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Adjusting surface integrity of gears using wire EDM to increase the flank load carrying capacity

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Abstract

High performance gears require high geometrical qualities. For these aspects expensive grinding processes are indispensable as finishing processes. This paper deals with the investigation of wire EDM (WEDM) as a technological substitution to grinding from part functionality point of view. Geometrical gear quality, surface integrity and load carrying capacity for WEDM and ground gears were analyzed and compared. No difference regarding gear shape was found for both processes. Residual stress and hardening profiles did not show significant differences. The topography features the process typical characteristics. Following, load carrying capacity of the tooth flank surfaces was investigated. The WEDM finished gears last three times longer than the ground gears due to a beneficial running-in topography formation with increased tribological characteristics.

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Nomenclature

α_n	normal pressure angle
β_2	helix angle of the workpiece
q	allowance
M_1	torque
m_n	normal module
z_1	number of teeth of the pinion
z_2	number of teeth of the gear
σ_{RS}	residual stresses
t	temperature
a	axis distance
n_1	rotation speed
b	gear width
d_a	tip diameter
x	addendum modification
C_α	tip relief
C_β	lead crowning

1. Introduction

In powertrain applications, gears are one of the most common mechanical elements. The application of gears ranges from low power, e.g. clocks, to high power applications, e.g. marine. To manufacture a gear, several process chains can be realized. In many of them, fine machining is the final machining process. Therefore, fine machining is the most important quality defining step in gear manufacturing.

This paper deals with the comparison of the load carrying capacity of gears finished by the common profile grinding process and the WEDM process as possible technological alternative. In particular, the influence of the finishing processes on the manufacturing related workpiece properties are taken into account.

Heavily loaded rolling contacts such as the gear tooth flank contact, are complex tribological systems. These systems are

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characterized by the interactions between the contact partners, the lubricant and the surrounding medium. The properties of the tribological system significantly affect the behavior in terms of friction, wear and fatigue in rolling contact. In the past, several experimental in gear running trials have been conducted. The rolling strength is significantly influenced by the material, the peripheral zone properties of the heat treatment, the surface finish as well as the operating parameters [1, 2, 3, 4, 5]. The friction of the rolling contact results from the type of lubrication, the contact temperature as well as the surface roughness and kinematic conditions in the contact gap [3, 6, 7, 8]. In order to decrease the friction in tooth contact and increase the flank load carrying capacity, the surface structure is modified [7, 8]. Compared to the 2D values Ra and Rz a complete surface topography measurement gives more information about the orientation and shape of manufactured surface features. Using an optimized surface topography, a reduction of the friction and a higher load carrying capacity in rolling contact can be realized [8].

2. Goal of study and trial conditions

The use of gears in high power density application requires high quality in terms of geometry and surface properties, in order to ensure structurally intended functionality. In the conventional process chain, the required quality of the gear is achieved by a grinding process after heat treatment. Because of the required additional machines and tools for gear grinding, this process leads to increased costs.

Because of this, alternative and more cost-effective process chains are of particular interest in industry. WEDM has been proposed as an alternative and innovative method for hard finishing of spur gears especially for prototype applications, see [9]. The WEDM process is characterized by high flexibility regarding workpiece geometry, since no special tools are required. The process forms the geometry easily by the axis movement of the wire electrode.

The general equal technological capabilities of contemporary EDM processes compared to other machining technologies was already shown in other works. Welling for example showed that WEDM provides an alternative to the established broaching process for the production of fir tree slots as shown by similar performance in according fatigue tests, cf. [10]. In another research work, the fatigue bending strength was investigated for WEDM samples under going cyclic loading. The results show that for titanium, similar bending fatigue strength of wire-eroded components and corresponding ground specimens are achieved. The analysis of the thermally influenced rim zones in the cross section showed that for both processes similar extents, although the surface roughness of the ground sample was significantly lower [11].

In order to evaluate the WEDM process as possible alternative, the final part functionality and the process induced surface integrity have to be analyzed in detail. Two processes with comparable surface integrities and therefore obligatory resulting similar utilization performance could then be treated as comprehensive alternatives from a technological point of view. Ideally, the manufacturing process can be adjusted in such a way that the required surface integrity can be deterministically achieved.

But in industrial practice, the generation of a desired surface integrity of high performance components is still an iterative process based on experience. Despite the findings of researchers correlating the process parameters with the resulting surface integrity, it is not possible to deduce the required process parameters from a given desired surface integrity. An example of this so-called inverse surface integrity problem is given in [12]. A collaborative work of the CIRP studied if a workpiece surface with defined compressive residual stresses of 200 MPa could be manufactured by experts using different machining strategies. The results – ranging from -800 MPa to + 600 MPa – show impressively that still a deterministic achievement of this goal is not possible.

The concept of Process Signatures is a promising strategy to achieve a knowledge-based solution of this inverse surface integrity problem, [13]. A first step within this context is to identify comparable machining technologies for a given industrial test case. Figure 1 gives an overview of the gear data used in the presented investigation, the production process chain of the gear and the test rig concept for investigating the rolling strength.

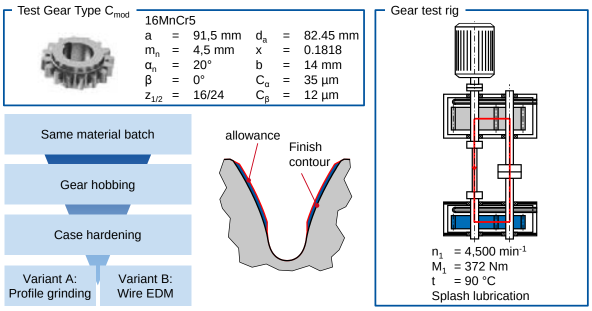

Fig. 1. Gear variants and test rig

A standard test gear geometry (C_{mod}-type) is used [1, 3, 6]. Compared to the conventional gear design of the C-type test gear set, flank modifications are defined with a tip relief of C_a = 35 µm and lead crowning that amounts to C_β = 12 µm. The gear load carrying capacity test rig is in according to ISO14635, with a center distance of a = 91.5 mm and was run under splash lubrication controlled to T = 90 °C [14]. Using the common profile grinding and the WEDM process, two different surface topographies were adjusted on the tooth flank surface on the pinion. All test pinions were paired with a profile ground gear.

3. Gear manufacturing

All machining processes were performed at RWTH Aachen University allowing a detailed control of the test parts properties. After turning, the parts were hobbed on a gear hobbing machine Gleason-Pfauter P600/800. The hob was a coated PM-HSS tool [15]. After soft machining the parts were heat treated by atmospheric case hardening. Up to this point of the process chain the batch was provided identically.

Next the batch was separated in two variants. The parts of variant A were fine machined by profile grinding on a grinding machine Kapp KX500 Flex. The parts of variant B were fine machined by the WEDM process. Both processes were used to machine a defined allowance of q = 120 µm.

The WEDM process was executed on a state-of-the-art machine with a water-based dielectric and the latest generator technology in order to reduce the process inherent thermal impact onto the surface (see [16]). Six trim cuts based on the standard machining practice for steel parts were executed. The gears were mounted on the workpiece table with a special clamping system with bridge connections on the tooth tips in order to allow the machining of all circumferential flank geometries in one set-up. More details on this procedure can be found in [9].

4. Workpiece characterization and surface integrity

For the analysis, macroscopic and microscopic aspects as well as surface zone properties of the material were taken into account. Figure 2 shows the results of the measurement of the macroscopic geometry and the surface roughness after fine machining. For the geometry measurement, a gear measurement machine of type Klingelnberg P40 was used.

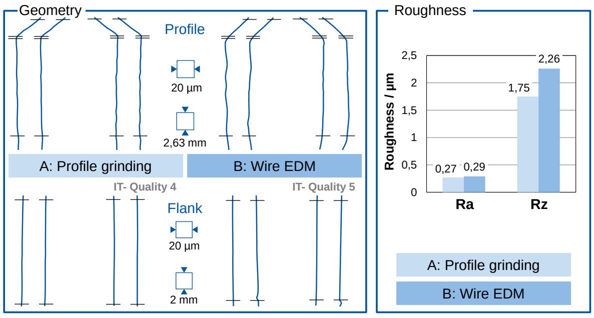

Fig. 2. Gear geometry and surface roughness

Figure 2 shows the profile and lead line measurements of parts of both variants. The result of the profile line measurement showed that in both cases the geometry of the parts including the tip relief is comparable. Also the results of the lead line measurement are comparable between the two variants. All test gears reached a required gear quality of IT 5 after hard machining. The following measurements were focused on the surface integrity of the parts. The results of the surface roughness measurements show that the values for R_a are nearly the same for profile grinding Ra = 0.27 µm and for WEDM Ra = 0.29 µm. The values of the Rz measurement are different. The parts fine machined by the profile grinding show a lower roughness of Rz = 1.75 µm, and the parts machined by EDM hard Rz = 2.26 µm.

In order to characterize a machined surface, e.g. gear flank, the measurement of the values Ra and Rz is not sufficient. These values do not give information about the surface structure, which is required to deduce the relation between running behavior and machining process. To characterize the surface structure SEM micrographs on parts of both variants were made, see Figure 3 left. The surface of the ground parts is characterized by directed grinding marks. These grinding marks are oriented in flank direction along the whole flank width. A more inhomogeneous, statistically distributed structure is visible on the surface of the WEDM machined part. The whole flank surface is textured with small craters resulting from the EDM process. These craters do not have a predominant direction along the surface. The proliferation of the crater structure along the whole flank is homogeneous.

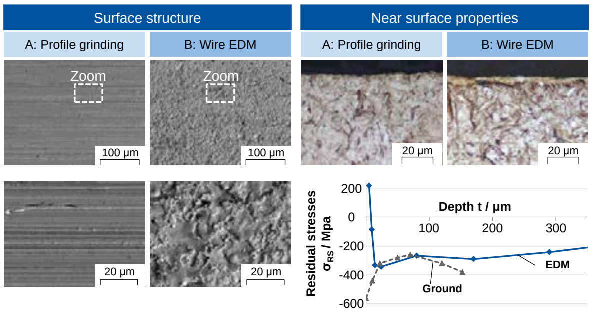

Fig. 3. Surface structure and properties

Besides the surface structure, the near surface properties are also measured. On the right hand side micrographs of the material structure of both variants are shown as cross sections into the material. In the WEDM tooth flank, only a small white layer is detected. This is a result of the optimized process parameters during WEDM with the latest generator technology. However, within the first 10 µm a small thermal effect on the peripheral zone by the electric discharge removal occurred. In this area tensile residual stress were measured. From a depth of about 10 µm, both variants exhibit compressive residual stresses. The critical zone for the occurrence of pitting damages is at a depth of 30 to 100 µm.

The profile ground parts showed a typical case hardened steel microstructure and a characteristic profile of residual stresses. In the hardness depth profiles of both versions, no significant differences were observed, which is due to the same batch of material and heat treatment and finally the fact that both processes seem to have no specific significant influence on this parameter. Moreover, the gears were examined by nital etching on a structural damage that could not be detected for both processes.

In summary, it can be concluded that from Process Signature point of view, WEDM reaches a similar and comparable surface integrity for the given application compared to grinding.

5. Load carrying capacity investigation

Subsequently, an investigation on the load carrying capacity in a test rig should provide a conclusion on the performance of the gears relating the hard machining processes to profile grinding and WEDM. The investigation included two trials per variant in the finite life region. The limiting number of load cycles was reached if the size of the pitting grows to 4% of the entire area of the flank at a single tooth [17]. Figure 4 shows the attained number of load cycles for both variants. The parts hard finished by WEDM reached 21.8 million load cycles in average, 223 % more than the profile ground parts. In both cases, the two trials for each variant were in a small spread, as symbolized.

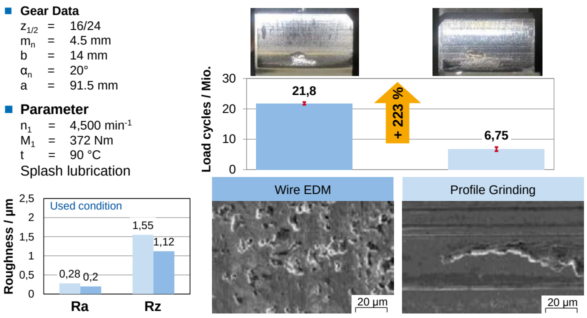

Fig. 4. Pitting flank load carrying capacity

For a detailed analysis of the load carrying capacity of the test gears surface an analysis on the used flanks was made. The surface roughness after the test run of the WEDM variant is more planed than of the conventional profile ground surface. The values are Ra = 0.2 µm for the WEDM parts and Ra = 0.27 µm for the profile ground parts. Furthermore, SEM micrographs of the used flanks were made. The SEM micrographs of the surface structure after the test run in Figure 4 confirm the roughness measurement.

Through the load by rolling, on the WEDM gears a smooth surface with a cup-shaped structure with no predominant direction arises. The profile ground surface is largely intact after rolling load. Along individual roughness peaks several outbreaks occur due to micro fatigue. These are indicators of increased stresses on the manufacturing related surface topography peaks and lead to accelerated fatigue.

The conclusion of the load carrying capacity is that the behavior of the WEDM surface under rolling load leads to decreased stresses on the manufacturing related peaks and thus, to a higher number of sustainable load cycles due to a better running-in characteristics with finally better tribology. The main cause is the non-directed statistically distributed surface structure. The observation of improved tribological conditions with non-directed surface structures is also seen in for laser-marked surfaces [8]. With WEDM, adjusted surfaces are manufactured which have an increased load carrying capacity compared to ground parts.

6. Summary

This paper deals with the comparison of the load carrying capacity of gears manufactured with two different finishing processes. On the one hand, the common profile grinding for hard finishing was used. On the other hand, the WEDM process for hard machining of gears was investigated. To compare both processes and the performance of the parts, a characterization of the surface integrity of the parts was made. In this, a macroscopic and microscopic analysis of the surface and the near surface layer was made. The gears were investigated on a load carrying capacity test rig for gears. The WEDM machined gears reached a 228% higher number of load cycles for a load level in finite life region than the common profile ground gears. The characteristic surface structure of the EDM processes leads to beneficial tribological conditions in rolling contact. The effect of statistically distributed surface asperities needs to be investigated further by additional trials and simulation of the tribological contact conditions.

7. Acknowledgements

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