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Abstract:	Gear Hobbing is one of the most common soft-machining processes for pre-toothing. The process kinematics result in a characteristic tooth-flank topography, which is mainly determined by so-called feed marks. For an economical finishing process by gear grinding in automotive applications, the feed-mark depths should not exceed a maximum value of 35 µm. In the present study the validity of this limit has been investigated in view of the development of increasingly powerful grinding machines and grinding wheels. For this purpose, gears with feed-mark depths δ x below and above 35 µm were machined and ground by means of discontinuous profile gear grinding afterwards. The influence of the feed marks on the grinding process with roughing parameters was systematically evaluated on the basis of various process variables such as the increase in spindle power P s or the degree of grinding-wheel clogging Z s , while the resulting gear quality was mainly analyzed by various parameters to describe macro- and micro-geometry deviations of the ground tooth flanks. With increasing feed-mark depth, an increase in spindle power was found due to the additional machined volume. An influence of increasing feed-mark depths on the clogging degree, the grinding-wheel wear and the gear quality could not be proven. Therefore, economical finishing of gears by gear grinding is also possible with feed-mark depths of more than 35 µm. A new definition of this limit should be sought.

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Title:

Influence of gear hobbing feed marks on the resulting gear quality after discontinuous profile grinding

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Abstract:

Gear Hobbing is one of the most common soft-machining processes for pre-toothing. The process kinematics result in a characteristic tooth-flank topography, which is mainly determined by so-called feed marks. For an economical finishing process by gear grinding in automotive applications, the feed-mark depths should not exceed a maximum value of 35 µm. In the present study the validity of this limit has been investigated in view of the development of increasingly powerful grinding machines and grinding wheels. For this purpose, gears with feed-mark depths δ_x below and above 35 µm were machined and ground by means of discontinuous profile gear grinding afterwards. The influence of the feed marks on the grinding process with roughing parameters was systematically evaluated on the basis of various process variables such as the increase in spindle power P_s or the degree of grinding-wheel clogging Z_s, while the resulting gear quality was mainly analyzed by various parameters to describe macro- and micro-geometry deviations of the ground tooth flanks. With increasing feed-mark depth, an increase in spindle power was found due to the additional machined volume. An influence of increasing feed-mark depths on the clogging degree, the grinding-wheel wear and the gear quality could not be proven. Therefore, economical finishing of gears by gear grinding is also possible with feed-mark depths of more than 35 µm. A new definition of this limit should be sought.

Keywords: Gear hobbing, feed marks, gear grinding, geometric gear quality

1. Introduction, motivation and research objective

In gear manufacturing, gear hobbing is one of the most common soft machining processes for pre-toothing [1, 2]. Due to the process kinematics, a characteristic periodical tooth-flank topography is formed during the gear-hobbing process (Figure 1) [2].

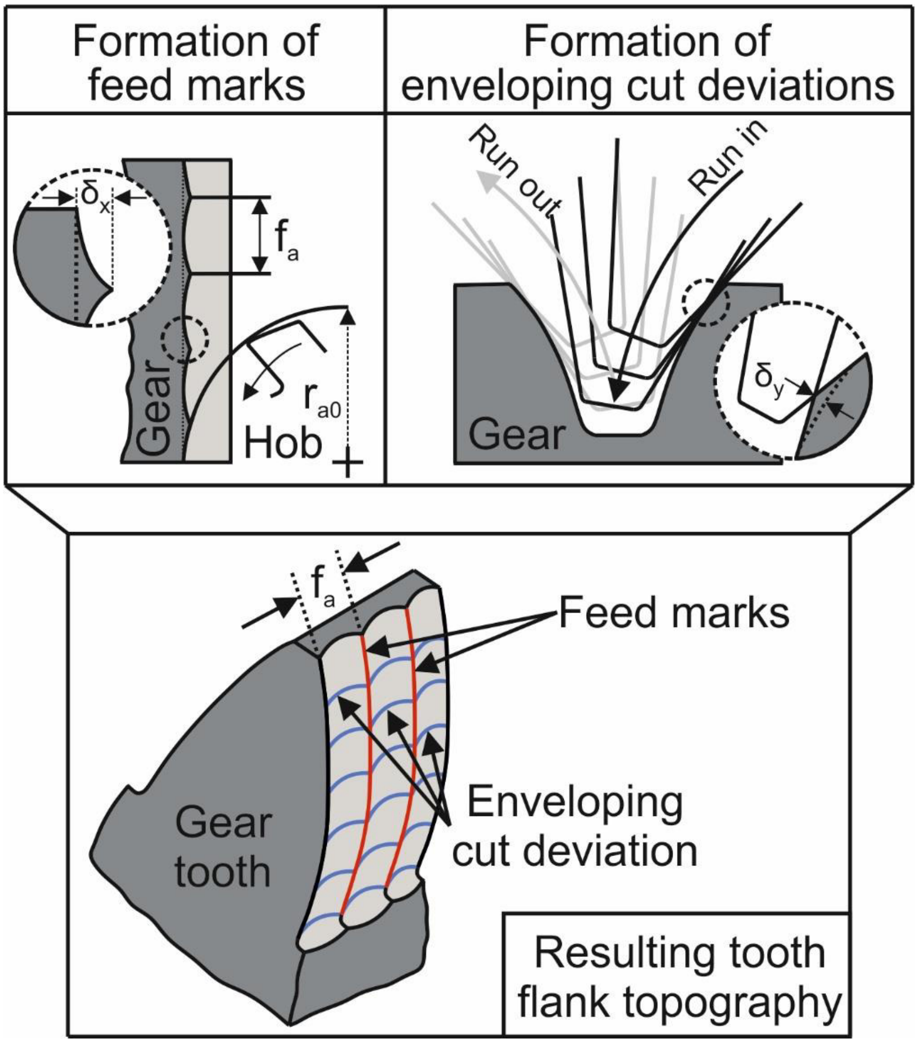


Figure 1. Formation of the tooth-flank topography due to the hobbing process.

The tooth flank topography is a superposition of the enveloping cut deviations and the feed marks. The enveloping cut deviations are caused by the interrupted hobbing process of the grooved hobbing cutter on the tooth flank. Feed marks, on the other hand, are caused by the feed movement of the hob in axial direction of the gear. Since the enveloping cut deviations are usually much smaller than the feed marks, the tooth-flank topography is mainly determined by the latter [4]. An estimation of the feed-mark depths δ_x resulting after the hobbing process can be made with the help of formula 1.

$$\delta_x = \left(\frac{f_a}{\cos(\beta)}\right)^2 \cdot \frac{\sin \alpha_n}{4 \cdot d_{a0}} \qquad (1)$$

The feed-mark depths δ_x depend not only on the geometric sizes of the hob (hob diameter da_0) and the gear to be produced (normal pressure angle α_n, helix angle β), but above all on the axial feed f_a. The axial feed f_a is also a decisive factor for the efficiency of the hobbing process. An increase of the axial feed f_a leads to a decrease in the main time and thus to a faster hobbing process. However, this in turn means that the resulting feed-mark depths increase. Depending on which process for gear finishing is used, the feed-mark depths should not exceed defined maximum values [5]. This also results in a maximum selectable axial feed and a limitation of the productivity of the gear-hobbing process. In the literature such as [5] and [6] a maximum feed-mark depth of 35 µm is recommended for gear grinding. It is stated that the grinding process of gears with feed-mark depths above this value is uneconomical. That is why this recommendation has become generally accepted in industry. In view of the increased performance of gear grinding machines and grinding wheels in recent years, the validity of this limit should be questioned and, if necessary, a new limit should be defined. In this study, an extensive investigation of the influence of different feed marks on discontinuous profile grinding and the resulting gear quality was carried out. For this purpose, gears with different feed-mark depths, which were below and above the recommended limit value of 35 µm, were machined. Subsequently, the influence of different feed marks on the grinding process (spindle power, clogging degree) and the quality of the ground gears (deviation of flank line, profile line, concentricity, span and pitch) were investigated.

2. Experimental setup and procedure

The procedure chosen for this study is shown in Figure 2.

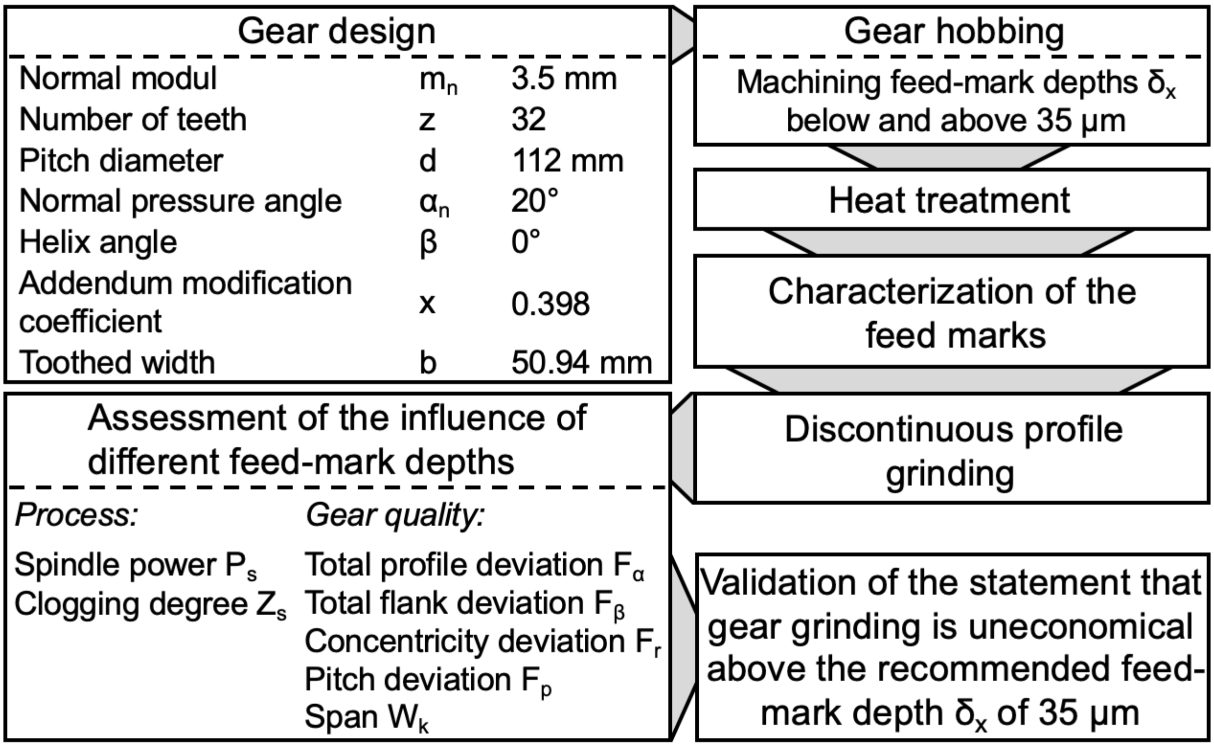
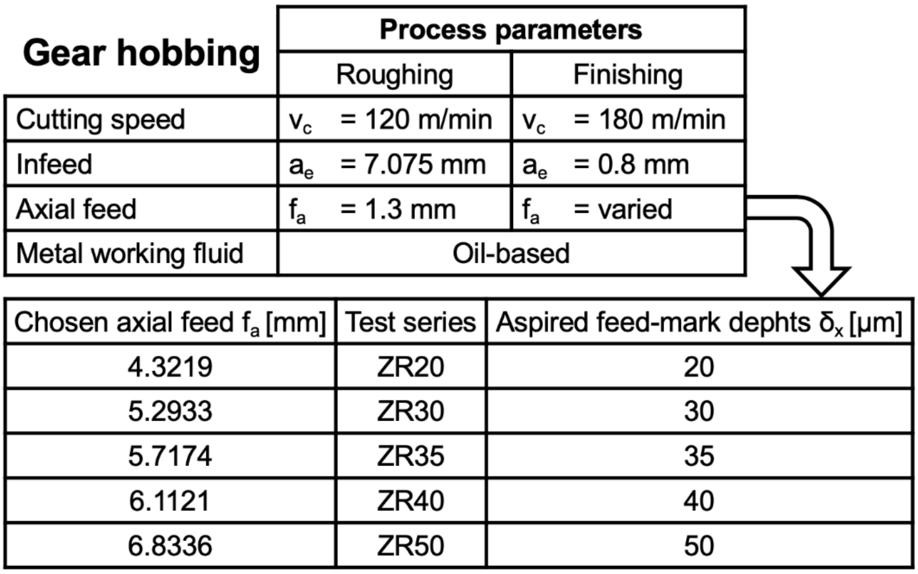


Figure 2. Procedure for this study.

At first a suitable gear was designed. The gear parameters are also shown in Figure 2. In order to keep the effort in characterizing the feed marks as low as possible, the gear to be produced should be a spur gear (β = 0°). The used material was the case-hardening steel 1.6523 (20NiCrMoS2-2).

The gears were machined using a two-stage hobbing process on the hobbing machine tool GP130 (Gleason-Pfauter GmbH). The selected process parameters can be found in Table 1. The required feed-mark depths δ_x were generated during the finishing cut by varying the axial feed f_a. The values δ_x were calculated according to formula 1. After machining the gears were conventionally case-hardened after carburizing. The tactile roughness tester ‘Surftest SV-3200’ (Mitutoyo GmbH) was used to characterize the feed marks. Using the measurement records, the resulting feed-mark depths could be determined and compared with the calculated values (Figure 3).



Gear hobbing	Process parameters	
	Roughing	Finishing
Cutting speed	v_c = 120 m/min	v_c = 180 m/min
Infeed	a_e = 7.075 mm	a_e = 0.8 mm
Axial feed	f_a = 1.3 mm	f_a = varied
Metal working fluid	Oil-based	

Chosen axial feed f_a [mm]	Test series	Aspired feed-mark depths δ_x [µm]
4.3219	ZR20	20
5.2933	ZR30	30
5.7174	ZR35	35
6.1121	ZR40	40
6.8336	ZR50	50

Table 1. Process parameters for gear hobbing.

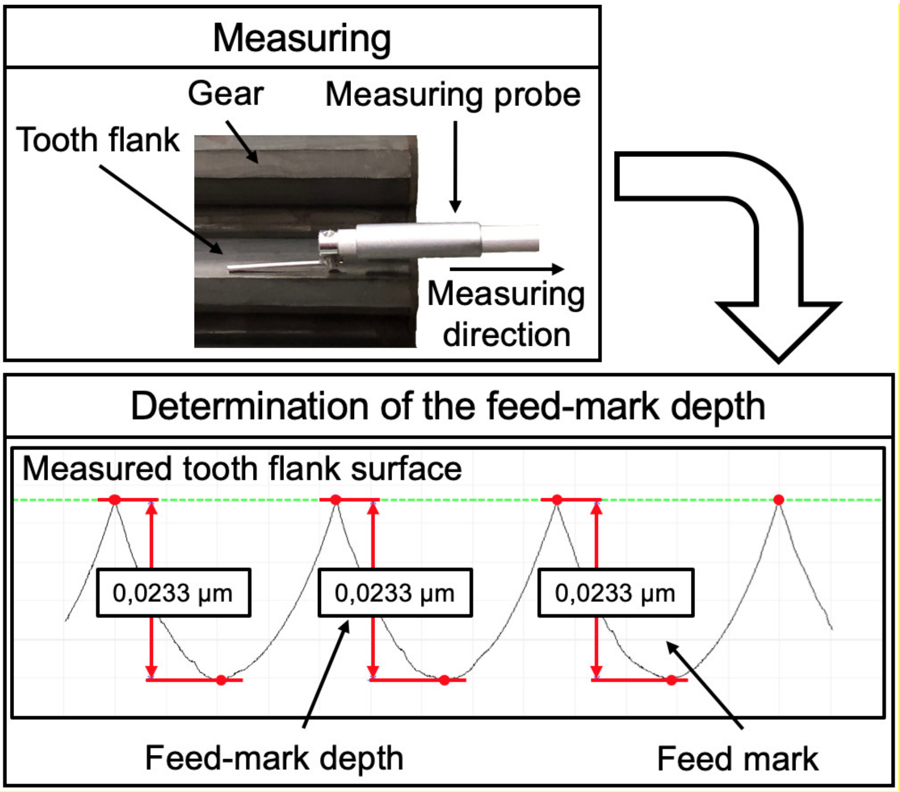


Figure 3. Procedure for the determination of the feed-mark depth.

The grinding experiments were carried out on the gear grinding machine tool KX 500 Flex (Kapp GmbH & Co. KG). The selected process and dressing parameters can be found in Table 2.

Grinding parameters

Grinding wheel: SK 23W 60/1 G/H 10 V 10 (sintered corundum + white corundum)		
Cutting speed	v_c	= 35 m/s
Infeed	a_e	= 3 x 146 µm
Feed rate	v_{fa}	= 5000 mm/min
Specific material removal rate	Q'_w	= 12.2 mm³/mm s

Dressing conditions

Dresser: Electroplated diamond dressing roll form dressing (point contact)		
Dressing speed	v_d	= 35 m/s
Dressing infeed	a_{ed}	= 1 x 50 µm
Overlap rate	U_d	= 2
Speed ratio	q_d	= 0.7

Metal working fluid (MWF) supply

Oil-based		
Conventional tangential nozzle		
Flow rate	Q_{MWF}	= 330 l/min

Table 2. Process parameters for discontinuous profile grinding.

Per feed-mark depth two gears (64 tooth gaps, $V'_w \approx 1428\ mm^3/mm$) were machined without intermediate dressing. Each tooth gap was ground with three strokes. It has to be emphasized that on purpose three times the same **roughing parameters** were applied. The tests were not meant to achieve the best possible final quality, but rather to determine possible differences related to feed marks. The spindle power P_s was determined for each stroke. In addition, the clogging degree Z_s of the grinding wheel was measured in-situ using the optical measuring system ‘GrindingVision’ which was developed at the Leibniz Institute for Materials Engineering [7]. This system is consisting of a camera which is surrounded by four powerful light sources. With the camera a picture of the grinding wheel surface is taken. After that, the clogged area (i.e. the area of higher reflection due to steel inclusion) within the measuring area is determined in percent with an image analysis. In order to guarantee a comparable initial state of the grinding wheel before each test series, the grinding wheel was dressed with 30 strokes. After the grinding experiments, the deviation of the flank line, profile line, concentricity, pitch and span were measured on the precision measuring center ‘P40’ (Klingelnberg GmbH).

3. Results and discussion

Characterization of the generated feed-mark depths

In order to verify whether the desired feed-mark depths were achieved after gear hobbing and the subsequent heat treatment, these were measured on the right and left tooth flank on 6 different teeth per gear. Figure 4 shows the measured and calculated feed-mark depths δ_x as a function of the axial feed f_a.

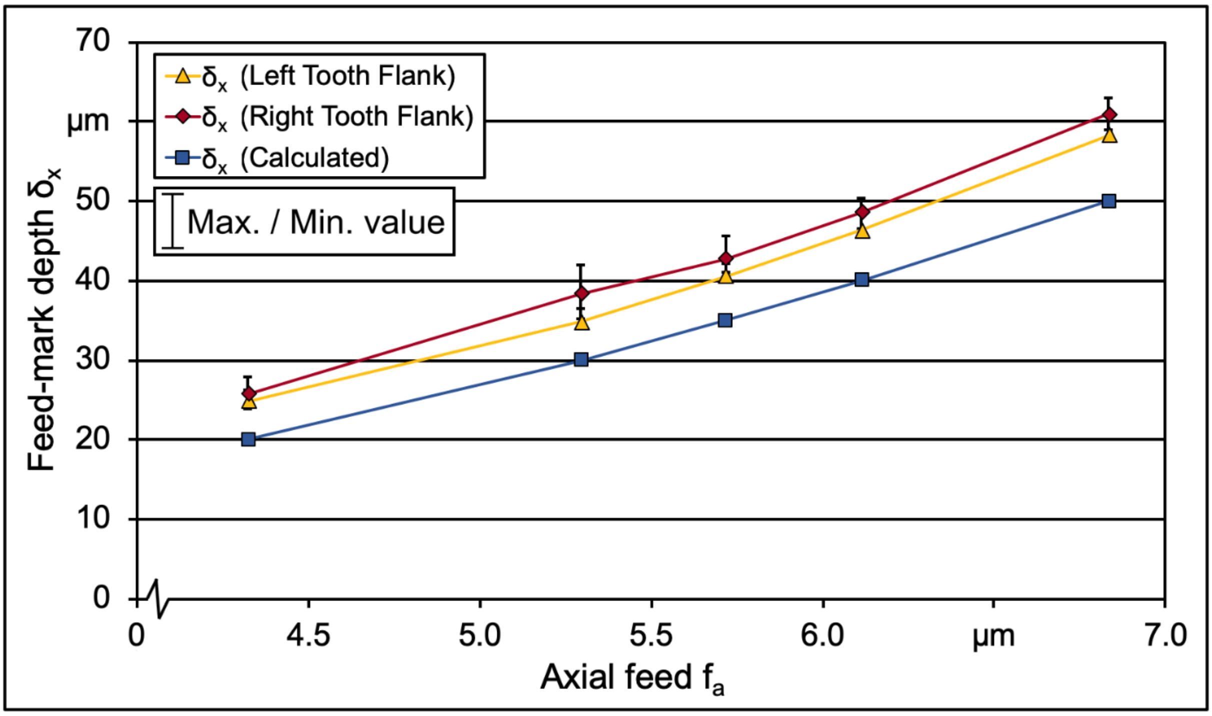


Figure 4. Comparison between the calculated and the measured feed-mark depths in dependence of the axial feed.

As expected, an increase of the axial feed f_a results in an increase in the feed-mark depths. A significant and systematic difference between the calculated and the measured feed-mark depths can be determined. Thus, the measured feed-mark depths on the right flank are about 20% higher than the calculated values. This is due to the tool, clamping and process kinematics tolerances, which lead to a deviation from an ideal hobbing process [8]. This results in a systematic error, which promotes higher feed-mark depths. It is also shown that the feed-mark depths on the left and right tooth flanks differ. On the right tooth flank higher depths were formed. This has also been observed in other studies such as [9] and [10]. It can be assumed that this difference is caused by the varying tool motion during the formation of the two tooth flanks. Thus, the material on the left tooth flank is machined by hob teeth that move towards the tooth root. When machining the right tooth flank, the hob teeth move in reverse starting from the tooth root towards the tooth tip.

Influence of different feed-mark depths on the grinding process

In order to evaluate the influence of different feed marks on discontinuous profile grinding, the spindle power was determined during the machining of two gears without intermediate dressing. In Figure 5 the spindle power P_s is plotted against the number of ground tooth gaps and the specific material removal volume V'_w. The spindle power per gap represents the arithmetic mean of the maximum power per stroke. The designations ZR20 to ZR50 reflect the machined feed-mark depths according to table 1 (i.e. ZR20 represents the aspired feed-mark depth of 20 µm).

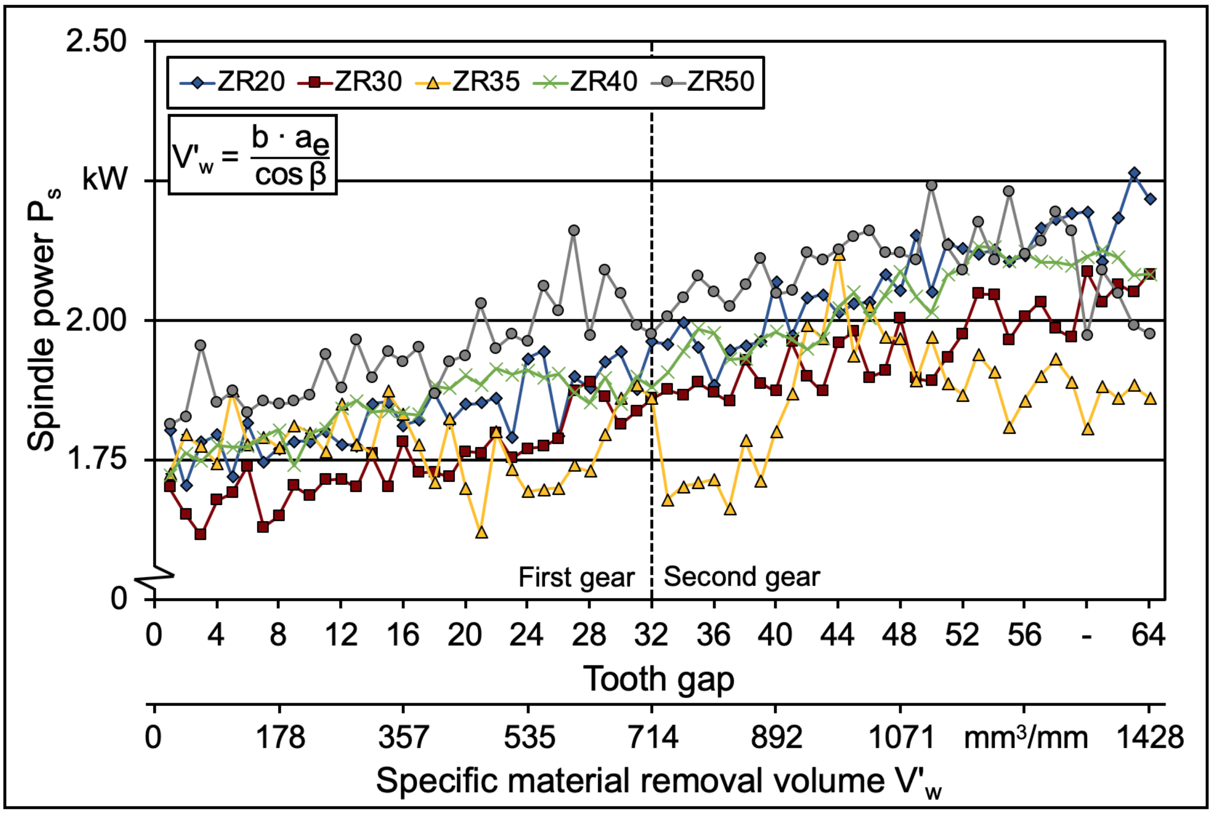


Figure 5. Progression of the spindle power according to the ground tooth gaps and the specific material removal volume for each test series.

It can be seen that the spindle power increases from gap 1 to gap 64 as wear and clogging of the grinding wheel progresses. It can also be observed that greater feed-mark depths tend to lead to higher spindle power. It can be assumed that the increase of the spindle power is due to the higher removed volume during the first stroke. In order to verify this assumption, the spindle power per stroke for the different feed marks is shown in Figure 6. The spindle power per stroke P_s is averaged over the 64 tooth gaps.

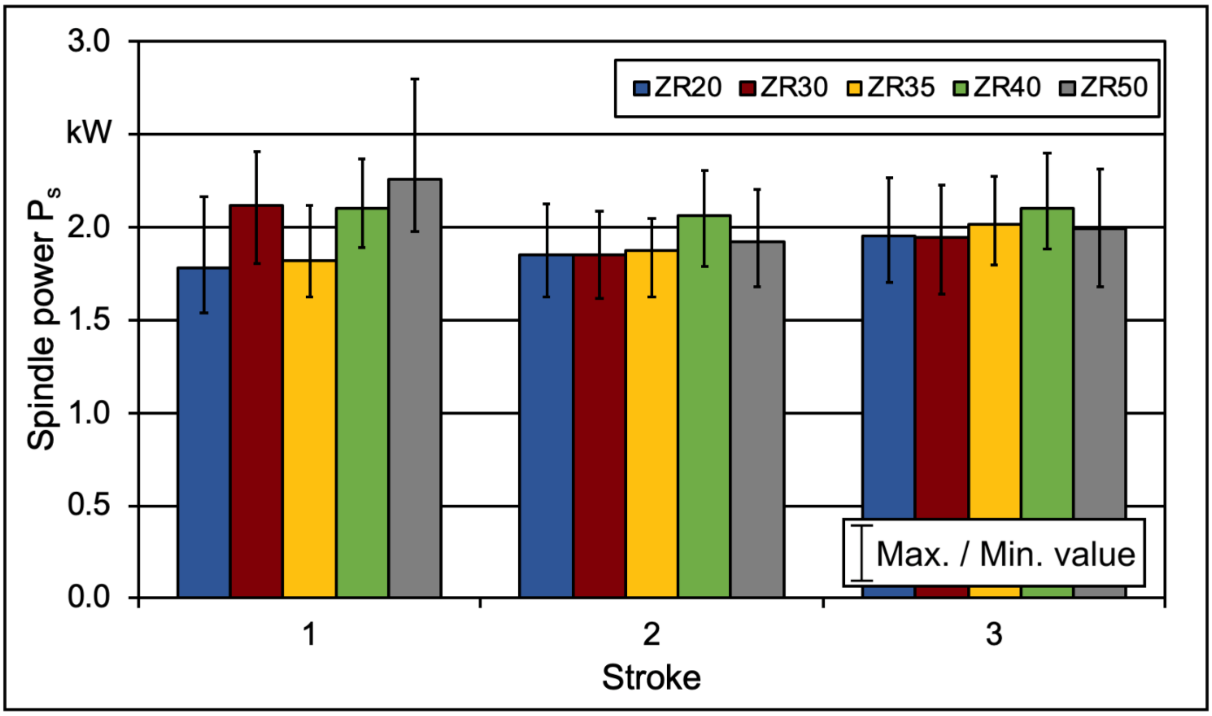


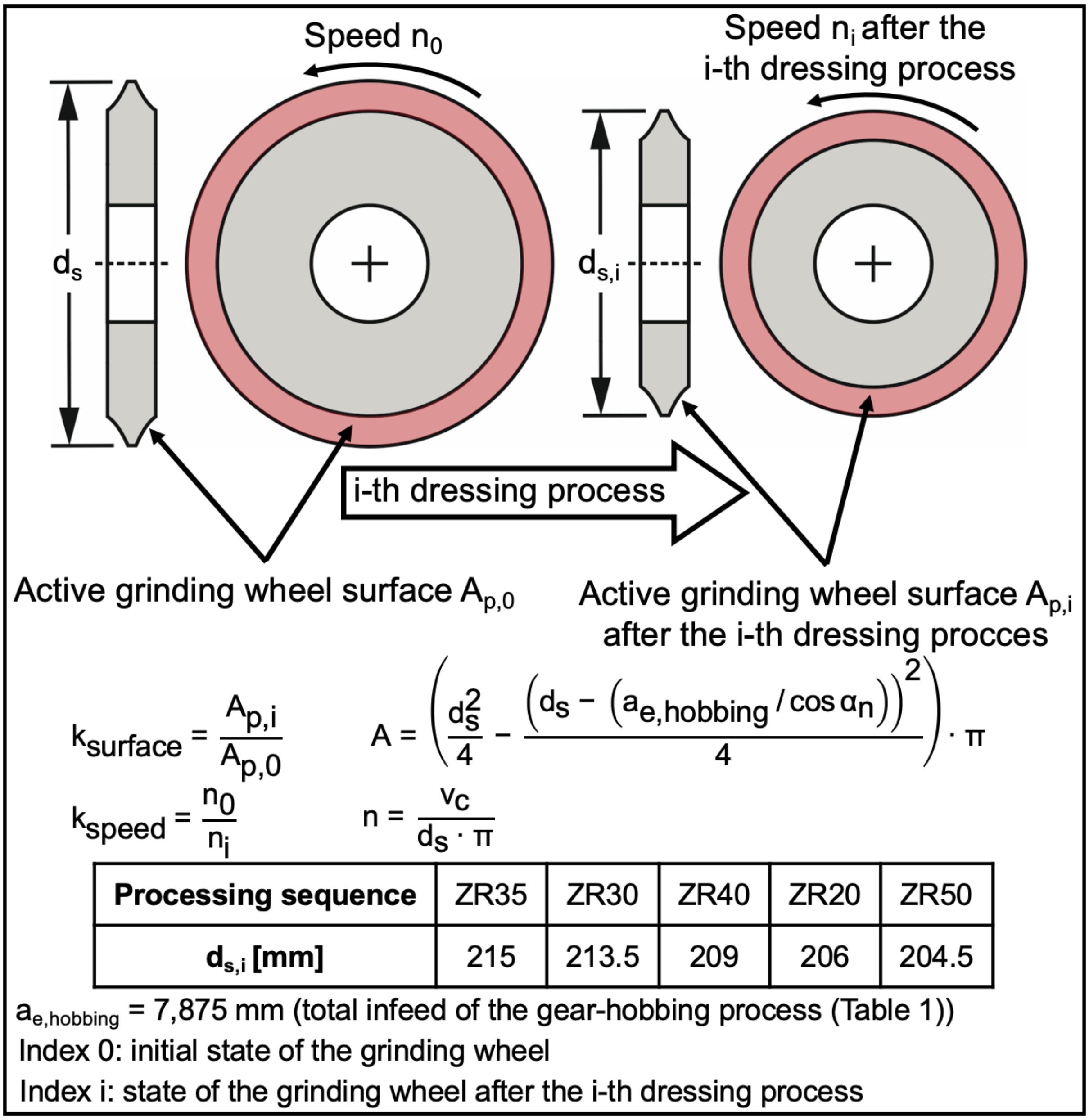
Figure 6. Measured spindle power per stroke for each test series.

For the first stroke, a tendency of an increase in spindle power with increasing feed-mark depth can be observed. As already mentioned, this can be explained by the additional machined volume. For the remaining two strokes, approximately the same spindle power was measured regardless of the different feed-mark depths. This is due to the fact that the same volume was removed during these strokes according to the radial infeed a_e. However, it is not possible to make a clear statement whether different feed-mark depths have a considerable influence on the spindle power, since the spindle power for each stroke lies within the same range of variation.

The increasing spindle power P_s in Figure 5 can be explained by progressing wear and clogging of the grinding wheel. This means that chips are increasingly deposited in the pore space of the grinding wheel and workpiece material remains on the grinding grains (so-called welded clogging) [7]. The clogged pore space leads to a decrease of the lubricant supply to the contact zone. Due to the resulting increase in friction between grinding wheel and workpiece, there is also an increase in process forces and thus in the spindle power [11, 12, 13]. In order to verify whether the grinding wheel bears more clogging with increasing feed-mark depths and thus with the additional removed volume during the first stroke, the clogging degree ΔZ_s was determined with the aid of the optical measuring system 'GrindingVision' during discontinuous profile grinding. The clogging degree indicates the increase of wheel clogging from tooth gap 1 to tooth gap 64. Due to the dressing processes the grinding wheel diameter is successively reduced. However, the smaller the grinding wheel becomes, the more often each area of the grinding wheel surface is involved in the machining process. So, with a smaller grinding wheel, the clogging is distributed over a smaller area, which means that the increase of clogging is greater than with a grinding wheel with a larger diameter. In order to assess a possible influence of the feed marks on the grinding-wheel clogging, the measured clogging degree ΔZ_s must be related to the grinding wheel diameter (formula 2).

$$\Delta Z'_s = \Delta Z_s \cdot k_{surface} \cdot k_{speed} \qquad (2)$$

The related clogging degree $\Delta Z'_s$ is the product of the measured clogging degree ΔZ_s and the two factors $k_{surface}$ and k_{speed}. The meanings of the factors and the description of their calculation are shown in Figure 7.



$$k_{surface} = \frac{A_{p,i}}{A_{p,0}} \qquad A = \left(\frac{d_s^2}{4} - \frac{\left(d_s - \left(a_{e,hobbing} / \cos \alpha_n\right)\right)^2}{4}\right) \cdot \pi$$

$$k_{speed} = \frac{n_0}{n_i} \qquad n = \frac{v_c}{d_s \cdot \pi}$$

Processing sequence	ZR35	ZR30	ZR40	ZR20	ZR50
$d_{s,i}$ [mm]	215	213.5	209	206	204.5

$a_{e,hobbing}$ = 7,875 mm (total infeed of the gear-hobbing process (Table 1))
Index 0: initial state of the grinding wheel
Index i: state of the grinding wheel after the i-th dressing process

Figure 7. Description and calculation of the defined factors $k_{surface}$ and k_{speed}.

With the factor $k_{surface}$ the active grinding wheel surface is taken into account, which also gets smaller with decreasing grinding wheel diameter. A decrease of the active grinding wheel surface causes a reduction of the total pore volume, which in turn promotes a faster grinding-wheel clogging. In order to achieve a constant cutting speed v_c of 35 m/s with decreasing grinding wheel diameter, the rotational speed of the grinding wheel must be increased. However, an increase in speed leads to the effect that each area of the active grinding wheel surface is more often involved in the machining process, which also promotes a greater wheel clogging and is taken into account with the factor k_{speed}. The initial diameter of the grinding wheel in the experiments was 215 mm. Before each test series, the grinding wheel was dressed with 30 strokes and a dressing infeed a_{ed} of 50 µm to produce the initial state. Thus the grinding wheel diameter was reduced by minimum 1.5 mm before each test series. The clogging degree ΔZ_s and the calculated related clogging degree $\Delta Z'_s$ are shown in Figure 8 according to the processing sequence.

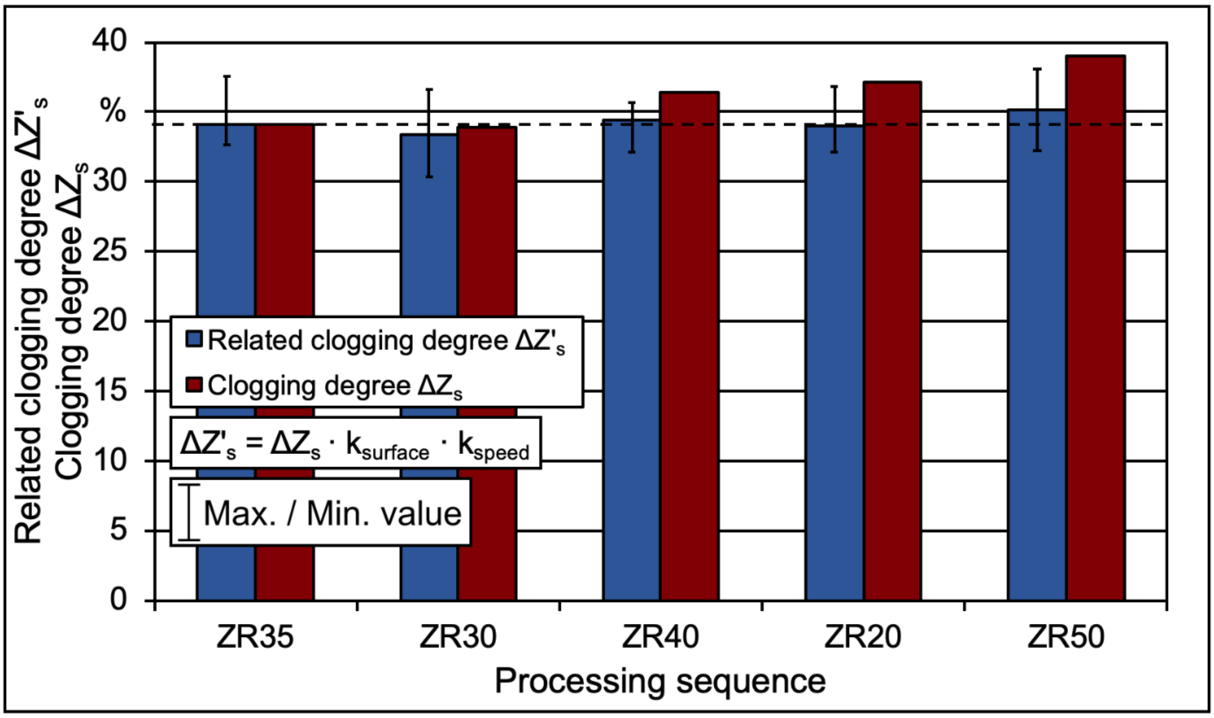


Figure 8. Measured clogging degree ΔZ_s and calculated related clogging degree $\Delta Z'_s$ according to the processing sequence.

As already mentioned, it can be observed that there is an increase in the clogging degree according to the processing sequence due to the decrease of the grinding wheel diameter. However, a correlation between the related clogging degree and the different feed marks cannot be determined. The values are approximately constant and in the same range of variation. An increase of the grinding-wheel clogging due to higher feed-mark depths and the additional removed volume during the first stroke cannot be confirmed by the experiments carried out.

Influence of different feed-mark depths on the geometric gear quality

In order to verify whether there is an influence of different feed-mark depths on the geometric gear quality after the grinding process, the flank and profile deviations as well as the concentricity, pitch and span deviations were determined after discontinuous profile grinding. In Figure 9 the total flank F_β and total profile deviation F_α are plotted against the test series. The deviations were determined on one gear (32 teeth) for the left and right tooth flank.

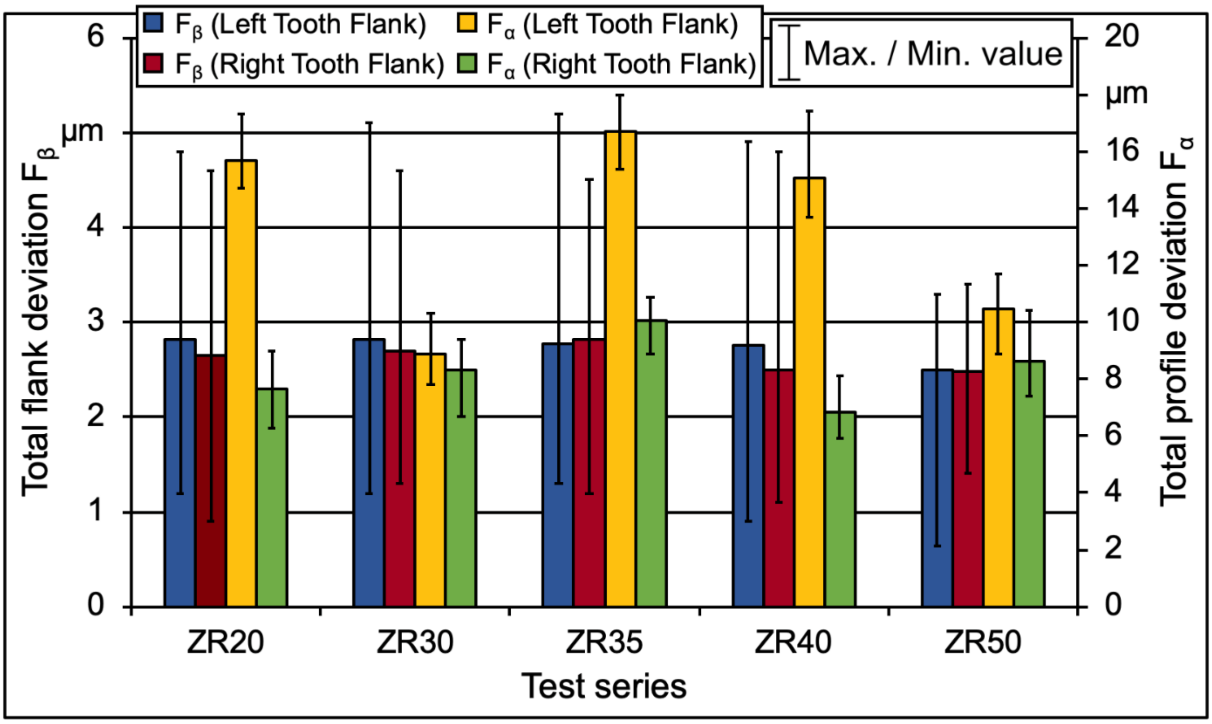


Figure 9. Measured total flank and total profile deviation for each test series.

An influence of the different feed marks on the flank- and profile line cannot be determined. The deviations of the flank line on the left and right flank have approximately the same values. For the profile line, higher deviations can be determined for the left flank. This can presumably be explained by partially different machining conditions on the left and right tooth flank, which probably occurred due to slightly varying centering of the grinding wheel to the tooth gap after each workpiece change. It should also be noted that the discontinuous profile grinding was carried out without a finishing stroke in order to minimize the amount of experiments. It can be assumed that after a finishing stroke, the differences in the profile line between the left and right flanks would be much smaller.

In addition, it was examined whether there is a possible influence of increasing feed-mark depths on the concentricity F_r, the pitch F_p and the span W_4. The results obtained can be seen in Figure 10.

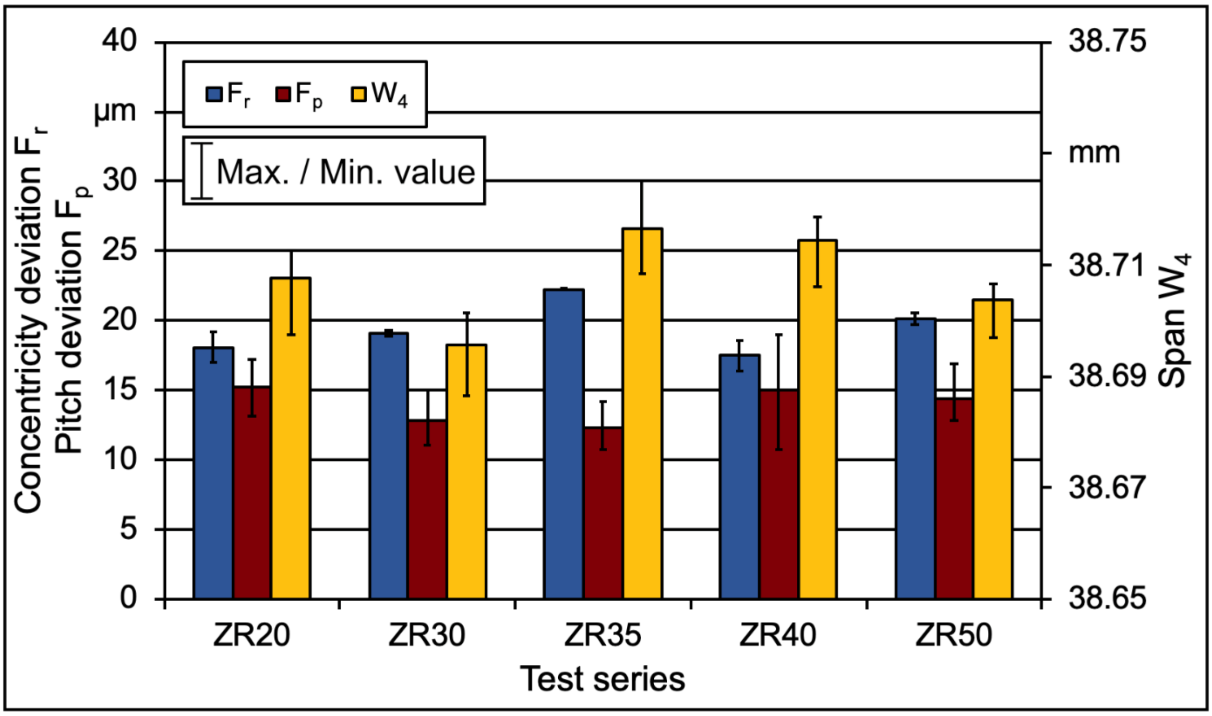


Figure 10. Measured concentricity, pitch and span deviation for each test series.

As shown in figure 10, no correlation can be found between the increasing feed-mark depths and the concentricity, pitch and span deviation. Therefore, a reduction of the gear quality with increasing feed-mark depths cannot be confirmed. The fact that a loss of the geometric gear quality due to increasing feed-mark depths cannot be determined in Figure 9 and 10, can probably be attributed to the grinding-wheel wear, which also seems to be unaffected by higher feed-mark depths (Figure 11). To confirm this assumption, the grinding-wheel wear was determined indirectly for each test series by means of the increase in span W_4. With increasing wear, the span gets accordingly higher. In Figure 11 the difference of the span between tooth gap 1 (TG1) and tooth gap 64 (TG64) for all test series is shown.

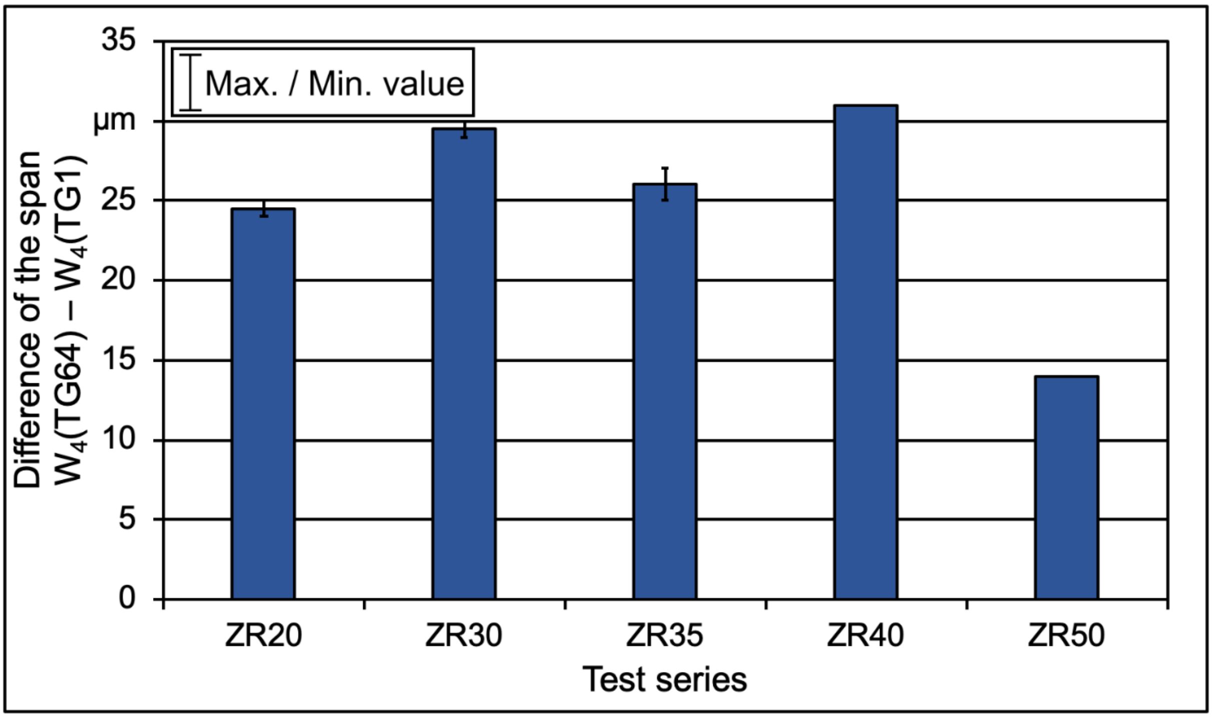


Figure 11. Measured span for tooth gap 1 (TG1) and 64 (TG64) for each test series.

It can be seen that there is no correlation between the increase of span and the different feed marks. For example, an increase in span of about 24 mm can be determined for a feed-mark depth of 20 mm (ZR20), but an increase of 14 µm for a feed-mark depth of 50 µm. Since with the aid of span an indirect determination of the grinding-wheel wear can be made, an influence of the feed marks on the grinding-wheel wear and in turn on the geometric gear quality can also not be proven.

4. Conclusion and outlook

In order to investigate the influence of different feed-mark depths δ_x on discontinuous profile grinding and the geometric gear quality after the grinding process, gears with feed-mark depths below and above the recommended value of 35 µm were machined and ground afterwards. During the grinding process with roughing parameters, spindle power P_s and clogging degree Z_s of the grinding wheel surface were determined. The evaluation of the gear quality was carried out by measuring the total flank F_β and total profile deviation F_α as well as the concentricity F_r, the pitch F_p and the span deviation W_k. It was shown that higher feed-mark depths lead to an increase of spindle power due to the additional machined volume. An increase in clogging degree Z_s and thus an elevated clogging of the grinding wheel due to the additionally removed volume could not be determined. Likewise, a correlation between an increase in the feed-mark depth and the grinding-wheel wear and thus a deterioration in gear quality could not be proven. The statement that gear grinding is uneconomical at feed-mark depths of more than 35 µm cannot be confirmed by the results obtained. Therefore, a new definition of this limit should be aimed. Higher feed-mark depths also necessitate the use of higher axial feeds f_a, which in turn would result in a potential increase of the productivity of gear hobbing.

In further studies, feed-mark depths of more than 50 µm and their influence on the grinding process and the resulting gear quality will be investigated. If a new limit is found, its general applicability for different gear geometries will be proven. Similar investigations as for discontinuous profile grinding shall be carried out for continuous generating grinding. It has to be clarified whether a common limit can be specified for both gear grinding processes. When assessing the gear quality as a result of the grinding process, the surface integrity properties will also be determined in order to examine a possible influence of increasing feed-mark depths, e.g. on the thermal load or the surface quality of the ground workpiece. In this study the wear of the grinding wheel was determined indirectly by gear measurements. In future works, the wear will be measured directly on the grinding wheel to obtain a clear statement about a possible influence of feed-mark depths on the wear behaviour of the grinding wheel.

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