Prediction of Process Forces in Gear Honing

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Introduction and Challenge

In order to improve the load-carrying capacity and excitation behavior, case hardened gears are usually hard finished. For the hard finishing, several high performance processes with undefined cutting edges are available. The dominating processes in the industrial application are gear honing, discontinuous profile gear grinding and continuous generating gear grinding (Refs. 1 and 2).

Gear honing is widely used for automotive applications to hard finish small and medium sized gears (Ref. 3). The automotive industry benefits from the high economic efficiency of the gear honing process in serial production. Another advantage of the gear honing process is the machinability of gears with interfering contours. Various preliminary tests on gears with a module $m_n > 5$ mm have shown that these gears can also be honed economically (Ref. 4). Compared to generating gear grinding and profile gear grinding, in gear honing minor deviations of the pre-processing quality have a bigger effect on the process stability. Even small changes in gear geometry, surface hardness or varying input quality can lead to process related machine vibration. The results can be inadequate gear quality, tool breakage and rejects. The low robustness results from high process forces, which vary in direction and magnitude due to the variable contact conditions between workpiece and tool. These alternating process forces can lead to a self-regenerating excitation (Ref. 5). The self-regenerating excitation makes it difficult to achieve the required quality (Ref. 6). Previous honing trials have shown that a consideration of the average process force is not sufficient to model the excitation (Ref. 4).

Due to the reasons mentioned above, it must be clarified how the process-specific parameters and tool specifications influence the gear honing process. Therefore, an understanding of the kinematics and geometric conditions during the process is necessary. In order to describe the interaction between the gear honing process and the machine structure, a force model for gear honing of external gears has to be derived and parameterized with gear honing analogy trials. With this model, it will be possible to predict the process forces during honing locally and temporally resolved, which leads to an improved process understanding.

State of the Art

Process characteristics and kinematics of gear honing. Gear honing is a grinding process with low cutting speeds and can be used for hard-finishing of both external and internal gears (Ref. 7). The most common application of gear honing is hard finishing of external gears in the module range from $m_n = 0.5$ mm to $m_n = 5$ mm (Ref. 3). In this paper, the machining of external gears by means of an internally geared honing tool with geometrically undefined cutting edges is considered. The gear honing tool meshes with an external gear under a cross-axis angle Σ. The achieved cutting speeds are very low compared to discontinuous profile gear grinding and continuous generating gear grinding. Due to the low cutting speeds of $v_c = 0.5$ m/s up to $v_c = 15$ m/s, the occurrence of thermal structural damage of the workpiece is unlikely (Ref. 8). The low cutting speed and the resulting low thermal influence on the workpiece material during gear honing lead to high compressive residual stresses in the near surface zone of the gear (Ref. 7). Despite the low robustness of the gear honing process and tendency to self-regenerating excitations, there is no scientific research regarding the process-machine-interaction.

The kinematics and the resulting contact conditions in gear honing correspond to the kinematics of a helical rolling type gear transmission. Although the contact conditions in this process are complex, the contact between workpiece and tool can be described as a line contact for each rolling position (Ref. 9). In gear honing, the main influence factor on the process productivity is the cutting speed v_c (Ref. 10). Due to the cross axis angle Σ, a relative velocity v_c exists between the gear flank and the tool so that material can be machined (Ref. 10). The relative speed v_c is composed of a tangential component in the direction of the involute (due to the rolling motion) as well as a component in the direction of the flank line (due to the cross axis angle) (Fig. 1). This results in the surface structure typical for the gear honing process, which is referred to as a "herringbone pattern" (Ref. 8).

The infeed-per-revolution is carried out continuously in the radial direction during the process and is in the sub-micrometer range. The cutting speed increases with the increase of the cross axis angle at a constant honing tool

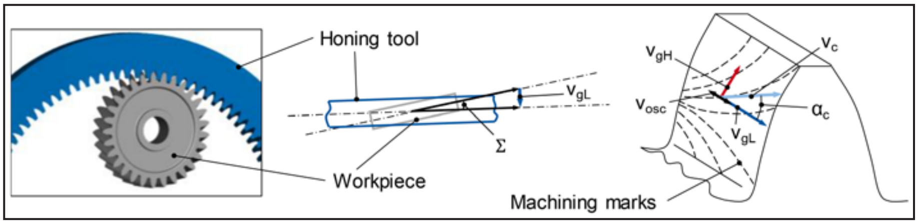

Figure 1 Kinematics and velocities in gear honing according to (Ref. 1).

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rotational speed. Along the profile of the gear, a large gradient of the cutting speed is existent for small cross axis angles, whereas the gradient of the cutting speed is very low for large cross axis angle. This relationship results because the longitudinal sliding speed v_{gL} is lager in magnitude than the lateral sliding speed v_{gH} and approximately constant over the tooth height. At small cross-axis angles, the dominant portion of the longitudinal sliding speed is reduced, so that the change in the lateral sliding speed v_{gH} along the tooth height is more strongly reflected in the cutting speed. In addition, the tracks on which the abrasive grains of the honing tool penetrate the gear change due to the cross axis angle. While long and flat grain paths occur during machining with large cross axis angles, the grain paths are steep and short at small cross axis angles. The shape of these grain paths therefore depends on the cutting speed as well as on the position on the gear profile (Ref. 8). The relationships resulting from the contact conditions and the kinematic parameters and their influence on the local process forces are not yet sufficiently known.

Force models for conventional grinding processes. The contact between grinding tool and workpiece consists of a probabilistically disordered sequence of single interactions of different abrasive grains following a defined path through the workpiece material. Not all grains of the grinding tool get into contact. Therefore, Kassen established the term of the number of dynamic cutting edges N_{dyn}. This factor takes into account the average number of cutting edges being involved in the cutting at any given time. Neglecting the elastic and plastic deformation of workpiece and tool, the number of dynamic cutting edges is exclusively dependent on the contact geometry, the grinding kinematics and the grinding tool properties (Ref. 11). The formulated connections were taken up by Werner and extended to a force model for the calculation of the specific normal grinding force F'_n during surface grinding, Eq. 1 (Ref. 12).

$$F'_n = \frac{F_n}{b_{s,eff}} = \int_0^{l_k} k \cdot A_{cu}(l) \cdot N_{dyn}(l) \cdot dl \qquad (1)$$

The specific normal grinding force F'_n is the normal grinding force F_n related to the effective contact width $b_{s,eff}$. Furthermore, the specific normal grinding force F'_n is calculated with the chip cross section area A_{cu}, the number of dynamic cutting edges N_{dyn} and the specific grinding force coefficient k. The chip cross section A_{cu} and the number of dynamic cutting edges N_{dyn} are dependent on the contact length l. In addition to the calculation of the grinding normal force during surface grinding, Werner formulated the necessary adjustments to transfer his model onto internal and external grinding. For this purpose, the equivalent grinding wheel diameter d_{eq} needs to be calculated according to Eq. 2 (Ref. 12). The grinding wheel diameter ds is subtracted from the workpiece diameter d_w for internal grinding. For external grinding, both diameters are added to each other. This results in a modified contact length l_g for internal and external ground workpieces, Eq. 3 (Ref.13).

$$d_{eq} = \frac{d_w \cdot d_s}{d_w \pm d_s} \qquad (2)$$

$$l_g = \sqrt{a_e \cdot d_{eq}} \qquad (3)$$

Bock developed a force model for internal grinding with a transfer onto internal grinding and parameterization of the force model according to Werner. Therefore, Bock introduced the specific values of the contact length related to chip thickness h_{eq}/l_g, Eq. 4, and the normal force related to the contact length F_n/l_g, Eq. 5 (Ref. 13).

$$\frac{h_{eq}}{l_g} = \frac{v_{ft}}{v_c} \cdot \sqrt{\frac{f_r}{d_{eq}}} = q \cdot \sqrt{\frac{f_r}{d_{eq}}} \qquad (4)$$

$$\frac{F_n}{l_g} = a_1 \cdot b_c \cdot \left(q \cdot \frac{h_{eq}}{l_g} \right)^{b_1} \qquad (5)$$

The contact length related chip thickness h_{eq}/l_g is influenced by the tangential feed rate v_{ft}, cutting speed v_c, radial feed f_r and the equivalent grinding wheel diameter d_{eq}. The division of the tangential feed rate v_{ft} and the cutting speed v_c equals the velocity ratio q. The normal force F_n related to the contact length l_g can be calculated with the velocity ratio q, the contact width b_c and chip thickness related to the contact length h_{eq}/l_g. The empirical influences of tool, workpiece and cooling lubricant are taken into account by the coefficients a_1 and b_1.

Several existing grinding force models have been developed which were combined to a basic force model by Tönshoff et al. (Ref. 14). To calculate the grinding force with these force models, the contact conditions have to be constant during the process. Due to the changing contact conditions during gear honing, the existing force models cannot be transferred onto gear honing. To calculate the locally resolved forces in gear honing, the contact conditions have to be transferred into a local stationary process.

Approach to Model Process Machine Interaction in Gear Honing

Due to the existing challenges in gear honing, the project—"Process-Machine-Interaction in Gear Honing"—funded by the German Research Foundation (BR 2905/71-1 and KL 500/152-1), was initiated. The objective of the research project is the prediction of the excitation behavior in the gear honing process and thus the mapping of the occurring vibrations. The coupling of a suitable force model with a dynamic machine tool model is intended to enable the honing process to be designed more efficiently, to avoid vibrations and to derive optimization approaches for the machine tool. In Figure 2, the approach to modeling process-machine-interaction is shown.

Due to the variable contact conditions between workpiece and tool during gear honing, the grinding force cannot be calculated with existing grinding force models. Therefore, a force model for gear honing has to be developed. The intersecting volume of the honing tool and the workpiece can be calculated with a penetration calculation. The intersecting volume equals the un-deformed chip geometry, which is necessary to calculate the grinding force. After the calculation of the grinding force with the force model, the grinding force has to be transferred onto the dynamic machine tool model. Within the machine tool simulation, the force and its magnitude and direction have to be applied to the machine tool structure and the displacement has to be calculated. Afterwards, the displacement has to be taken into account in a subsequent simulation loop in the penetration calculation. In order to close the simulation loop, the gear geometry already produced by the preceding machining step has to be taken into account. As a result, the current geometry must be stored and loaded in the next increment after each simulated increment. A particular challenge in gear honing is the low infeed, which results in a high necessary accuracy of the geometric models used. The total process force in gear honing is influenced by a number of different factors. In addition to the grinding force, the total process force is influenced by gear meshing and frictional forces. The kinematic relationships necessary for determining the grinding force can be adequately described analytically, while the local geometric parameters can be determined by means of numerical approaches. In addition to the kinematic and geometric parameters, there are other factors, which must be determined in empirical trials. These influencing factors include the honing tool specification, the material to be processed, the cooling lubricant and the friction behavior.

Gear Honing Analogy Process

For the determination of the force model factors of the grinding tool, friction and cooling lubricant, the process forces have to be measured in a stationary process. The variable contact conditions between workpiece and tool can be transferred into a local stationary analogy process (Ref. 8). The analogy process is based on the fact, that each point on an involute can be approximated by a circle with the same radius of curvature. Consequently, the gear honing process can be described for any desired point on the gear flank profile by the analogy process.

The gear honing analogy process can be seen as an internal grinding process with the particularities that the workpiece is inside the grinding tool and the contact between workpiece and grinding tool takes place under a cross axis angle Σ (Fig. 3).

The analogy process is used to determine the process forces independent of the dynamic influences in the gear honing process. The empirical influences of tool, workpiece and cooling lubricant are taken into account by the force measurements in the force modeling. A definite determination of the separate influences is not possible. The measured forces are regarded as the locally resolved grinding forces in the gear honing process and are implemented in the manufacturing simulation (Ref. 15). Afterwards, the resulting grinding forces out of the manufacturing simulation are compared to force measurements in gear honing trials.

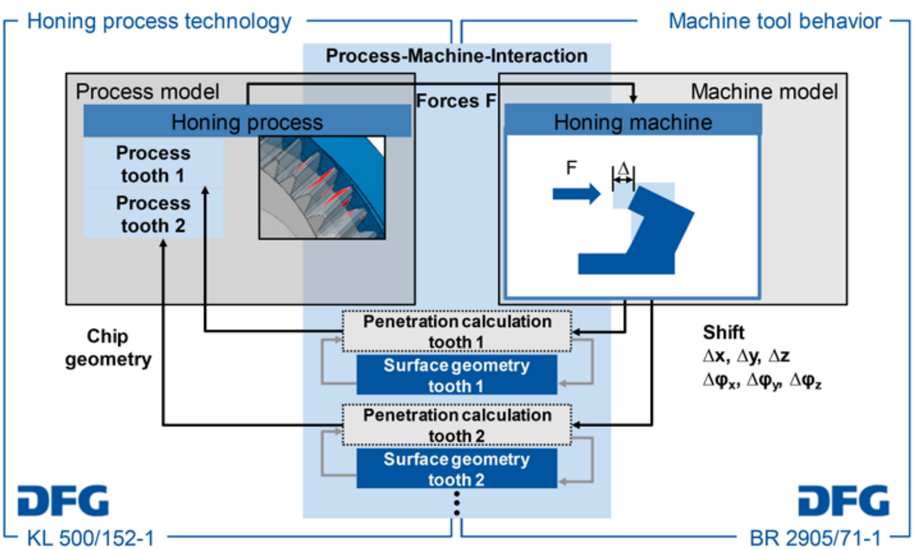

Figure 2 Approach to modeling process-machine-interaction.

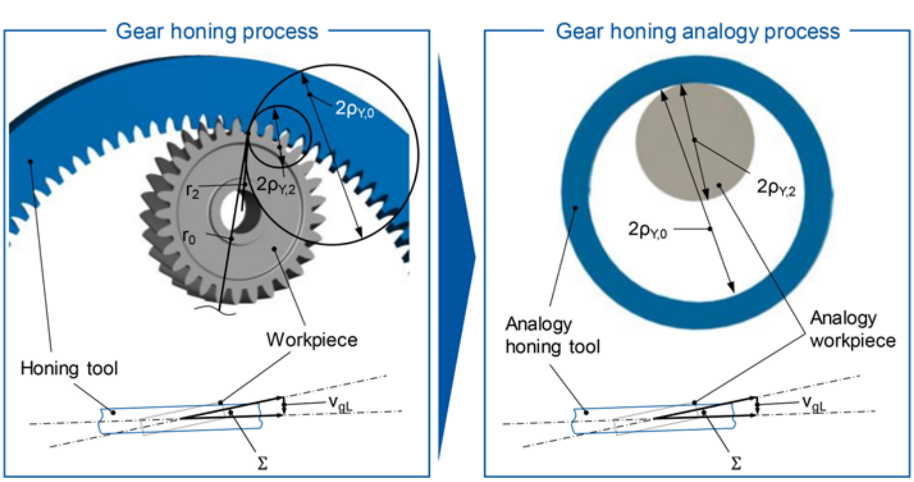

Figure 3 Derivation of the gear honing analogy process.

Trial Gear and Design of Experiments

To determine the local grinding forces during gear honing, the machining of a typical automotive type gear is analyzed. The gear has a normal module of $m_n = 2.28$ mm. Furthermore, the number of teeth is $z = 43$, the helix angle is $\beta = -33°$, the tip diameter is $d_a = 120.3$ mm and the face width of the gear is $b = 18.5$ mm. The gears are made of 16MnCr5 and casehardened to a resulting surface hardness of 59-62 HRC. Due to the reason that the honing tool is dressed during the tool life, the diameter of the tool varies. The change of tool geometry is compensated by adjustment of the cross-axis angle. For the test, different honing and analogy tools were used, dressed with a cross-axis angle of $\Sigma = 11.66°$, $\Sigma = 13.78°$ and $\Sigma = 15.42°$. These three cross-axis angles correspond to the geometry of the tool close to the new state, in the middle of tool life and at the end of tool life. The number of teeth of the honing tool is $z = -78$. The rotational speed was set to $n_0 = 800\ \text{min}^{-1}$, $n_0 = 600\ \text{min}^{-1}$ and $n_0 = 400\ \text{min}^{-1}$. The tests were carried out on a 150SPH gear honing machine from Gleason-Hurth.

Force Modeling for the Gear Honing Analogy Process

The state of the art shows that grinding force models exist, but cannot be used for gear honing due to the changing contact conditions. The process forces can be measured during the analogy process without being subjected to the dynamics of the gear honing process. With knowledge of the forces in the analogy process, it is possible to parameterize the model according to Bock. This model has to be adapted to gear honing and the final gear honing force model needs to be validated.

The grinding force for the internal grinding process was calculated based on Bock, Eqs. 2–5 (Ref. 13). The gear honing analogy process differs from the internal grinding process by the cross-axis angle Σ between the workpiece and the grinding tool, the intersecting geometry and the lower cutting speeds v_c. Therefore, the calculation of the equivalent grinding wheel diameter d_{eq} has to be adjusted with regard to the influence of the cross axis angle Σ, Eq. 6. The cross axis angle Σ causes an increasing path length of the grain through the workpiece. Considering the cross axis angle Σ, the geometric contact length $l_{g,\Sigma}$ can be determined according to Eq. 7. The indices of the diameters represent the analogy tool (index A, 0) and analogy workpiece (index A, 2).

$$d_{eq} = \frac{d_{A,2}\cdot d_{A,0}\cdot\cos(\Sigma)}{d_{A,0}\cdot\cos(\Sigma)-d_{A,2}} \qquad (6)$$

$$l_{g,\Sigma} = \frac{\sqrt{f_r\cdot d_{eq}}}{\cos(\Sigma)} \qquad (7)$$

With these enhancements and the equations according to Bock, a grinding force model for the gear honing analogy process is derived. The grinding normal force F_n, Eq. 8, and the grinding force F_c, Eq. 9, are calculated based on the values for the equivalent grinding wheel diameter d_{eq}, the geometric contact length $l_{g,\Sigma}$, the speed ratio q, the radial feed f_r and the contact width b_c.

$$F_n = a_1\cdot l_{g,\Sigma}\, b_c\cdot\left(q\cdot\sqrt{\frac{f_r}{d_{eq}}}\right)^{b_1} \qquad (8)$$

$$F_c = a_2\cdot l_{g,\Sigma}\, b_c\cdot\left(q\cdot\sqrt{\frac{f_r}{d_{eq}}}\right)^{b_2} \qquad (9)$$

Analogy trials were carried out with three different analogy workpieces with a width of $b_{A,2} = 18.5$ mm and diameters of $d_{A,2.1} = 26.34$ mm, $d_{A,2.2} = 41.24$ mm and $d_{A,2.3} = 52.7$ mm. The used analogy tools had a width of $b_{A,0} = 25$ mm. By measuring the forces during the analogy process, the parameters a_1, a_2, b_1 and b_2 were determined empirically (Ref. 16). The curves of the parameterized grinding force model are shown (Fig. 4). The grinding force relative to the contact area is plotted over the specific chip thickness.

Using the force model, for each point mapped in the analogy process proportionality factors $k_{c,loc}$ and $k_{n,loc}$ are determined. These take into account the different geometric kinematic contact

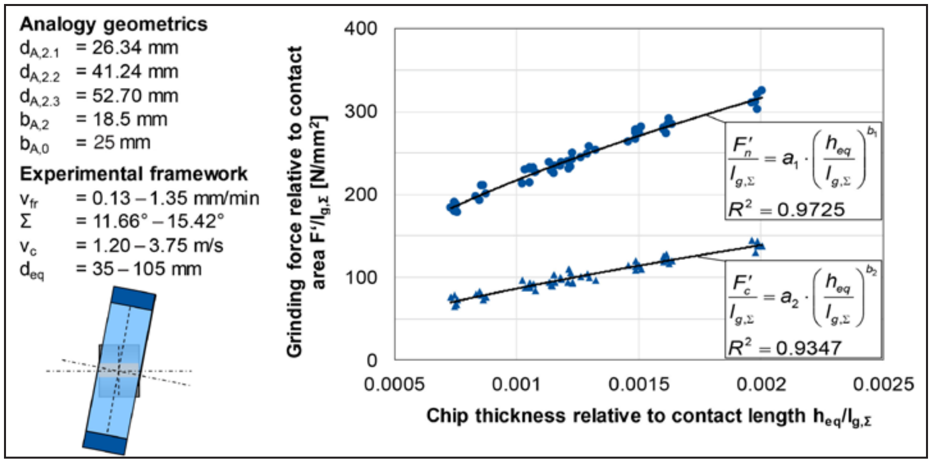

Figure 4 **Force model for the gear honing analogy process.**

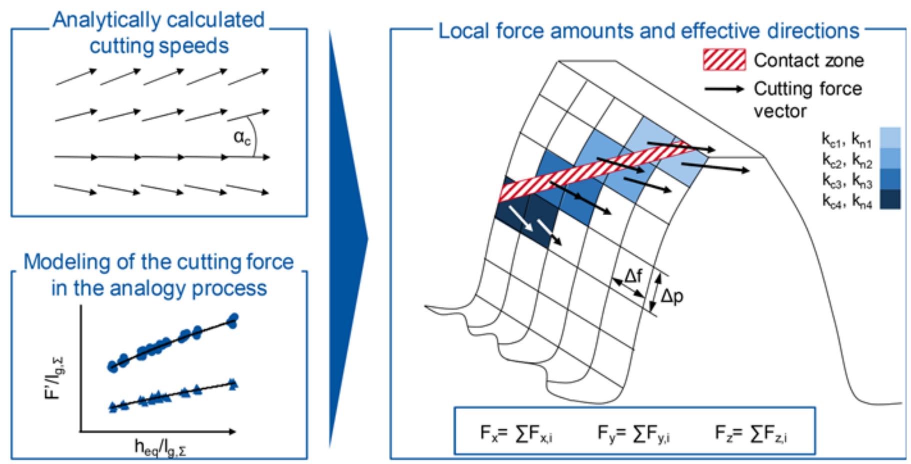

Figure 5 **Map-based calculation of the grinding forces.**

conditions. For each diameter combination of analogy workpiece and tool constant proportionality factors $k_{c,loc}$ and $k_{n,loc}$ are obtained. During the transfer of the local forces of the analogy onto the gear honing process, these proportionality factors represent locally specific proportionality factors on the involute profile.

Transfer of the Local Forces from the Analogy Process On to Gear Honing

With the analogy trials, a force model was derived and parameterized. This model was transferred onto gear honing by means of a manufacturing simulation (Ref. 15). For discrete meshing positions of the tool and workpiece, the undeformed chip geometry is determined. Those penetration geometries are locally comparable to the analogy trial. In contrast to the analogy process, different cutting conditions exist for each point on the involute profile. In addition to the variation in the local penetration geometries, the pressure angle, the helix angle and the cutting speed components are also variable. This results in a variable cutting angle α_c and the typical machining marks in gear honing. The cutting speed components and therefore the cutting angle can be calculated analytically (Ref. 9), (Fig. 5).

The local process forces can be calculated by multiplying the distances of the points in profile and flank direction Δp and Δf with the chip thickness $h_{cu,loc}$ and the proportionality factors $k_{c,loc}$ and $k_{n,loc}$. Contrary to the constant proportionality factors in the analogy process, the proportionality factors vary over the involute profile during the gear honing process.

Due to the analytically calculated cutting angle α_c, the process forces can be divided into the forces in the main directions of the machine coordinate system. To calculate the total force during the gear honing process, simultaneous machining on several teeth is considered by an addition of all contacts between tool and workpiece in the manufacturing simulation. Therefore, several rolling positions and the spatial positions of the penetration geometries are calculated. Subsequently, the occurring forces are added up again for each direction. These calculated mean machining forces are compared with measured forces in the gear honing process. In Figure 6, the comparison of the forces divided into the three spatial directions is shown.

For the three spatial directions, the magnitude of the measured and the calculated forces are similar. The good comparability of the measured and the calculated forces validates the transferability of the local grinding force model from the analogy process onto the gear honing process. The difference between the measured and the calculated forces may result from vibration during gear honing. The vibration leads to deviations in penetration of tool and workpiece.

Summary and Outlook

Gear honing is a highly productive process for the production of small and medium sized gears and is used mainly in the serial production of the automotive industry. The low robustness of the process is a particular challenge in gear honing. The consequences range from an inadequate gear quality to an early breakage of the honing tool.

In order to describe the process-machine interaction, the machining forces must be known. The forces for internal grinding have been successfully described by Bock by adapting the grinding force model according to Werner. Due to the varying engagement between the workpiece and the tool along the tooth profile, the force varies in direction and magnitude and existing force models cannot be used for gear honing. Therefore, the gear honing process was first transferred into an analogy process. The internal grinding force model according to Bock was transferred to an internal grinding set up under a cross axis angle. The geometric and kinematic similarity between the analogy process and the internal grinding was used to parameterize an empirical-analytical force model. Taking into account the cross axis angle, the model according to Bock was parameterized with the results of the force measurement in the analogy process and therefore a force model for the analogy process was derived. By combining this force model with a penetration calculation of the gear honing process and an analytical calculation of the effective velocities, the process forces during gear honing could be determined locally and temporally resolved for all three spatial directions. The comparison of the measured and calculated process forces in the machine coordinate system showed a good agreement and, thus, validated the presented method.

In the future, the coupling of the presented force model with the machine model must take place. This allows not only the prediction of the average grinding force, but also the force amplitudes. In addition to the coupling of the process model to a machine model, a further step is the implementation of the oscillating motion of the gear honing process in the penetration calculation as well as in the force model.

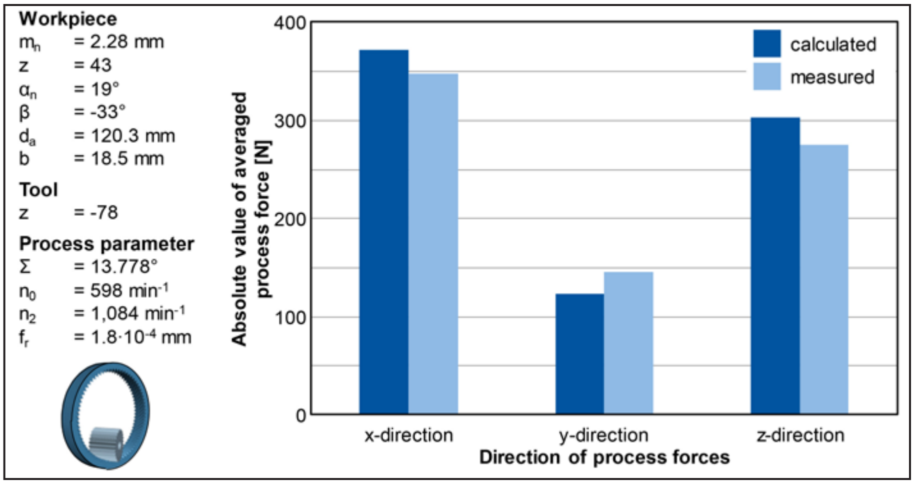

Figure 6 **Calculated and measured gear honing process forces.**

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