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Surface integrity aspects of milled large hardened gears

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Abstract

With the rising performance of wind turbines the requirements for large scale gears are growing. Due to the bigger loads based on the higher megawatt output per turbine gears especially at slewing bearings need to be hardened. Rising demands for better gear qualities and higher loads require a hard machining of these hardened gears. The development of special cutting materials for geometrically well-defined cutting edge processes enables the manufactures to mill these gears in hardened condition on standard milling machines. The process of milling hardened gears needs control of the surface integrity of the tooth flanks. The generation of white etching areas must be avoided and can be influenced by process parameters (e.g. cutting speed and feed rate). Preferably compressive residual stresses should be generated in the surface and sub-surface of the tooth flank. The paper describes the potentials of milling theses hardened gears instead of grinding and reveals the generated surface integrity state.

Keywords: Gear cutting; surface integrity; large scale components

1. Introduction

Large-diameter ball bearings are provided with gears for many applications in order to ensure the turning and positioning of the respective technical facilities. Due to the high forces which have to be transmitted, hard machining of gears is unavoidable in many cases.

A classic application for a positioning operation realized by teethed large-diameter ball bearings is a wind turbine. In these systems they are either applied as yaw (azimuth) bearings or as rotor blade pitch bearings [1].

In recent years, an enormous increase in megawatt performance per wind energy system (WES) is recorded. A closer look shows a doubling of nominal power in megawatts every three to four years [1]. Due to this rise in performance, the components applied are of increasing size so that the used large-diameter ball bearings have to absorb greater forces and moments. With the current power stage of 5 to 6 MW (as prototypes even up to 7.5 MW), the mass to be moved as well as the loads to be absorbed increased due to the increased performance (one rotor blade bearing of a modern WES needs to bear wind loads of up to 30 t). This increase in mass caused an increase of noise emission [1] as well as an increase in the number of required drives for the azimuth and rotor blade pitch. Furthermore a hardened gear is necessary due to the high load. Related to the respective design of the large-diameter ball bearing and the maximum achievable accuracy resulting from distortion and deformation due to heat treatment, a hard machining of teeth at the end of the process chain is applicable in order to meet the required accuracy.

Another classical application of geared large-diameter ball bearings are tunnel driving machines. The use of these special machines requires large-diameter ball bearings to rotate continuously, as the rotary motion of the drilling shield is generated by these bearings. Shield diameters of 16 meters are nowadays rather the standard than the exception. Partly up to 24 hydraulically operated pinions are running in these tunnel driving machines as drive of the large-diameter ball bearings and therefore of the drilling shield. The modules for gears in this special type of large-diameter ball bearings range from 40 to 44 mm. Modern high performance gearing machines with machining diameters of 10,000 mm can

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manufacture gears up to module 60. Tooth widths of 400 to 600 mm are thereby no curiosity.

However deformations result from the machining and hardening processes, which can cause a tooth traces total variance of 1 to partially 2 mm in gearing. Hard machining is therefore inevitable.

In the named applications such as WES and tunnel driving machines as well as in other applications up to 10,000 mm diameter hard machining of gears is mostly performed by a geometrically well-defined cutting edge.

The application of modern, extremely hard cutting materials enables an economic optimization of manufacturing with additional direct influence on the surface integrity of the workpiece. The durability of the workpiece can thereby be significantly influenced.

2. Investigation in industry

The tests for this project were carried out specifically under realistic industrial conditions in order to ensure a transferability of the results into practice right from the beginning. An internally toothed gear is chosen as test workpiece (see table 1).

The workpiece for the research program consists of a high-alloyed steel of type 42CrMo4 (EN 1.7225; AISI 4137). The tooth flanks were induction hardened for the tests and have a surface hardness of 56 to 58 HRC.

The workpieces were manufactured at a gear hobbing machine of type Liebherr LC 4000 (see figure 1) in single tooth gap machining.

Table 1. Geometry of the test workpieces

Module	m	14 mm
Number of teeth	z	-162
Addendum modification	m·x	-7 mm
Pressure angle	α	20 °
Helix angle	β	0 °
Pitch diameter	d	-2268 mm
Gearing width	b	200 mm
Outer ring diameter	d_a	2500 mm

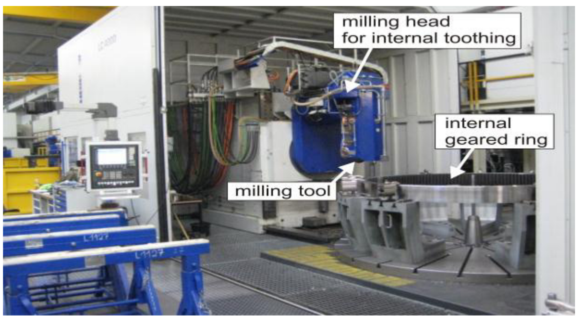

Figure 1. Experimental setup

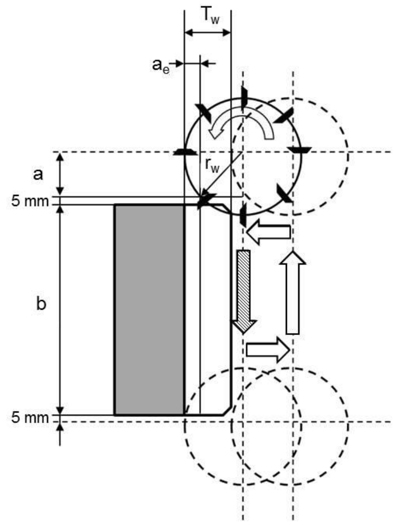

Figure 2. Principle of single tooth gap form milling in up-cut mode

Up-cut milling was chosen as milling strategy in order to introduce normal forces into the workpiece support and not to lift the gear from the workpiece clamping. Figure 2 shows the principle of single tooth gap form milling as it was executed in the tests.

Also Bouzakis has confirmed that up-cut milling with cutting speeds between 100 and 200 m/min is beneficial compared to down-milling [2]. As cutting materials for the tests, coated tungsten carbide P20-P40 types as well as uncoated P25 types were used. Theses materials represent the current cutting materials for the geometrically well-defined dry machining of hardened gears applied in practice [3].

In the context of these tests further modern high-performance cutting materials were tested in order to achieve process optimization. As for the tested ultrafine grained tungsten carbide (UF-HM) as well as for the examined polycrystalline boron nitride (PCBN) tool, the ideal technological application parameters for hard machining of gears were determined in tests [4, 5]. The comparison of the two modern cutting materials led to the conclusion that the tungsten carbide is superior to the PCBN under economic and technological aspects. For this reason only limited tests on PCBN are presented here. The PCBN was used with a content of 90% CBN due to the higher ductility [6, 7, 8, 9].

Following the chip removal analyses, hardened gearings with the respective ideal technological parameters were milled with each cutting material. Subsequently, the analysis of gearings concerning a thermal influence on the surface integrity, namely thermal overload, was executed. In the following the term "***milling burn***" is used for the first time in the style of "grinding burn" from non-defined cutting edge processes [10, 11].

3. Cutting tests

In the context of the cutting tests, the current applied cutting materials P20-P40 (coated) and P25 (uncoated) with standard specified cutting data were used until the end of tool life. The maximum allowed width of flank wear land was defined with VB = 0.2 mm. The wear criterion was considered to be reached when VB was exceeded on one of the cutting edges.

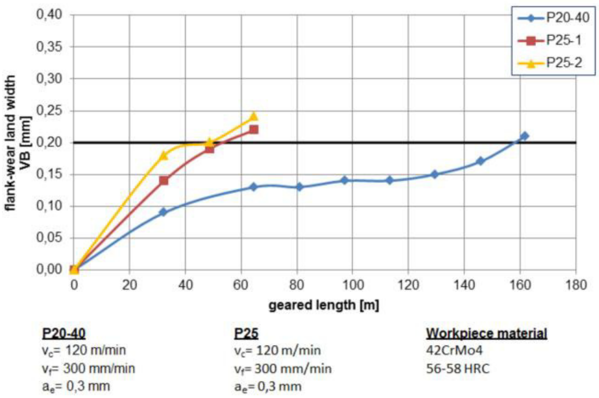

Figure 3. Results of standard cutting materials

Figure 3 shows the wear behavior and the technological parameters of the current cutting materials. There was an enormous wear increase for the cutting material P25 so that a second test was executed in order to support the results. It can be stated that this cutting material has only a short tool life. After approximately 1.5 milled circumferential turns on the chosen gear the abrasion maximum is reached.

The cutting material P20-40 can be used considerably longer. The maximum width of flank wear land is only reached after nearly 5 turns. This shows a much higher potential for application of this cutting material.

Also modern high-performance cutting materials were tested. The tests dealt with the current coated ultrafine grained tungsten carbide (UF-HM) with the type designation THMU and a PCBN with the type designation BZN 6000. Milling tests for both cutting materials were run in order to determine the optimum operating parameters. Figure 4 shows the wear behaviour of the respective cutting materials referring to the determined optimum technological parameters. Surprisingly the UF-HM (2.7 milled turns) is superior to the PCBN (2 milled turns) in terms of the maximum tool life. Due to the high costs for PCBN, the cutting material UF-HM is regarded to be more appropriate for the individual case of application.

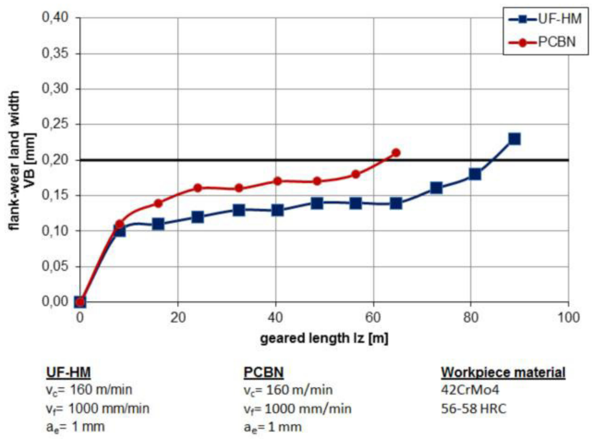

Figure 4. Results of cutting tests with different tools

The reached tool life with UF-HM is shorter compared to the cutting material P20-40. However the feed of a_e= 1 mm is slightly more than three times higher. Furthermore, the cutting data are significantly increased, so that the cutting material UF-HM can be regarded as most suitable for the machining task.

4. Results Barkhausen noise testing

Mechanical load on workpieces results in compressive residual stresses, whereas thermal loads lead to tensile residual stresses [12, 13, 14, 15]. The detection of these surface integrity modifications can be done by different methods, preferably non-destructive testing is chosen such as Barkhausen noise (BN) analysis [16, 17]. The testing of the tooth flanks to detect thermal overload was done with a BN measuring device of the company Stresstech, type Rollscan 300 and a sensor of type Mini GP executed by manual sensor handling. The chosen sensor showed the maximum repeatability of BN values at testing with manual manipulation. In order to increase the repeatability, defined tooth flanks were cut-out of the gear.

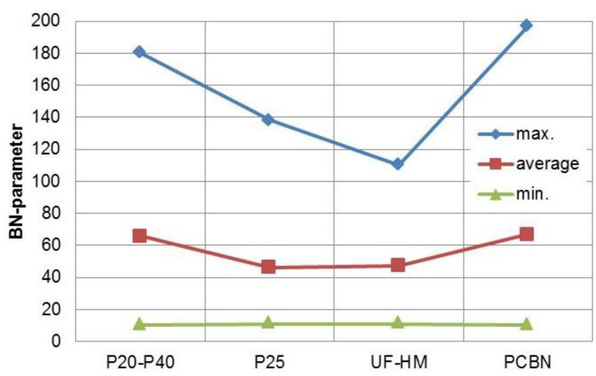

Figure 5. Results of Barkhausen noise measurement

At each flank 4 scans in the direction of the flank and 5 scans in the direction of the profile were performed. The results of the BN testing are shown in figure 5. It should be noted that indications of thermal impacts are detectable on almost all measured flanks for all tested cutting tool materials via Barkhausen noise.

5. Nital Etching

This industry-established method is grounded on an acid-based attack of different metallographic structural conditions of hardened steel [18]. Following the Barkhausen noise testing, a flank testing was executed via nital etching in order to verify the BN results.

Table 2: Results of nital etching

detection of milling burn via nital etching				
cutting material	P20-P40	P25	UFK-HM	PCBN
inspection first milled flank	no	no	no	no
inspection last milled flank	light	light-heavy	no	light

Table 2 shows the testing results for the respective first and last tooth space milled at the tool life travel path for each cutting material. It has been registered that there are little thermal impacts for some cutting tool materials at the end of the tool life. Only the uncoated standard cutting material P25 showed severe thermal impacts.

The results of the BN measurement could not be sufficiently verified by nital etching since at some flanks with very large Barkhausen noise amplitudes absolutely no milling burn could be proved by etching.

6. Micro structure and micro hardness profile

Following the nital etching, several tooth flanks were cut in profile direction in order to prepare a cross-section of the surface. As no evidence for milling burn by slightly etching of the tooth flanks can be provided, edges have been chosen at which the local scattering of the Barkhausen measuring data is very high. At the local maxima determined by means of Barkhausen noise a cut has been executed with the help of a water-cooled cutter with very low feeds in order not to affect the micro structure of the material. After the subsequent polishing the cutting area was etched and examined. Figure 4 illustrates a micrograph of the interesting area, showing an equally formed, fine-grained structure consisting of annealed martensite with a small fraction of ferrite. In the hardened area the expected, typical, acerous, martensitic hardness structure is found. A thin near to the surface "white layer" without visible structure which indicates a severe thermal impact cannot be detected at all specimen. It shows only a slightly decarburized sub-surface area which is typically to be expected after repeated thermal actions without shielding gas atmosphere at a material quality such as 42CrMo4. The non-problematic crystalline structure could thus be detected at all examined tooth flanks.

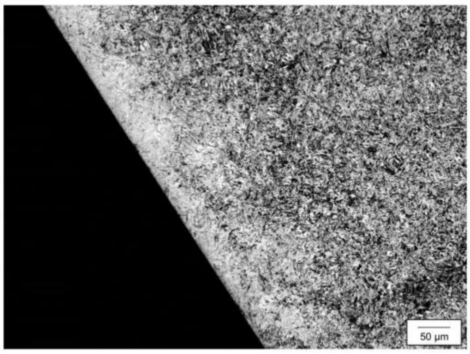

Figure 6. Micro structure of one representative tooth

In addition to the cross-section check a verification of the determined local Barkhausen noise maxima has been carried out by preparing micro hardness profiles. Measuring the micro hardness was effected according to the measuring positions of the Barkhausen noise at 4 positions in edge direction. Figure 7 illustrates the micro hardness profile of one sample. All other recorded micro hardness profiles show a similar profile. At the edge zone there is no decrease in hardness in any of the measured profiles.

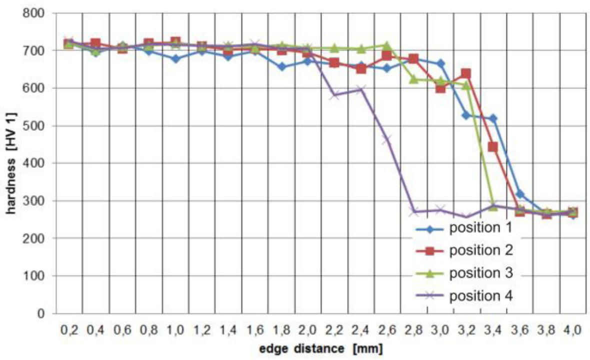

Figure 7. Micro hardness profile

The metallographic testing cannot confirm the high local maxima of the Barkhausen noise testing in analogy to the nital etching.

7. Residual stress analysis

During the course of the test, residual stress depth profiles were created at the tooth flanks by X-ray diffractometry, which have shown very high local maxima in Barkhausen noise testing. The measurements were carried out via an X-ray diffractometer of type Xstress 3000 with a goniometer G3 of company Stresstech. For verifying the signals of the Barkhausen noise, measurements of the residual stress were made in areas with the determined local maxima. The residual stress profiles were created by electrochemical material removal of the tooth flanks up to a depth of 0.2 mm. The determination of the residual stress has been carried out on the one hand in longitudinal direction (0°) and on the other hand in transverse direction (90°) to the tooth flank. The measuring directions as well as the chosen measuring area are shown in figure 8.

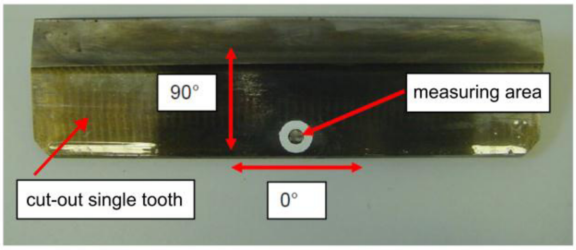

Figure 8: Location of residual stress measurement (surface was etched prior to X-ray measurement)

During the previous cutting tests the cutting material UF-HM showed a great performance in terms of operating parameter and tool life compared to the standard cutting material P20-P40 and P25, so that the machined parts of this cutting tool material have been examined more in detail.

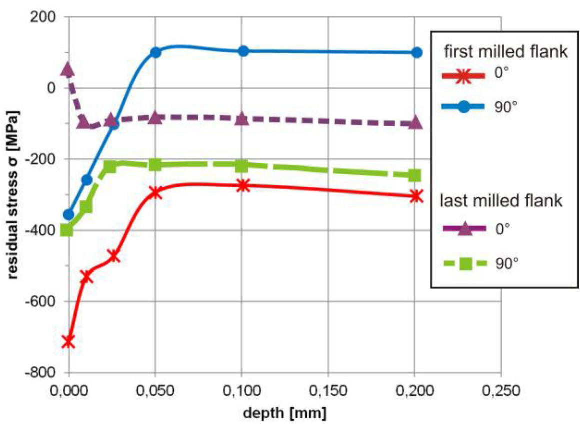

Figure 9. Residual stress profiles over tool lifetime of a coated UF-HM cutting tool

Figure 9 illustrates the residual stress profiles of the milled tooth gaps at the beginning and end of the tool life of the material UF-HM. It becomes apparent that the residual stress changes with increasing wear of the inserts. During the entire operating time, compressive residual stresses are observed. Only when reaching the maximum tool life, a change to a moderate tensile residual stress level is discovered in the 90° direction. However the level of this stress state is very low and can be considered as non-critical.

The cutting tool material P20-P40 shows a similar profile as UFK-HM in the first tooth gap, figure 10.

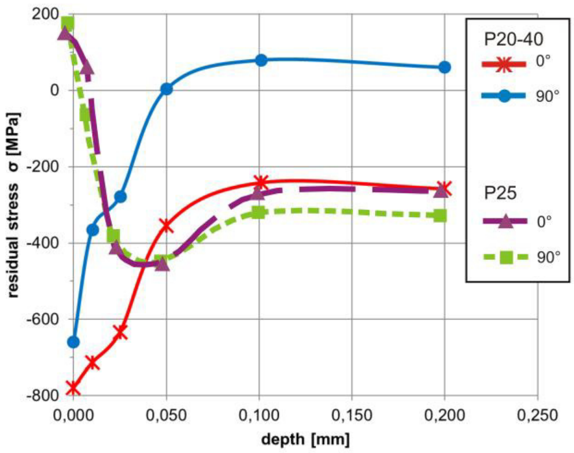

Figure 10. Residual stress profiles of different tungsten carbide tools

It can be seen that especially coated ultrafine grained tungsten carbide inserts are suited for dry cutting of hardened large gears and may promote the function-oriented characteristic of compressive residual stresses. The uncoated cutting tool material P25 shows a very high residual tensile stress level when reaching the tool life. Hence it is derived that this cutting tool material is only of limited suitability for the hard machining. For the cutting tool material PCBN no residual stress tests were carried out, as the performance of this cutting material fell far short of the results of the UF-HM. It can be concluded from the tests, that the identified local maxima of the Barkhausen noise in all cases cannot be detected via X-ray diffractometer.

8. REM investigations

All testing methods could not confirm the determined local maxima of BN measurement as milling burn. Furthermore, the BN maxima could not be confirmed after the milled surface was nital etched. This effect could also be achieved by a very slight polishing of the surfaces with a domestic polishing pad.

That is why it can be assumed that the Barkhausen noise signal is affected by surface adhesions lifting the sensor respectively magnetic pole, resulting in high measuring values mocking milling burn. The chosen milling strategy of up-cut milling can be the reason for these adhesions. The first cut is carried out with minimal chip thicknesses in this type of milling, which may cause slight quenching and pressing of chips on the surface.

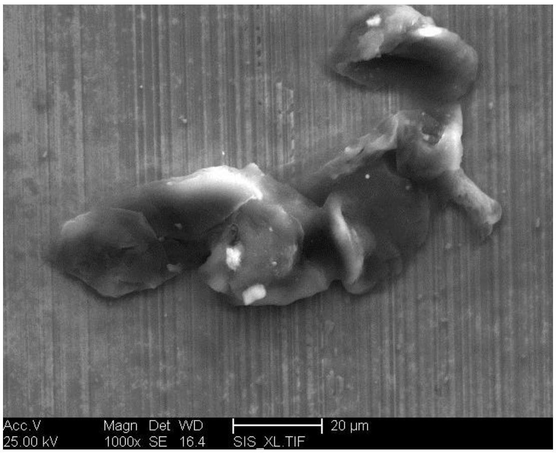

Figure 11. Chip particle on milled surface

Furthermore a reason for the "false detection" of the BN signal is to be searched for in smeared materials due to built-up edges.

In order to verify this assumption, areas with local maxima were examined via scanning electron microscope. As shown in figure 11 tiny particles adhering at the surface can be detected. These are not loose on the surface, but stick to it. Furthermore it appears that the feed marks are not interrupted but covered. This indicates that there are adhering materials on the surface, which arise after the real cutting process.

If the magnetic pole of the BN sensor is guided over such an adherence while testing, there can be increased signal amplitudes at this point due to the changing local surface, which reports in this way a non-existing milling burn.

9. Conclusion

The tests have shown that the geometrically well-defined dry cutting of hardened gears has great potential for practical use. If adapted technological parameters are chosen the process appears to be non-critical with regard to the formation of milling burn. Appropriate conditions lead to the formation of compressive residual stresses in the workpiece.

However, the detection of milling burn proves to be complicated in practical use in accordance with current knowledge, as the Barkhausen noise can tend to false detections on hard-machined surfaces. The presented tests have shown that these false detections are caused by small superficial smeared materials, which are not known from processes with geometrically non-defined cutting edges like grinding. Thus the milled surfaces need special treatment prior to BN checking like simple tactile cleaning to avoid false signals. If these measures are taken, BN is qualified to be used as sufficient quality control for the surface integrity state of hard-milled gears.

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