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Abstract: Besides high demands on surface integrity machining of gears aims on very low surface roughness and high shape accuracy. These properties will have positive impacts on the lifetime of gears. In this context the challenges of profile grinding of cylindrical gears by using elastic bonded grinding wheels are addressed. For this new gear fine finishing

Fine finishing of gears with high shape accuracy

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Besides high demands on surface integrity machining of gears aims on very low surface roughness and high shape accuracy. These properties will have positive impacts on the lifetime of gears. In this context the challenges of profile grinding of cylindrical gears by using elastic bonded grinding wheels are addressed. For this new gear fine finishing approach, the very high potential of the process is revealed by analyzing the influence of the grinding wheel specification and the machining parameters on surface finish. Results show that gears with high shape accuracy and very good surface finish with almost optical quality can be achieved.

Grinding, Surface, Finishing

1. Introduction

Currently it can be observed that the already high demands on shape accuracy and accuracy grade as well as surface quality (roughness, surface layer properties etc.) of dynamically highly loaded parts, like gears, slide tracks and bearings, are elevated to an even higher level. This is the result of ongoing efforts to improve the drivetrain efficiency regarding fuel and energy consumption as well as to reduce the noise and emissions effectively [1,2]. By improving the surface roughness tribological stress conditions get favored between the gear part components. Together with positive surface layer properties - which can also be optionally set by the manufacturing process - the endurance of machined parts increases. For example a low surface roughness of gear flanks works against micro-pitting and noise emission [3-5].

Against this background, the approach presented here intends to reduce the surface roughness of gears significantly, down to near optical surface quality by fine finishing with grinding tools. This can be achieved by using grinding wheels with elastic bonding systems based on foamed polyurethane with embedded conventional abrasives. As a reference for the highest achievable surface quality during conventional gear grinding, a fine-grained vitrified grinding wheel with ceramic bonding can be taken and used. After roughing for pre-machining and finishing (Rz = 3 - 4 µm) with a vitrified tool, when required shape accuracy is achieved, the elastic bonded grinding tools are used for a final fine finishing operation to increase the surface quality significantly maintaining shape accuracy from preceding grinding. At the same time the new fine finishing operation has the potential to increase the surface integrity as it had been inspired by the development of the grind-strengthening process from earlier research [6-8].

1.1 Discontinuous gear profile grinding

In discontinuous gear profile grinding the profile of the tooth gap is generated by the grinding wheel requiring a workpiece-bound tool geometry. Thus the gear flanks are not machined by several cuts like it is the case in generating processes [9-12]. In addition, there is a line contact between tool and gear flank in tooth height direction [13]. Therefore, a quite high risk of thermal influence of the gear flank is given for the discontinuous gear profile grinding [14]. Nevertheless, profile grinding is the most frequently used grinding process for hard fine finishing, applied for internal as well as external gearing with a wide field of application (module m = 1 – 35 mm) in single piece and large batch production [1].

1.2. Preliminary investigations and consideration on surface and surface integrity achieved with elastic bonded grinding wheels

Hard fine finishing of gears is an application field for elastic bonded grinding tools which has not been investigated until now. Therefore, preliminary investigations were needed to determine the basic properties of elastic abrasive tools and its effect on resultant process properties.

Gear grinding with elastic bonded grinding wheels represents both: A path and force controlled process with the focus to improve the surface properties of workpieces. It is comparable to polishing, but with bonded abrasives. Since the tool comprises an elastic behavior the tool-part system has to be pre-load to achieve a material removal. This is basically carried out by varying the depth of cut. The depth of cut is set in a way that the material stock removal lies in the range of the roughness depth of the pre-machined workpiece (2 - 8 µm). The choice of the optimum depth of cut is depending on the grinding wheel specification (bond hardness, grain size and grain density), the geometry of the part and the surface topography after pre-machining. The complex influence of the grinding wheel specification on the work result is illustrated in figure 1. It can be assumed that a softer bond material leads to a lower surface roughness and – at the same time – has a negative influence on the resulting shape accuracy of the workpiece. The decrease of the grain size leads to better surface finish but has a negative influence on the cutting ability of the grinding wheel. As a consequence, a quite low material removal can be assumed. However, an adequate material removal is needed in fine finishing to remove the roughness peaks of the pre-ground tooth flanks.

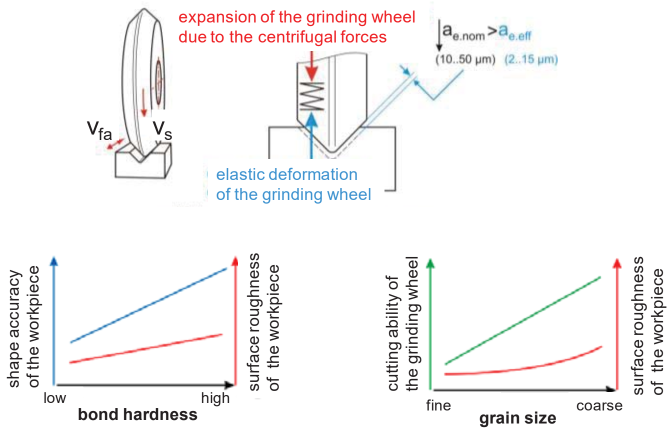

Fig. 1. Behavior of elastic bonded grinding wheels.

To demonstrate the application-potential of elastic bonded grinding wheels for the machining of case hardened steel parts, preliminary investigations were conducted. Profile grinding experiments were carried out using workpieces of AISI 5115 (16MnCr5 (HRC 63)), in which V-shaped grooves were pre-machined by milling in the soft material state. The workpieces were pre-ground with a conventional vitrified grinding wheel. Subsequently, a finishing process with an elastic bonded grinding wheel was conducted. The surface layer properties of the ground surfaces depending on the grinding wheel specification and the process parameters were examined by X-ray residual stress measurements. For all workpieces which were ground with an elastic bonded grinding wheel, a positive influence on the surface layer properties was observed. Due to high process forces in normal direction to the machined workpiece surface, compressive residual stresses were induced into the surface layer (figure 2). The residual stress profiles are influenced by grinding wheel specification, process parameters and the resulting process forces respectively.

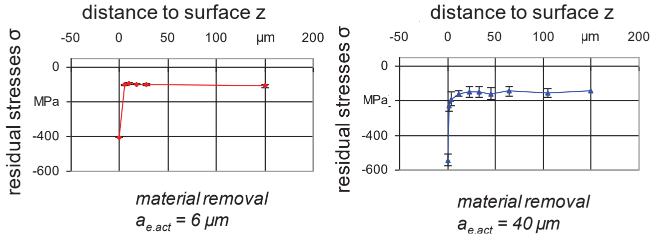

Fig. 2. Residual stresses after fine finishing.

High depth of cut as well as high removal rates did not cause detectable thermal influences on the ground surfaces. Thus, it can be assumed that profile grinding of hardened workpieces with elastic bonded abrasive tools bears a very low risk of grinding burn.

2. Experimental setup

The following section reports on the development of the new fine finishing process with elastic bonded wheels. As mentioned above, the target was to grind gears with high shape accuracy and high surface finish based on the results from preliminary investigations. In profile grinding experiments pre-machined, case hardened gears were machined on a gear grinding machine KAPP KX 500 FLEX, which allows for the machining of gears with a diameter up to 500 mm and a maximum module of m = 10 mm with conventional and superabrasive tools. For process monitoring the machine is equipped with a three-component-force-dynamometer and an acoustic-emission measurement system. In addition, a gear measurement system is integrated in the workspace of the machine-tool, for the in-situ evaluation of the shape accuracy.

For the profile grinding experiments a twin-adapter allows to carry two grinding wheels on only one spindle. Due to the use of the twin-adapter, alignment errors (e.g. one-sided grinding) can be avoided and the whole process time reduced. The tooth gaps are pre-grounded to a tooth flank quality grade of 3 according to ISO 1328 (DIN 3962) [15] by a roughing and finishing operation with a conventional vitrified grinding wheel. This pre-machining results in a surface roughness of Rz = 3 – 4 µm. Subsequently, the elastic bonded grinding wheel is used for fine finishing of the tooth flanks.

3. Generated surface roughness

For the purpose of identifying suitable process parameters when using the elastic bonded tools in fine finishing, the depth of cut a_e and the axial feed rate v_{fa} were variied for tools with different bond hardnesses and grain sizes in a single stroke. Wheel specifications (colors/grain size/bond hardness) referring to figure 3:
EK 400 (purple/coarse/high)
EK 400 (yellow/coarse/low)
EK 400 (red/coarse/medium)
EK 800 (green/fine/low)
EK 600 (grey/medium/high)
Figure 3 shows exemplarily the ten point average roughness Rz dependent on the axial feed rate v_{fa} for constant a_e = 50 µm. The surface roughness ranges from Rz = 0.8 µm to 1.9 µm. A clear influence of the wheels specification can be observed. The influence of v_{fa} on surface finish seems to be insignificant. Lowest Rz values can be found for the wheels: EK 400 (purple) with a coarse grain size and high bond hardness and EK 800 (green) with a fine grain size and a low bond hardness. It seems, that a combination of low/fine and high/coarse grain size and bond hardness are leading to the desired results. Therefore, these specifications were used for further investigations. Variation of the nominal depth of cut a_e revealed that an even lower roughness (down to Rz = 0.5 µm) can be achieved.

Workpiece:		**Tool:**	**Process paramters:**		**Dressing parameters:**	
AISI 4820 (20MnCr5)		var.	v_c	= 35 m/s	v_d	= 35 m/s
z	= 47		a_e	= 50 µm	U_d	= 7
m_n	= 4.5 mm	**Cooling lubricant:**	v_{fa}	= var.	q_d	= -0.8
b	= 65 mm	Oil	Q'_w	= var.	a_d	= 30 µm
α	= 24	90 l/min			n_d	= 3
β	= 16					

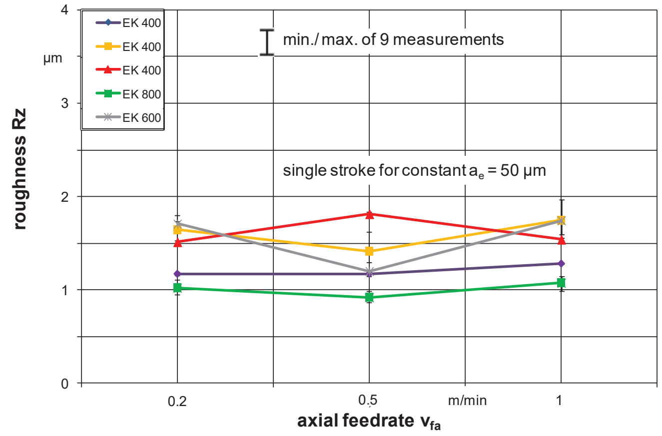

Fig. 3. Roughness Rz in dependence of the axial feed rate v_{fa}.

By adapting the grinding wheel specification as well as the process parameters, a grinding process was set up in which a double stroke (two times single stroke by using the same nominal depth of cut) operation leads to a tooth flank surface roughness of Rz = 0.30 ± 0.09 µm (EK 800) and Rz = 0.40 ± 0.10 µm (EK 400). For a comparison, the generated surface qualities and the corresponding Abbott-curves are shown in figure 4 for different process steps. While the tooth flank *a* which was pre-ground with a conventional vitrified wheel (SG-80) merely exhibits a material contact area R Mr(-0.25; 5.0) = 9.1 %, superfinished flanks *b* + *c* show a significantly higher material contact area R Mr (-0.25; 5.0) = 95.1 – 97.9 % which refers back to elastic wheel specification.

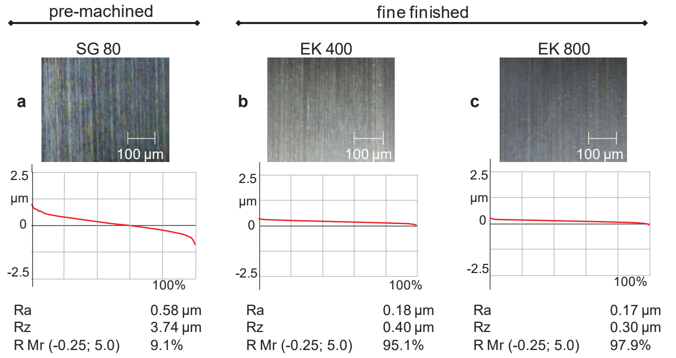

Fig. 4. Generated surfaces depend on wheel specification.

Therefore, the above mentioned tooth gaps showing Rz = 0.3 µm were optically measured by a white light interferometer (WLI). Figure 5 shows measurements of the tooth flank after pre-machining (*a*) and fine finishing (*b*). Contrary to vibratory finished gears, which are characterized by an orderless surface topography, the tooth flank generated by fine finishing reveals distinctive grinding marks in one predominant direction. This is due to the engagement kinematics during discontinuous profile grinding of gears. The WLI measurements of the surface roughness values lead to Sa = 0.012 µm and Sz = 0.081 µm. Also the results of Sa and Sz lower than 100 nm show a great potential of gear grinding with elastic bonded grinding wheels.

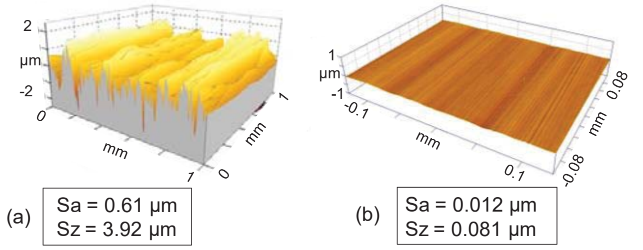

Fig. 5. Surface roughness after pre-machining (a) and fine finishing (b).

4. Shape deviation

Pre-loading of the tool-workpiece-system leads to a difference between the depth of cut set on the machine tool (nominal value) and the actual depth of cut (effective value). This elastic behavior of the wheels represents a big challenge with respect to the demanded tooth flank quality after hard fine machining of gears. While the vitrified (rather stiff) grinding wheel does not result in large differences between nominal and effective material removal, the elastic bonded grinding wheels show a significant difference during the grinding process, which has to be taken into account for ensuring the desired shape accuracy. Figure 6 depicts the comparison between nominal and effective depth of cut for single and double stroke discontinuous profile grinding for different depth of cuts a_e and axial feed rate v_{fa}. The depth of cut a_e varies between 10 and 50 µm and the axial feed rate v_{fa} varies between 200 und 1000 mm/min.

Workpiece:		**Tool:**	**Process paramters:**		**Dressing parameters:**	
AISI 4820 (20MnCr5)		EK 800	v_c	= 35 m/s	v_d	= 35 m/s
z	= 47		a_e	= var.	U_d	= 7
m_n	= 4.5 mm	**Cooling lubricant:**	v_{fa}	= var.	q_d	= -0.8
b	= 65 mm	Oil	Q'_w	= var.	a_d	= 30 µm
α	= 24	90 l/min			n_d	= 3
β	= 16					

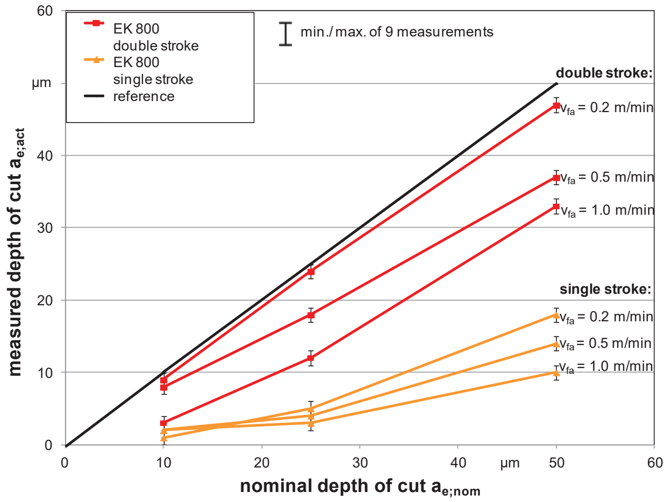

Fig. 6. Difference between nominal and effective depth of cut.

It is quite obvious that an increase of the nominal depth of cut leads to an increase of the effective depth of cut. On the other hand, an increase of the axial feed rate v_{fa} leads to a decrease of the measured values. This can be explained by the rising process forces which result from the increase of axial feed rate v_{fa} and push the grinding wheel aside respectively increase the wheels deformation. Additionally within double stroke grinding, a smaller difference between nominal and effective value occurs. Thus it is highly recommended that grinding with elastic bonded grinding wheels should be carried out by double stroke and low axial feed rate v_{fa} to achieve high shape accuracy.

Apart from deviations mentioned above there are also deviations in dimension and shape of the tooth flanks (profile and lead shape). The causes for these deviations are discussed in the following. In a second step compensating countermeasures are taken and their effects are analyzed.

The value of the deviation increases together with the increasing depth of cut a_e (see figure 6). In order to determine the effects which cause these deviations, pressure resistant foils were glued into tooth gaps. The grinding wheel was statically pressed on the foils with a force which matched the radial force measured during grinding. These investigations visualize that the highest pressures can be found close to the tooth root area (figure 7).

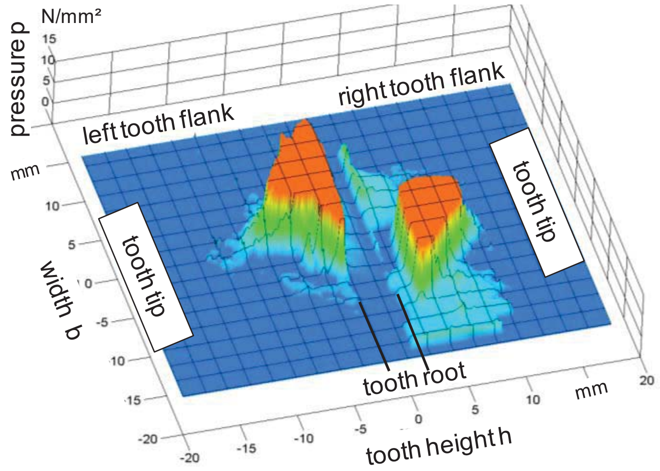

Fig. 7. Inhomogeneous pressure distribution in the contact zone.

The deviations lead to a tooth flank quality grade of only 5 according to ISO 1328 (DIN 3962) (figure 8). Thus gears cannot be machined in high tooth flank quality without profile adjustments of the tool. This modification has to be chosen in a way that a crowning is given to the grinding wheel. The dimension of the crowning is to be set while profiling of the elastic tool. The value of the crowning does not directly correspond to the measured deviation but has to take into account the elastic behavior as already shown for the difference of the nominal and effective depth of cut in section 4 (figure 6). If the wheel with the corrected profile is loaded with a certain force F (figure 8) it adapts to the tooth gap profile and the pressure is distributed more evenly over the whole tooth profile which ensures a high tooth flank quality.

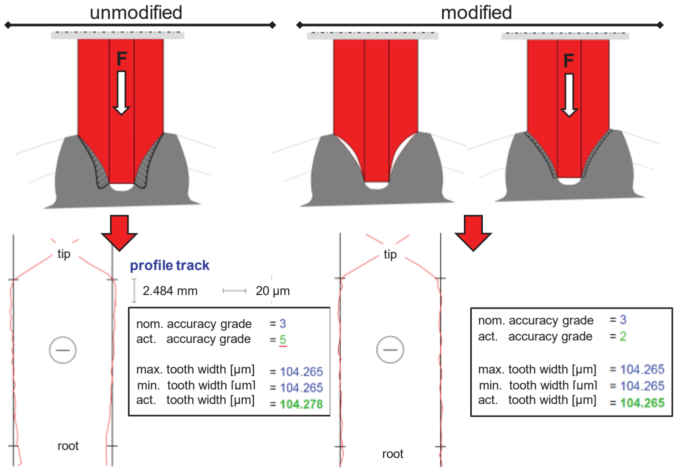

Fig. 8. Profile deviation and modification by using elastic bonded grinding wheels.

Regarding the influence in direction of the lead track it also can be observed that there are high deviations from the desired geometry. These can be explained by the asymmetric line of contact which is given while grinding of helical cylindrical gears. Similar to the profile track the measured lead track shows that grinding without adjustments is inappropriate to ensure good shape accuracy.

While the deviations of the gear profile can be avoided by a correction during profiling of the grinding wheel, the deviations in the lead track require a kinematic correction. During conventional grinding with vitrified grinding wheels the asymmetry of the flank line would be avoided by optimizing the swing angle. Be aware of that this attempt will fail if elastic bonded grinding wheels are used. For achieving a better tooth flank quality grade of at least 3 according to ISO 1328 (DIN 3962) if using elastic wheels, there have to be corrections in the lead track by interpolation in Z-C- (correction of the asymmetry) and Z-X-axis (generation of the crowning). Those have to be carried out in addition to the profile correction. The corrections have to be adapted to every change of the nominal depth of cut a_e, the axial feed rate v_{fa} or grinding wheel specification. With this kind of corrections the tooth flank quality grade can be improved by up to 2 accuracy grades.

5. Conclusion

The application of elastic bonded grinding wheels for the finish operation of gears within a discontinuous profile grinding process shows very high potential for achieving a high surface finish with high shape accuracy. Within the research work presented here, very fine surfaces on tooth flanks with a ten point average roughness of $Rz \leq 0.3$ µm and a tooth flank quality grade of 3 according to ISO 1328 (DIN 3962) were generated. In conclusion, gear grinding with elastic bonded grinding wheels manifest a very low risk of grinding burn as well as it is applicable on conventional gear grinding machines. Thus in conventional grinding it is possible to achieve a high workpiece quality in one set up which currently can only be achieved by subsequent processes (vibratory finishing, lapping, honing), which are expensive and time-consuming. The use of fine finishing is about four times faster compared to vibratory finishing (e.g. m = 4.5 mm; z = 47; b = 65 mm) and generates significantly higher surface quality. Furthermore, fine finishing with elastic bonded grinding wheels seems to offer a potential for large batch production with high productive processes like continuous generating grinding or continuous profile grinding (with globoid worm) with elastic bonded grinding wheels, further research is needed here. Also the intended improvements of subsurface properties (compressive residual stresses) should be an important issue for further investigations on lifetime behavior of gears and noise characteristics.

Acknowledgments

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