An Approach to the Calculation of Process Forces during the Precision Honing of Small Bores

Christina Schmitta,*, Dirk Bährad

*a Institute of Production Engineering, Saarland University, 66123 Saarbrücken, Germany
* Corresponding author. Tel.: +0049 681 302 57559; fax: +49 681 302 4858. E-mail address: christina.schmitt@mx.uni-saarland.de

Abstract

Honing is an abrasive machining process that can produce very exact results regarding geometry, form and surface quality of the honed work piece. It is mainly used as the final finishing operation for ready-made bores and has to meet high demands regarding process stability and repeatability. As it can create a high ratio of bearing contact area to total area together with a high surface quality it is often used for highly stressed parts. During the process, the honing tool combines three movement components: a rotation around the tool axis, an oscillation along the tool axis and a radial feeding movement of the honing stone. The interface between honing stone and workpiece and the movement of the honing stone are very important for the process. Nowadays, there are two different control strategies for the feeding movement of the honing stone: feed-controlled and force-controlled honing. While force-controlled honing tries to keep a constant process force, feed-controlled honing feeds the honing stone in certain steps in certain time intervals. The force-controlled approach can bring better results of the process regarding the quality parameters and the tool wear. But to be able to hone force-controlled the correlation of the process forces has to be known. This paper presents a first theoretical approach to the relations between the forces during the honing process. Some parameters that are needed for the calculation are derived from experimental results.

Keywords: Precision machining; honing; force analysis; surface finishing

1. Introduction

The use of the honing process is one of the best alternatives as the last step in the production process for high precision cylinder bores. Honing can improve the dimensional and form accuracy as well as the surface quality of premachined parts. As it is the last step and the honed parts bear high costs, the requirements for the process stability and repeatability for honing are very high [1]. To help to improve these properties there is a new approach to the control of the honing process called force controlled honing [2, 3, 4], which tries to keep the forces constant. A problem is that in case of machining small bores it is not possible to measure the forces directly at the honing stone, but only indirectly above the feeding cone. To be able to still hone force controlled, the relations between the cone force and the cutting force at the honing stone have to be known. An important interface in the process is the one between honing stone and workpiece. This can be characterised by the tangential force coefficient, the ratio between tangential and normal force at the honing stone [5]. These coefficients will be examined for a certain typical combination of honing stone, workpiece material and cooling lubricant in the following paper. Further on an easy theoretical approach for the calculation of process forces during the honing of bores will be discussed and a calculated signal compared to a measured signal.
2. The Honing Process

The honing process is characterised by three overlaying movements of the honing tool. These are the rotation around the tool axis, the oscillation along the tool axis and the feeding movement of the honing stone in radial direction (see Figure 1).

![Fig. 1. Schematic diagram of an internal long-stroke honing process with a single stone tool [6].](image1)

For the precision honing of small bores (2-12mm) mostly single-stone tools equipped with one honing stone and two guide stones as shown in Figure 1 are used. The honing stone is responsible for the abrasion of workpiece material, the guide stones are supposed to only guide the tool in the bore. An axial movement of the feeding cone is transmitted into a radial movement of the honing stone at the cone face. This movement is highly important for the honing process, it can be either feed- or force-controlled. By feed-controlled honing, the honing stone is fed outwards in certain steps in certain time intervals without any monitoring of the process. By force-controlled honing the process forces are monitored and, by feeding or taking steps back, held constant. The height of the feeding steps for force-controlled honing is dependent on the difference between wanted and measured process force (see Figure 2). This leads to different process forces during the honing process. While the process force tends to rise at the end of a feed-controlled process as shown in Figure 2 (upper part), it stays constant for force-controlled honing (Figure 2, lower part). Both process forces are influenced by the oscillation movement.

At the moment, the control variable for force-controlled honing is the cone force $F_k$, measured above the feeding cone. Figure 3 shows the position of the force sensor. As the measured signal is not the actual cutting force at the honing stone, there are two possibilities for a further improvement of the process.

![Fig. 2. Differences in feed movement and force for feed and force controlled honing [4].](image2)

![Fig. 3. The system honing machine – honing tool – honing stone with the position of the force sensor for force-controlled honing.](image3)
The first is an integration of the force sensor at the honing stone in the tool, as it has been realized for the honing of bigger bores (example given: cylinder bores for cars, diameter around 70-100mm [7]). Then, the force can be directly controlled. The second possibility is an exact analysis of the correlation between signals that can easily be measured and the actual cutting force at the honing stone. This approach will be discussed in the following. It is also an important requirement to know about the connection between the feed movement and the corresponding feeding force at the cone pole and the cutting force at the honing stone to be able to make a reasonable development for the regulation of the process.

Figure 3 shows the transmission path from the rotational movement of the feed drive to the axial movement of the honing tool, where the cone force \( F_{k} \) is measured, and the feeding cone. This is at the honing stone finally translated into the radial feeding movement \( \Delta r \) and the radial force at the honing stone \( F_{hr} \). The many interfaces with their axial and torsion stiffness influence the relation between feeding movement and force at the cone pole and feeding movement and force at the honing stone. These will not be further discussed in this article, in the theoretical approach here the system is assumed to be stiff. The interface between feeding cone, honing stone and workpiece is in the focus of consideration.

3. Forces during the Honing Process

![Figure 4: Forces at the honing tool according to Mushardt [9.]](image)

Figure 4 shows the force relations at the honing tool as described by Mushardt [9]. If the transmission is assumed ideal at the interfaces between the force sensor and the feeding cone and deformations and inertia are neglected, \( F_{k} \) is the force at the feeding cone. With the coefficient of friction \( \mu \) between feeding cone and honing stone and the cone angle \( \varphi \), \( F_{hr} \) can be evaluated as depicted in Formula (1).

\[
F_{hr} = F_{k} \cdot \frac{(\cos(\varphi) + 2 \cdot \mu \cdot \sin(\varphi))}{\sin(\varphi) - \mu \cdot \cos(\varphi)}
\]  

(1)

![Figure 5: Forces at the honing tool](image)

Figure 5 shows the forces at the circumference of the honing tool which occur at the honing stone and the two guide stones. These forces can be used to calculate the moment around the tool, which can easily be measured by an external dynamometer underneath the workpiece mounting during the honing process.

The resulting moment \( M \) follows from the tangential forces \( F_{ht} \) at the honing stone and \( F_{stt} \), and \( F_{c2} \) at the guiding stones together with the workpiece diameter \( r_w \):

\[
M = r_w \cdot (F_{ht} + F_{stt} + F_{c2})
\]  

(2)

The tangential force components \( F_{ht} \), \( F_{stt} \), and \( F_{c2} \) are in a certain relation to the radial force components \( F_{hr} \), \( F_{str} \), and \( F_{c2r} \). \( F_{hr} \) can be calculated as a function of the cone force \( F_{k} \) using the tool geometry (\( \varepsilon \): angle between honing stone and guiding stone, \( \delta \): angle between the two guide stones, as shown in Figure 5 and cone angle \( \varphi \) between feeding cone and honing stone as shown in Figure 4). As previous studies show, there is a proportional relation between \( F_{ht} \) and \( F_{hr} \) [5, 8]. The ratio between tangential and normal force at the honing stone has been defined by [5] as the tangential force ratio \( \mu_t \):

\[
\mu_t = \frac{F_{ht}}{F_{hr}} = \frac{F_{ht}}{F_{hr}}
\]  

(3)

With the help of the tangential force ratio, the relation between the normal and tangential forces at the honing stone can be calculated. This gives:

\[
F_{hr} = \mu_t \cdot F_{ht} \quad \text{with} \quad F_{ht} = f(F_{k}, \text{tool geometry})
\]  

(4)
The same can be supposed for the guiding stones.
\[ F_{str} = \mu_s F_{str} \quad \text{and} \quad F_{s2r} = \mu_s F_{s2r} \] (5)

If two identical guide stones are used, as it is usually done, it can be assumed that \( \mu_{s1} = \mu_{s2} = \mu_s \). This gives the moment as:

\[ M = r_w \cdot \left( \mu_b \cdot F_{sw} + \mu_s \cdot F_{str} + \mu_s \cdot F_{s2r} \right) \] (6)

\( F_{str} \) and \( F_{s2r} \) can be evaluated using the power balance at the honing tool as shown in Figure 4 with the assumption of a gimbal mounted workpiece (no lateral forces).

\[ F_{str} = \mu_s \cdot F_{s2r} + F_{sw} \cdot \sin(\varepsilon-\delta) - \mu_h \cdot F_{sw} \cdot \cos(\varepsilon-\delta) \] (7)

\[ F_{s2r} = \left( \frac{F_{sw} \cdot ((\mu_h \cdot \mu_s) \cdot \sin(\varepsilon-\delta) + (\mu_s \cdot \mu_s + 1) \cdot \cos(\varepsilon-\delta))}{\mu_s^2 + 1} \right) \] (8)

With this, the moment \( M \) can be calculated as:

\[ M = \Psi * F_k \] (9)

where \( \Psi \) is dependent on \( \mu_s, \mu_h, \mu, \varphi, \beta = \varepsilon\delta \).

\[ \Psi = \frac{a + b \cdot \cos(\beta) + c \cdot \sin(\beta) \cdot (\cos(\varphi) - 2 \mu \cdot \sin(\varphi) \cdot r_w)}{(\sin(\varphi) + \mu \cdot \cos(\varphi) \cdot (\mu_s^2 + 1))} \] with the parameters \( a, b, \) and \( c \) as:

\[ a = \mu_h \cdot \mu_s^2 + \mu_h \]
\[ b = \mu_s^2 + \mu_s^2 \cdot \mu_h - \mu_s \cdot \mu_h + \mu_s \]
\[ c = \mu_s^2 \cdot \mu_h + \mu_s \cdot \mu_h + \mu_s \cdot \mu_s - \mu_s^2 \] (10)

To be able to compare a calculated moment to a measured moment, the missing parameters (\( \mu_s, \mu_h, \mu, \varphi, \delta \) and \( \varepsilon \)) have to be known. \( \varphi, \delta \) and \( \varepsilon \) are given with the geometry of the tool used. \( \mu, \mu_h \) and \( \mu_s \) have to be determined. In the following, an approach to determine one of the missing parameters, the tangential force ratio \( \mu_t \) for a defined combination of honing stone – workpiece material – honing oil is presented and a signal is calculated and compared to a measured signal.

4. Experimental Setup

Figure 6 shows the experimental setup at the Institute of Production Engineering. The workpiece is made from hardened steel and put into the workpiece collet of a turning machine. The honing stone is pressed onto the workpiece, the tangential and normal force components are measured by a force sensor. The forces are saved and evaluated by a mobile data recorder. The provision of honing lubricant was carried out in a special oil circuit. In this setup, the workpiece performs the rotational movement while the honing stone performs the feeding movement and the oscillation. This external honing was chosen because of the much easier possibilities to measure the forces. Furthermore, an analysis of abrasion and wear effects for the honing stone can also be realized with this setup. The results are conferrable to internal honing.

![Figure 6. Experimental setup for the determination of the tangential force coefficient \( \mu_t \)](image)

The experiments were conducted using a honing stone with cutting grains made from Cubic Boron Nitride (CBN) in a metallic bonding. Table 1 shows the different variations of the parameters cutting velocity and normal force. Before the start of the experiments, the honing stones were dressed with a mounted point; honing oil was used during the experiments. The experiments lasted 20s each, a time comparable to the internal honing with parameters for this combination. Both honing stone and workpiece were 20mm long with a suitable oscillation overrun on both sides of the workpiece.

| Cutting velocity [m/min] | 10  | 15  | 20  |
|-------------------------|-----|-----|-----|
| Normal force [N]        | 100 | 150 | 200 |
| Workpiece material      | 20MnCr5 (1.7147), hardened to 60HRC |
| Honing stone            | CBN, average grain size 83\( \mu \)m in metallic bonding, concentration 50 |

5. Experiment Results

Figure 7 shows the tangential force \( F_{str} \) measured in correlation to the normal forces \( F_{sw} \). The cutting speed
was the same for all normal force levels, namely 10m/min. The normal force was varied between the values 100N, 150N and 200N, which gives pressures on the honing stone of 1.67N/mm², 2.5N/mm² and 3.33N/mm². The honing stone and the honed workpiece were both 20mm long. The oscillation length was 14mm. The tangential force coefficients from the measurements had values between 0.1723 and 0.2020.

The graph in Figure 6 can be approximated as:

\[ F_{ht} = a + b \cdot F_{hr} \]  

with \( a = 0.6498 \)N and \( b = 0.1956 \). The linear regression line has a coefficient of determination of 0.9766. As \( a \) is negligibly small in comparison to the forces in the honing process, the formula can be simplified to:

\[ F_{ht} = \mu_h \cdot F_{hr} \]  

with the tangential force ratio at the honing stone \( \mu_h \). In this case \( \mu_h \) is 0.1956, for the chosen combination of honing stone, workpiece material and honing oil. Figure 8 shows the results for higher cutting velocities of 15m/min (blue) and 20m/min (red). The normal force is again varied between 100N, 150N and 200N. As can be seen, there is no significant difference and the tangential force coefficient seems to be independent of the cutting speed. These results confirm previous studies on the subject [7, 8, 10], which have been conducted with honing stones with diamond cutting grains on cast iron. In detail, the coefficients varied between 0.1734 and 0.2060 for a cutting velocity of 15m/min and between 0.1817 and 0.1955 for a cutting velocity of 20m/min. Both can be approximated with roughly the same coefficients \( a \) and \( b \) as for a cutting velocity of 10m/min. Furthermore, there was a tendency of the tangential force ratio to become smaller during several experiments without a new dressing of the honing stone. This can be explained by the honing stone losing its sharpness and getting duller, as also detected in the experiments of [5, 10] for different combinations of honing stone – workpiece material – honing oil.

6. Comparison of a measured and a calculated signal

Figure 9 shows the comparison of the moment measured during a honing process to the moment calculated according to Formula (9). The parameters of the honing experiment are shown in Table 2, \( \mu = 0.192 \) has been taken from the experiments and the missing parameters have been assumed. As the typical value for the coefficient of friction for steel on steel with a slight lubrication, \( \mu = 0.13 \) has been chosen. The coefficient \( \mu_h \) was assumed to be 0.01. The moment calculated on the basis of the signal \( F_k \) measured during the honing process shows deviations of up to 25% from the measured moment.

![Tangential force ratio \( \mu_h \)](image-7.png)

![Tangential force ratio \( \mu_h \)](image-8.png)

![Comparison of measured (blue) and calculated (red) moment](image-9.png)
Table 2: Parameters for the honing experiments

| Parameters for the Honing experiment | Value                                      |
|-------------------------------------|--------------------------------------------|
| Honing machine                      | Kadia LH 30/300 R                          |
| Rotation speed                      | 1600min⁻¹                                  |
| Lifting speed                       | 0.26m/s                                    |
| Lifting acceleration                | 5m/s²                                      |
| Radial feed per step                | 0.0005mm                                   |
| Time between feed steps             | 0.25s                                      |
| Time of relaxation                  | 2s                                         |
| Honed diameter                      | 8mm                                        |
| Workpiece material                  | Steel 16MnCr5 ()                           |
|                                     | Hardened to 60±2 HRC                       |
| ε – δ – ϕ                           | 125° – 90° – 2.5°                          |
| Honing oil                          | Kadiol 50                                  |

This can be explained by the influence of the moving masses and their inertia. Figure 10 shows the signal $F_k$ measured during a no load operation. While for an inertia free system, the cone force $F_k$ should be constant, it is not in reality. At the lower reverse stop, the force is lowest as the feeding cone is moving downwards for a longer time than the rest of the system. During the time of constant velocity the force is zero and at the higher reverse stop the force it is highest. The differences are approximately +/- 5N, which fits for the moved masses of 500g (feeding cone and feeding pole). This shows that the used easy theoretical approach is not sufficient to explain the conditions for the honing process. They must be extended to include the dynamic part. The lower part of Figure 10 shows the influence of the rotation, which overlays the oscillation and also must be considered.

Fig. 10. a) Cone force and oscillation during a no-load operation, b) Influence of the rotation on the cone force.

7. Conclusion and Outlook

The paper showed a theoretical approach for the honing process with an assumed inertia free system. The exemplary use of the formula for the moment shows high deviations from the measured signal. These deviations can be explained with the in reality not inertia free system. Oscillation and rotation must be included in a further improved model. The conducted experiments showed the tangential force ratio $\mu_h$ for a typical combination of workpiece material, honing stone and honing oil for the precision honing of small bores. The workpiece material was hardened steel; the honing stone had cutting grains made from CBN. The tangential force ratio is one of the needed parameters for the calculation. Further experiments will be needed to determine the other process parameters like the tangential force ratio for the guiding stones. An improved process model should be able to explain the relations between the cone force, the actual cutting force at the honing stone and the moment at the honed work piece. This can be used for the further development of a regulation for honing.

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