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Cutting force model for gear honing

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ABSTRACT

In gear honing the low robustness of the process is a challenge in process design. The forces resulting from the machining interact with the dynamic behavior of the system which influences the quality of the workpiece and the tool life. Due to these reasons, the process forces during gear honing must be determined locally and temporally resolved. Therefore, a force model was derived and parameterized with gear honing analogy trials. This force model was combined with a process simulation for gear honing and an analytical calculation of the velocities. The model for gear honing was validated with gear honing trials.
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1. Introduction and challenge

The increasing requirements regarding load-carrying capacity and noise behavior have led to the use of case-hardened gears in high performance applications. In order to correct distortions from heat treatment and to meet the geometric requirements, case-hardened gears are 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 [1–3].

Gear honing is primarily used to hard finish small and medium sized automotive gears with a normal module less than $m_n \leq 4$ mm [4]. The automotive industry benefits from the high economic efficiency of the gear honing process in serial production. Due to the little space requirements, the gear honing process can be used for machining gears with interfering contours.

Compared to other hard finishing processes, in gear honing minor deviations of the pre-processing quality, e.g. the geometry or the surface hardness, have a bigger effect on the process stability compared to generating and profile gear grinding. The results can be inadequate gear quality, tool breakage and rejects. The low process 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 [5]. The self-regenerating excitation makes it difficult to achieve the required quality [6]. Previous honing trials have shown that a consideration of the average process force is not sufficient [7].

Due to the reasons mentioned above, models for the local process forces during the gear honing process are required. However, the identification of the process force is a big challenge. During gear honing several teeth of the gear are in contact with the tool and thus an assignment of the resulting process force to the contact points is not possible. Therefore, a force model for gear honing of externally toothed cylindrical 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.

2. State of the art

2.1. Process characteristics of gear honing

In gear honing both internally and externally geared workpieces can be hard finished. The most common application of gear honing is hard finishing of external gears. In this case an internally geared tool with geometrically undefined cutting edges meshes with an external gear under a cross axis angle. The achieved cutting speeds are very low compared to profile gear grinding and continuous generating gear grinding. The cutting speeds vary from $v_c = 0.5$ m/s up to $v_c = 15$ m/s, so that a thermal structural damage of the workpiece does not occur [8]. One benefit of gear honing is the machinability of workpieces with interfering contours. The maximum machinable workpiece size of current honing machines is limited to a tip diameter of $d_a = 270$ mm. Since the honing process is mainly used in the automotive industry, most scientific studies are based on gears with a tip diameter of less than $d_a \leq 150$ mm. Further process characteristics as well as advantages and disadvantages of the gear honing process are shown in Fig. 1 [7].

2.2. Process kinematics and cutting speeds in gear honing

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 can be described as a line contact for each rolling position [9].

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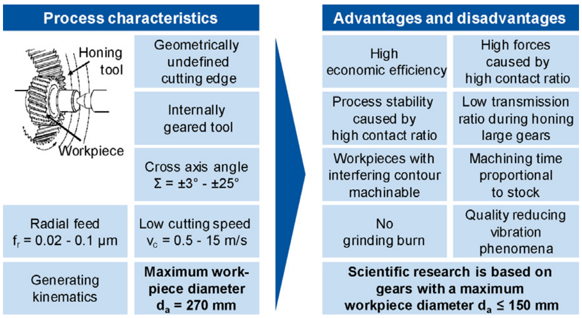

Fig. 1. Process characteristics of gear honing according to Ref. [7].

In gear honing the main influence on the process productivity is the cutting speed v_c [10]. The cutting speed v_c consists of the three components lateral sliding speed v_{gH}, longitudinal sliding speed v_{gL} and oscillation speed v_{osc}. Due to the low oscillation speed v_{osc} compared to the sliding speeds $v_{osc} \ll v_{gH}, v_{gL}$, the oscillation speed is negligible. Therefore, the cutting speed can be calculated by the vector sum of the lateral sliding speed v_{gH} and the longitudinal sliding speed v_{gL}, Fig. 2 and Eq. (1). The lateral sliding speed v_{gH} is calculated out of the radius of curvature of tool ρ_0 and workpiece ρ_2 and the angular velocities of tool ω_0 and workpiece ω_2, Eq. (2). The longitudinal sliding speed v_{gL} depends on the circumferential speed ω, the helix angle β, the radius r and the cross axis angle Σ, Eq. (3). To specify the direction of the cutting speed v_c, the cutting angle α_c is calculated with the lateral sliding speed v_{gH} and the longitudinal sliding speed v_{gL}, Eq. (4) [8].

$$v_c = \sqrt{{v_{gH}}^2 + {v_{gL}}^2} \tag{1}$$

$$v_{gH} = \rho_2 \cdot \omega_2 - \rho_0 \cdot \omega_0 \tag{2}$$

$$v_{gL} = r_2 \cdot \omega_2 \frac{\sin \Sigma}{\cos \beta_0} = r_0 \cdot \omega_0 \frac{\sin \Sigma}{\cos \beta_2} \tag{3}$$

$$\alpha_c = arctan\left(\frac{v_{gH}}{v_{gL}}\right) \tag{4}$$

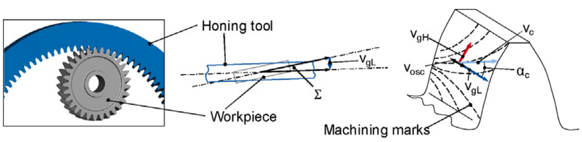

Fig. 2. Kinematics and velocities in gear honing according to Ref. [2].

2.3. Grinding force models

The contact between grinding tool and workpiece follows 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 wheel get into contact. Therefore, Kassen established the term of the number of dynamic cutting edges N_{dyn}, which represents the number of grains that actively take part in the chip formation. Neglecting the elastic and plastic deformation of workpiece and tool, the number of dynamic cutting edges is only dependent on the contact geometry, the grinding kinematics and the grinding-wheel properties [11]. Werner developed a force model to calculate the specific normal cutting force F'_n during surface grinding taking into account the number of dynamic cutting edges N_{dyn}, Eq. (5) [12].

$$F'_n = \frac{F_n}{b_{s,eff}} = \int_0^{l_k} k \cdot A_{cu}(l) \cdot N_{dyn}(l) \cdot dl \tag{5}$$

The specific normal cutting force F'_n is the normal cutting force F_n related to the effective contact width $b_{s,eff}$. Furthermore, the specific normal cutting force F'_n is calculated with the chip cross section A_{cu}, the number of dynamic cutting edges N_{dyn} and the specific cutting 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 already 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. (6) [12]. The grinding wheel diameter d_s is subtracted from the workpiece diameter d_w for internal grinding. For external grinding both diameters are added to each other.

$$d_{eq} = \frac{d_w \cdot d_s}{d_w \pm d_s} \tag{6}$$

A transfer and parameterization of the force model for internal grinding was developed by Bock based on the findings of Werner. Therefore, Bock calculated the chip thickness h_{eq} as well as the normal force F_n relating on the contact length l_k, Eqs. (7) and (8) [13].

$$\frac{h_{eq}}{l_k} = \frac{v_{ft}}{v_c} \cdot \sqrt{\frac{f_r}{d_{eq}}} = q \cdot \sqrt{\frac{f_r}{d_{eq}}} \tag{7}$$

$$\frac{F_n}{l_k} = a_1 \cdot b_c \cdot \left(q \cdot \frac{h_{eq}}{l_k}\right)^{b_1} \tag{8}$$

The chip thickness related to the contact length h_{eq}/l_k is influenced by the feed velocity v_{ft}, cutting speed v_c, feed rate f_r and the equivalent grinding wheel diameter d_{eq}. The division of the feed velocity v_{ft} and the cutting speed v_c equals the velocity ratio q. The normal force F_n related to the contact length l_k can be calculated with the velocity ratio q, the contact width b_c and chip thickness related to the contact length h_{eq}/l_k. The empirical influences of tool, workpiece and cooling lubricant are taken into account by the coefficients a_1 and b_1. Taking into account the stated relationships, the normal force related to the contact length can be calculated with Eq. (9).

$$\frac{F_n}{l_k} = a_1 \cdot b_c \cdot \left(q \cdot \sqrt{\frac{f_r}{d_{eq}}}\right)^{b_1} \tag{9}$$

Several grinding force models have been developed which were combined to a basic force model by Tönshoff et al. [14]. To calculate the grinding force with these force models, constant contact conditions are necessary. 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.

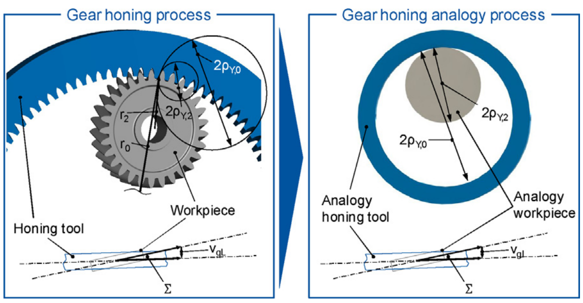

Fig. 3. Gear honing analogy process according to Ref. [8].

2.4. Gear honing analogy process

The variable contact conditions between workpiece and tool can be transferred into a local stationary process [8]. In the analogy process each point of the workpiece and tool profile can be

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