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Approach for the Calculation of Cutting Forces in Generating Gear Grinding

C. Brecher[a], M. Brumm[a], F. Hübner[a*]

[a]*Laboratory for Machine Tools and Production Engineering, Steinbachstraße 19, 52074 Aachen, Germany*

* Corresponding author. Tel.: +49-241-80-27311; fax: +49-241-80-22293. E-mail address: f.huebner@wzl.rwth-aachen.de

Abstract

One of the main challenges in generating gear grinding is the determination of cutting forces due to their significant influence on the dynamics of the grinding process. Thus, optimizing the cutting forces can lead to an increased quality of ground gears and a minimized wear behavior of the grinding worm. Currently, the knowledge of the generating grinding process is limited and research is based mostly on empirical studies. A theoretical model which help to predict the cutting forces is missing.
This paper presents an initial approach for calculating the complex contact conditions in generating gear grinding as well as cutting forces and key values to characterize the process. This approach gains more and more importance especially for large module gears, to reduce manufacturing costs. By means of the calculated forces, the manufacturing process can be optimized and the quality of the manufactured gear can be increased.

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Keywords: Machining; Gear; Grinding; Process; Simulation; Cutting forces; Expert System

1. Introduction and challenge

Gears are one key component of drivetrains and used in a continuously increasing quantity with improving quality. Generating gear grinding presents an economic process for finishing gears. This process is mainly used for large-scale production of gears with small or medium modules after case-hardening [1]. Continuous generating gear grinding is a dominating hard-fine finishing process, especially in the field of automotive gears.

Although continuous generating gear grinding is an industrially well-established process, only limited scientific knowledge of the process exists [2], [3], [4]. Amongst others, this is due to the complex contacting conditions. During the grinding process, several flanks of the workpiece are in mesh with the grinding worm. However, because of the kinematic coupling of tool and grinding worm, the number of contacting flanks is not constant but varies continuously. The left part of Fig. 1 illustrates the change in the contacting conditions during the process.

For the upper drawing, the contact is distributed over four points, for the lower drawing only at three points contact occurs. Due to the contacting conditions for generating gear grinding, changing cutting forces as well as a changing application of the forces result which can lead to unfavorable process dynamics [4].

As a consequence, characteristic form deviations along the profile, as shown in the lower right corner of Fig. 1, are created. Therefore, one step in avoiding profile form deviations is calculating the occurring cutting forces and contact conditions for generating gear grinding. Here, knowing the expected cutting forces and their course over time is necessary for describing and optimizing the process. The cutting forces can be determined with the help of the material removed by the grinding worm [5], [6], [7]. However, so far no calculating methods have been published for obtaining the course of the cutting forces over time for generating gear grinding.

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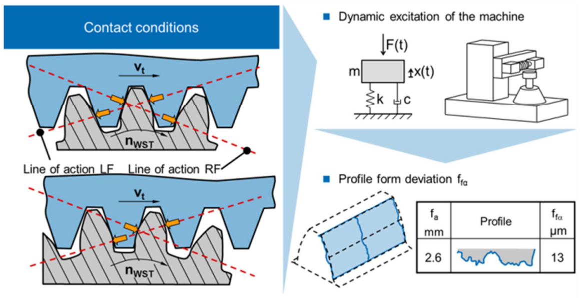

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Fig. 1. Generating Gear Grinding

2. State of the Art

The generating gear grinding process uses a geometrically undefined cutting edge and is applied to hard-fine finishing external gears and pinion shafts. The size of generating ground gears is generally within the range of a module of $m_n = 0.5$ mm to $m_n = 8$ mm [8], [2]. The outside diameter of ground gears is usually in the range of $d_a = 10$ mm to $d_a = 1000$ mm. By using new machine concepts, the process can also be used for processing larger gears of modules larger than $m_n = 14$ mm [9].

Generally, the cutting force F_c can be calculated for grinding processes by a vector sum of the cutting forces occurring at a single grain. In Fig. 2 the three components of the cutting force, tangential force, normal force and axial force are depicted for external cylindrical grinding.

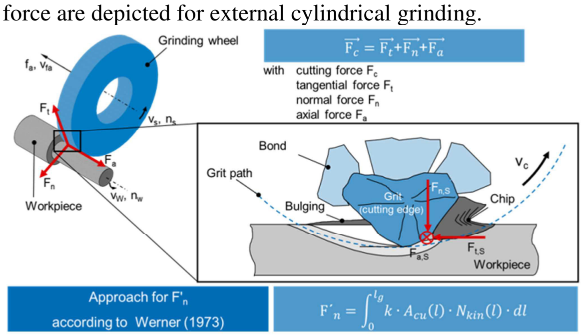

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Fig. 2. Manufacturing forces in face grinding

The tangential force is applied tangentially to the grinding wheel diameter on the abrasive grain at the location of cutting [10], [6]. In many cases the tangential force allows conclusions about the wear conditions of the tool. If the tangential force is raised, this generally points to an increased application of energy to the tool [8].

The line of action of the axial force F_a is parallel to the rotational axis of the grinding wheel. The normal force F_n, which causes deformation of the machine and workpiece, is applied radially to the grinding wheel. The sharper the grains are, the lower is the normal force.

The normal force for external cylindrical grinding can be calculated according to WERNER [6] by applying equation (1). In the process WERNER found out, that the normal force can be attributed to kinematic and geometrical characteristics. For reasons of better comparability between different processes, it has been proven to be advantageous to relate the force F'_n to the width of the active profile of the grinding wheel $b_{s,eff}$. This value is called the specific normal force F'_n.

$$F'_n = \int_0^s k \cdot A_{cu}(l)^n \cdot N_{kin}(l)\, dl \qquad (1)$$

In addition to this basic formula, WERNER has developed an approximation for external cylindrical grinding by solving the integral and substituting the chip cross-section as well as the number of kinematic cutting edges by empirical values (equation (2)).

$$F'_n = k \cdot \left(\frac{c_1^2}{K_s}\right)^{\varepsilon_1} \cdot \left(\frac{f_a}{v_c}\right)^{\varepsilon_2} \cdot a_e^{\varepsilon_3} \cdot d_{eq}^{\varepsilon_4} \qquad (2)$$

Based on (1) and (2), SALJE [11] and TÖNSHOFF [12] have developed further approaches for the calculation of cutting forces for several grinding processes. SALJE developed an approach for external cylindrical grinding and additionally an approach for internal cylindrical grinding. TÖNSHOFF expanded the approaches to influences caused by the cooling lubricant and grinding time.

The most general of the presented approaches is the basic formula according to WERNER (1) [6]. Based on this formula, several approaches of force models have been developed [11], [12], because it appears to be the approach influenced by hardly any assumptions.

3. Research Objective

The state of current knowledge shows that the need for determining the cutting forces and the contacting conditions for generating gear grinding is evident. So far, the process parameters for industrial application of this manufacturing process are chosen on the basis of experience. Up to now, no scientific investigations exist on the complex correlation between the individual parameters, the dynamics of the process and the occurring cutting forces.

Because of its high accuracy, flexibility and automation, a numerical approach was selected to calculate the local contact conditions. The selected approach was expanded and a force model was developed based on the results of a penetration calculation. For this, the calculation is supposed to be possible depending on various parameters, as for example module m_n, number of teeth z, pressure angle α_n, helix angle β or number of starts of the grinding worm z_0. This paper presents results, which have been calculated in a numerical approach. In addition to the method, calculated forces and measured forces in trial investigations will be compared.