid machining part of the gear with a worn out tool. The first 18 teeth will be machined with the first tool, while after the 18th operation, a tool change will be done in order that the final 18 teeth cavities are machined using a new tool. The results are shown in Table 3 (Sample 4). The total run out, while lowered, is still above the limit value. However, by using two tools, the tooth trace variation F_β increased beyond the limit. To investigate if the F_r further decreased when increasing the number of tools, the same test is now done with 4 tools. However, when the tools are changed, there are still points, just before tool change, that the limit with respect to the radial distance to the gear center and thus run out is crossed, indicating that even 4 tools is not sufficient This is confirmed by the F_r value in Table 3 (Sample 5). It is also clear that intermitting tool changes influence the tooth trace variation negatively. Since this does not sufficiently alleviate the run out problem and introduced excessive tooth trace variation, another method to cope with the tool wear should be used.

Table 3: Comparison between wear distribution Sample 3 (single tool), Sample 4 (2 tools) and Sample 5 (4 tools).

Parameter	Limit	Sample 3		Sample 4		Sample 5	
		L	R	L	R	L	R
Profile Angle Variation $f_{H\alpha}$ [µm]	6	5,8	-0,4	4,2	1,4	3,1	-0,8
Profile Form variation $f_{f\alpha}$ [µm]	8	3,4	4,2	1,8	2,1	2,2	2,5
Total profile variation F_α [µm]	10	6,2	4,3	4,2	2,1	3,2	2,3
Tooth trace Angle Variation $f_{H\beta}$ [µm]	12	0,5	1,3	-7,3	-5,3	6,6	5,9
Total tooth trace variation F_β [µm]	15	12,9	13,7	**39,2**	**15,2**	**37,5**	**15,9**
Tooth trace form variation $f_{f\beta}$ [µm]	9	0,6	0,6	0,2	0,3	0,4	0,5
Run out F_r [µm]	24	**35,9**		**28,5**		**29,8**	
Cumulative Pitch Error F_p [µm]	32	18,5	15,3	18,6	18,3	25,4	27,5
Single Pitch Error f_p [µm]	7	5,7	3,2	5,4	4	6,9	6,4
Pitch to Pitch error f_u [µm]	9	**10,5**	5,2	8,2	5,8	8,5	8,2
Total Milling Time [min]	1440	1197		1198		1199	

3.3. Wear Compensation

It was concluded in the previous section that the decrease in ball nose radius due to tool wear is the main cause for the excessive run out. A possible solution for this is to actively compensate the tool path for the tool wear. This can be done by measuring the tool after each machined flank and adapting the tool radius in the machine controller and thus compensating for the decrease in tool radius due to wear. However, due to the fact that the ball nose contact point is not constant during the finishing operation of a single flank, it is not possible to measure and compensate for the decrease in ball nose radius actively. Therefore, the choice has been made to finish the gear flanks with straight end mills, which have, in combination with a 5-axis machining strategy, a constant contact point with respect to the gear flanks.

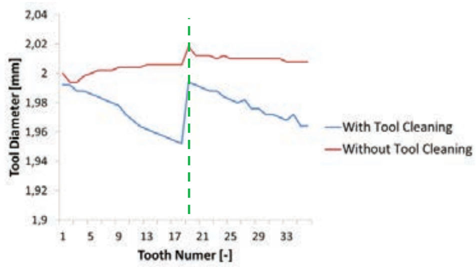

Fig. 2: Tool diameter for straight end mills, dotted green line = toolchange.

In Figure 2 the results of tool diameter measurements of two gears, machined with two tools each, including the strategy outlined in the previous section, is shown. A tool cleaning cycle, in the form of positioning and rotating at low RPM the tool against a metal brush mounted next to the gear setup, can be applied to remove any residual coolant and/or debris. It can be seen that if no cleaning is applied to the tool before measuring the diameter the tool diameter starts to grow after a few flanks, which is impossible. The reason for this is that the coolant film on top of the tool distorts the laser measurement. This leads to incorrect compensation steps and geometric errors, which are depicted in Table 4 (Sample 6). When a cleaning cycle is introduced after each flank, a correct radius measurement is performed, which allows compensation by the controller. Sample 7 has been machined using 2 end mills, a 5-axis strategy combined with tool compensation and cleaning. This method led to a ground quality gear with, except for machining time, all values below the specified limits. In order to lower the amount of flank passes, and to reduce the total milling time, the flank roughness is measured in function of the number of passes, see Figure 3.

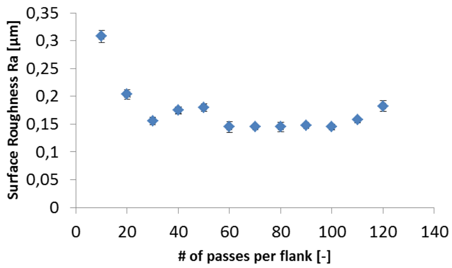

Fig. 3: Flank Surface Roughness Ra [µm] after 5 axis end-mill machining.

Table 4: Results for 5-axis 2-end mill strategy with tool compensation, Sample 6 without cleaning, Sample 7 with tool cleaning and Sample 8 with reduced flank passes (40 instead of 120).

Parameter	Limit	Sample 6		Sample 7		Sample 8	
		L	R	L	R	L	R
Profile Angle Variation $f_{h\alpha}$ [µm]	6	-0,9	-2	-0,9	-0,4	-0,3	-0,4
Profile Form variation $f_{f\alpha}$ [µm]	8	1	1,1	1,3	1,8	1,9	1,9
Total profile variation F_α [µm]	10	1,5	2,9	1,9	2,1	2,0	4,9
Tooth trace Angle Variation $f_{h\beta}$ [µm]	12	-26	- 20,8	1,2	-1,1	-2,4	-4,2
Total tooth trace variation F_β [µm]	15	**32,4**	**25,1**	13,2	13,3	14,4	14,9
Tooth trace form variation $f_{f\beta}$ [µm]	9	0,6	0,5	0,4	0,5	0,6	0,5
Run out F_r [µm]	24	**34,6**		12		18,6	
Cumulative Pitch Error F_p [µm]	32	24,9	14,9	12,3	11,3	24,5	20,1
Single Pitch Error f_p [µm]	7	**19,9**	5,9	4,6	2,3	6,6	5,9
Pitch to Pitch error f_u [µm]	9	**19,5**	8	5,9	3,1	**11,2**	8,2
Milling Time [min]	1440	**1526**		**1526**		902	

Currently, for the 5-axis end mill strategy 120 flank passes are applied, which leads to an R_a of 0.18 µm, far below the limit of 0.8 µm. Lowering the number of passes does not significantly increase the R_a value up to 30 passes, which indicates that there is an opportunity to lower the total milling time threefold by applying only 40 passes instead of 120 per flank. This has been done in Sample 8, and presented in Table 4. It can be seen that the run out F_r is within tolerances, but, however, the Pitch to Pitch Error f_u is 2 µm above the limit. This is caused by the deterioration of the flank geometry which accompanies the decrease in passes per flank. Therefore, in future research, there will be a focus on 50 to 60 passes per flank to achieve a minimal machining time with gear parameters within limits.

4. Conclusions

It was shown in this research that milling strategy, tool choice and even tool cleaning can play an important role in the quality of direct-milled prototype gears. A consecutive counterclockwise milling strategy, which uses a push-pull motion for every tooth cavity, in combination with a ball nose cutter led to severely deteriorated profile quality, run out and pitch errors. This was partly solved by applying an alternating milling strategy in which first the left flanks and then the right flanks were machined. However, from these tests it was clear that due to pitch errors, further wear distribution is required. A novel tool wear distribution strategy was used next, using either 1, 2 or 4 tools for machining the whole gear. This effectively removed the pitch errors by making sure flanks machined with a new tool are never near flanks machined with a worn tool. However, this caused excessive run-out by the concentration of dimensional error by worn tools and it is concluded that increasing the number of tools beyond 2 does not significantly improve this. This implied that active compensation of the tool wear is required, which was only possible using a 5-axis strategy combined with a straight end-mill. Combined with a tool cleaning operation, measuring and compensating after every flank allowed for the fabrication of a ground quality gear in 24h, which implies that instead of 10 weeks lead time, now only a few days are sufficient.

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