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Prediction of Surface Zone Changes in Generating Gear Grinding

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

One possible process for hard finishing gears is generating gear grinding. Due to high process efficiency, generating gear grinding has replaced other grinding processes like profile grinding in batch production of small and middle sized gears.

Despite the wide industrial application of generating gear grinding, the process design is based on experience and time and cost intensive trials. The science-based analysis of generating gear grinding needs a high amount of time and effort and only a few published scientific analyses exist. In addition, the transfer of existing knowledge from other grinding processes onto generating gear grinding is complicated due to the contact conditions between tool and gear flank, which change continuously during the grinding process.

One research objective for generating gear grinding is to increase economic efficiency and productivity of the process. At the same time gear quality must be equal or higher and the external zone must not be damaged. However, especially the influence of the grinding process on the external zone in generating gear grinding is unknown. In case of an inappropriate process design in combination with stock deviations an unwanted process result or even a thermal damage of the external zone can occur. In this report a thermo-mechanical process model, which describes influences on the surface zone in generating gear grinding, is introduced.

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Introduction and motivation

In order to improve load carrying capacity and noise behavior case hardened gears usually are hard finished [1]. One possible process for hard finishing of gears is generating gear grinding. Generating gear grinding has replaced other grinding processes in batch production of small and middle sized gears due to the high process efficiency.

Despite the wide industrial application of this process, only a few scientific analysis exist [2, 3, 4, 5], because the science-based analysis of generating gear grinding needs a high amount of time and effort and the continuously changing contact conditions complicate the investigation.

The lack of knowledge of cause-effect relationships results in an empirical process design in industrial practice. Therefore in most cases several trials must be performed to find a stable process design. By stock fluctuation or by an unfavorable process design an undesirable process result up to a process-related thermal damage of the external zone can occur. Therefore it is necessary to get a better understanding of the cause-effect relationships between process parameters, tool specifications and process in generating gear grinding.

State of the art

Hard finishing technology is used to remove deviations from hardening, to machine tooth flank modifications and to meet quality requirements. The case hardening process is necessary to enable the gear to transmit high torque with smaller gears in high power applications. In industrial applications generating gear grinding, profile gear grinding and gear honing are most commonly used as hard finishing processes for gears. Each of these high-performance processes is using geometrically undefined cutting edges. Continuous generating gear grinding has evolved to the dominant process in batch production for small and middle sized gears due to the high productivity.

Generating gear grinding

One of the most efficient processes for hard finishing of gears in batch production of external gears and gear shafts is generating gear grinding. Generating gear grinding is used for hard finishing of gears with a module of $m_n = 0.5 \text{ mm}$ to $m_n = 10 \text{ mm}$ [6, 4]. By the application of new machine tools the process can be used for grinding large module gears with an outside diameter up to $d_a = 1,000 \text{ mm}$ [7].

The cylindrical grinding worm, whose profile equates a rack profile in a transverse section, meshes with an external gear, Figure 1 left. The involute is generated by continuous rolling motion of grinding worm and workpiece by the profile cuts method [8, 4]. Profile cuts method in generating processes means that the profile form is generated by a finite number of profiling cuts. Due to the closed grinding worm no generating cut deviations, as in gear hobbing process, occur during generating gear grinding.

In generating gear grinding multiple points of the grinding worm are in contact simultaneously. The number of contact points changes continuously during tool rotation, Figure 1 right. In the upper right part of Figure 1, the contacts on the right and left flanks are balanced, with an even number of contact points. This leads to a consistent distribution of forces. With an uneven number of contact points, as shown in the lower right part of Figure 1, the distribution of forces will be unbalanced. This leads to an inconsistent distribution of the cutting forces. In the example with an uneven number of contact points, the force on the line of contact of the left tool flanks is split into two contact points. On the right tool flank the cutting force is not split, because only one contact point exists. This situation can lead to higher stock removal at the single contact point potentially resulting in higher excitation. The consequence can be the appearance of profile form deviations which reduce the achievable gear quality. Scientific publications of Meijboom [2] and Türich [3] describe this relation theoretically.

In comparison to other gear grinding processes the stock removal rate in generating gear grinding is very high. In most cases the stock removal rate is limited by the demanded gear quality [4]. Furthermore, the appearance of a detrimental process-related surface zone inducement (grinding burn) can be the limiting factor.

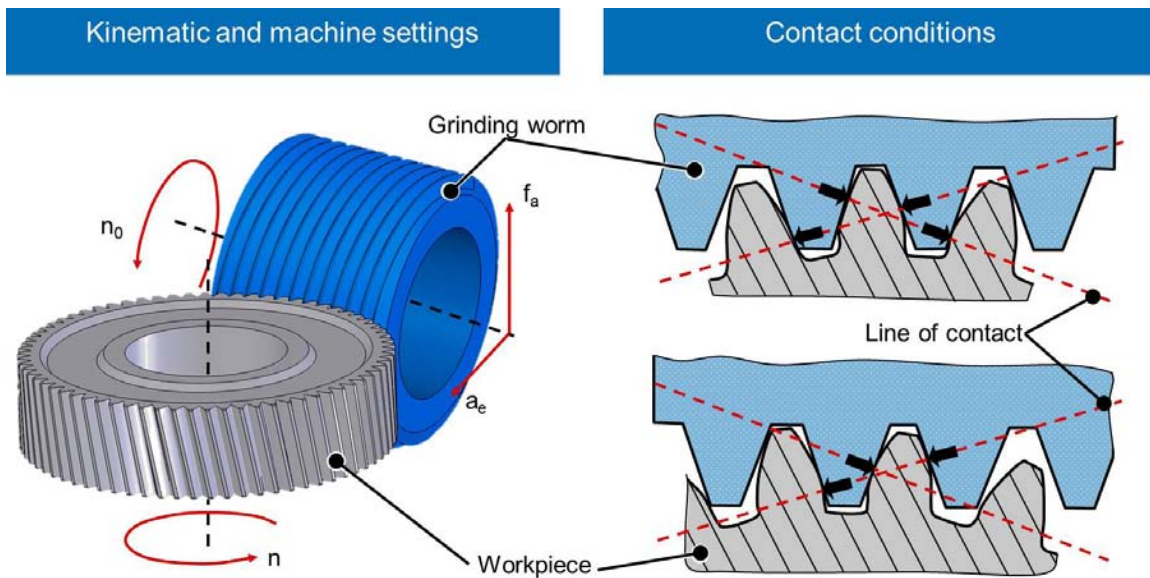


Figure 1. Generating gear grinding - principle, machine settings and contact conditions [9]

Publications [10, 11, 12], and the doctoral thesis of Meijboom [2], Türich [3] and Stimpel [5] show the influence of several parameters on the process results. But several technological correlations have not been analyzed or verified in experimental trials yet.

Current challenges

Due to limited scientific studies the technology users, grinding tool suppliers and machine tool manufactures face two main challenges.

On the one hand the process design and optimization is based on know-how of the process user. In cases, where no sufficient experience (e.g., new gear geometry, new grinding tools) exists, cost-intensive trials have to be performed to find a favored and robust process design. In this case, several trial iterations are usually necessary to obtain high process stability. In order to reduce the number of needed iteration loops the technological cause-effect relationships must be analyzed in detail.

On the other hand, the demand for increasing productivity leads to an increase of axial feed and cutting speed. With an increase of productivity the cutting force and thus the heat flow towards the workpiece are rising. This in turn leads to an increased risk of grinding burn during the grinding process. The challenge is to increase the productivity without causing grinding burn.

Research objective and approach

The research objective for generating gear grinding at WZL is the increase of process efficiency and process reliability in generating gear grinding by description of the technological cause-effect relationships for cutting forces as well as for occurrence of grinding burn in a model. For the analysis of the cause-effect relationships an analogy trial has been developed and will be introduced in this report.

The aim of this report is to present a model to predict grinding burn for generating gear grinding. Therefore cutting forces in analogy trials are measured and the interactions between process parameters and occurred grinding burn are taken into account. The measured cutting forces will be combined in an empirical cutting force model. With the ability to calculate the cutting force the heat flow density towards the workpiece can be estimated. With a comparison of the heat flow density and the grinding burn occurrence a critical heat flow density that leads to grinding burn can be determined. Thereby a model to predict grinding burn can be derived. In conclusion the prediction model will be transferred onto generating gear grinding and will be validated by generating gear grinding trials.

Analogy trial generating gear grinding

The complexity of the contact conditions between tool and workpiece during generating gear grinding complicates the analysis of generating gear grinding. On the one hand, the penetration volumes change over the tooth profile height during grinding. On the other hand, the number of engaged tool flanks and

workpiece flanks is variable. To investigate generating gear grinding on a single fixed point on the tooth profile, a geometric-kinematic model, the analogy trial, has been developed [12, 9]. The principle of the analogy trial for generating gear grinding is shown in Figure 2.

For each point of the involute the local radius of curvature ρ_y can be calculated [13]. For the analogy trial the contact conditions at different positions of the involute can be approximated. The radius of the workpiece in the analogy trial r_A equals the radius of curvature at the investigated point of the involute profile. Thus the diameter of the analogy workpiece depends on the number of teeth z , the module m_n , the helix angle β and the pressure angle α_n of the mapped sample gear. The rack profile of the grinding worm can be approximated in the investigated contact point by a face wheel with a conic working surface. [9]

Besides the workpiece and the tool geometry the chip geometry in the analogy trial has to be comparable to the chip geometry in generating gear grinding. Therefore the cutting length l_{cUA} and the chip thickness h_{cUA} have to be comparable between analogy trial and generating gear grinding.

Furthermore the kinematics of chip formation and the velocities must be fitted to generating gear grinding. During chip formation the lateral sliding speed v_{tA} , the axial feed speed v_{aA} and the cutting speed v_c interfere with each other. The cutting speeds in generating gear grinding and analogy trial are the same. The lateral sliding speed v_{tA} can be calculated by the rotational speed n_A of the workpiece and the requirement to be synchronous. The axial feed speed v_{aA} can be adjusted according to the generating gear grinding process as the product of rotational speed n_A and axial feed f_a . Rotational speed as well as axial feed in analogy trial and generating gear grinding is identical. The tool is a grinding wheel with an angled surface. The angle corresponds to the pressure angle α_{n0} of the grinding worm.

The mapped grinding process and the machine tool used are shown in Figure 3. The mapped grinding process is carried out with a spur gear with a number of teeth of $z = 31$ and a normal module of $m_n = 4.5$ mm. The material is 20MnCr5. The gears are case-hardened with a surface hardness of 60 HRC and a case-hardening-depth of $CHD_{550HV} = 1.4$ mm. The material and heat treatment of the analogy workpieces match with the spur gears. All generating gear grinding and analogy trials were performed on a model LCS380 grinding machine from Liebherr-Verzahn Technik GmbH that can perform both generating and profile gear grinding. For both analogy and generating gear grinding trials, corundum tools with a grain size F120 (average grain diameter $109 \mu m$) from Winterthur Technology AG are used.

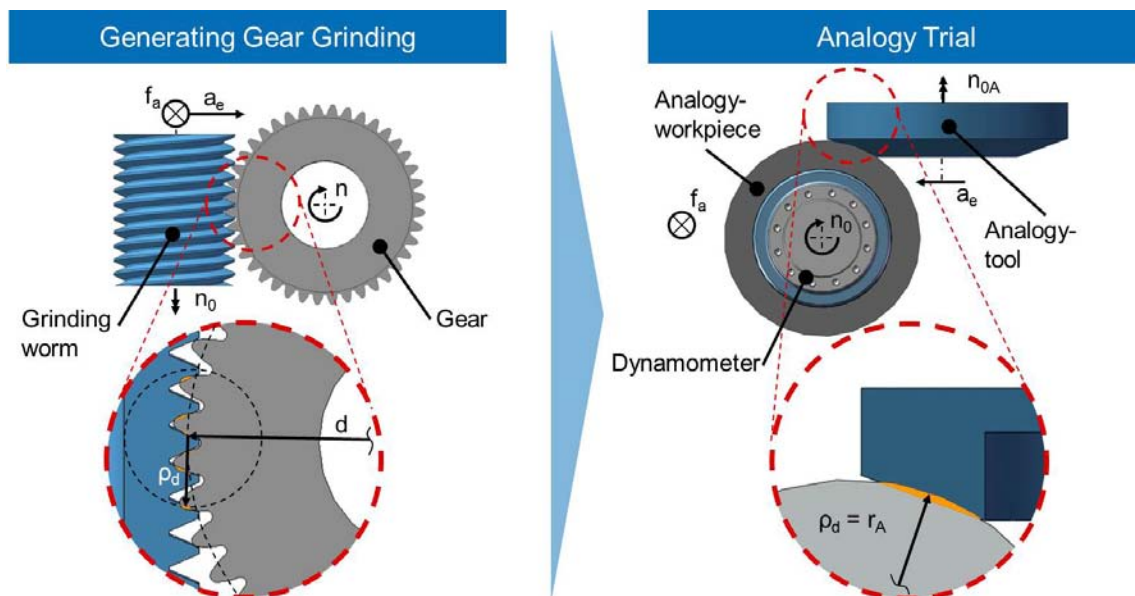


Figure 2. Analogy trial for generating gear grinding – principle and deduction of analogy workpiece geometry [9]