



Fine finishing of gears with high shape accuracy

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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 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.

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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 ($R_z = 3\text{--}4\ \mu\text{m}$) 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 $m = 1\text{--}35\ \text{mm}$) 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

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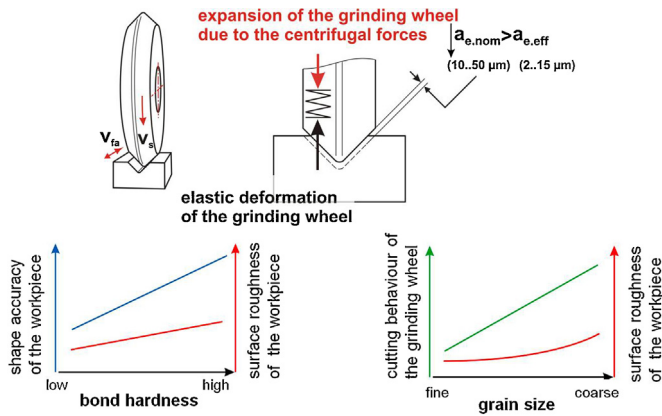


Fig. 1. Behavior of elastic bonded grinding wheels.

illustrated in Fig. 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.

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 (Fig. 2). The residual stress profiles are influenced by grinding wheel specification, process parameters and the resulting process forces respectively.

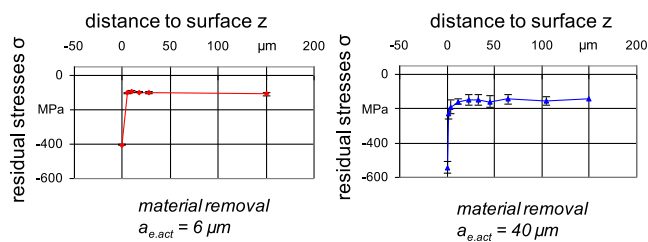


Fig. 2. Residual stresses after fine finishing.

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 $R_z = 3\text{--}4 \mu\text{m}$. 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 varied for tools with different bond hardnesses and grain sizes in a single stroke. Wheel specifications (colors/grain size/bond hardness) referring to Fig. 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)

Workpiece:	Tool:	Process parameters:	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:	$v_{fa} = \text{var.}$	$q_d = -0.8$
$b = 65$ mm	Oil	$Q_w = \text{var.}$	$a_d = 30$ μm
$\alpha = 24$	90 l/min		$n_d = 3$
$\beta = 16$			

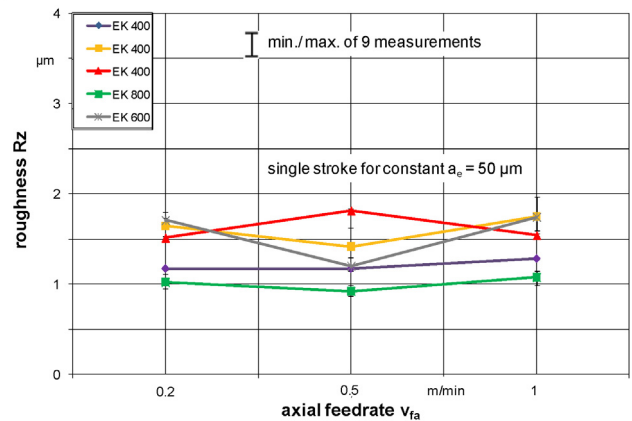


Fig. 3. Roughness R_z in dependence of the axial feed rate v_{fa} .

Fig. 3 shows exemplarily the ten point average roughness R_z dependent on the axial feed rate v_{fa} for constant $a_e = 50 \mu\text{m}$. The surface roughness ranges from $R_z = 0.8 \mu\text{m}$ to $1.9 \mu\text{m}$. A clear influence of the wheels specification can be observed. The influence of v_{fa} on surface finish seems to be insignificant. Lowest R_z 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 $R_z = 0.5 \mu\text{m}$) can be achieved.

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