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Analysis of Different Surface Structures of Hard Metal Guiding Stones in the Honing Process

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Abstract

Honing is a precise abrasive machining process with high standards for the resulting form, dimension, and surface quality. Additionally, honing further improves geometrical tolerances of the machined workpieces, especially when compared to the drilling process. In order to achieve a high adherence it is essential that the honing tool and the workpiece interact accordingly. The following paper will describe the static and dynamic correlations of the process forces of a honing tool equipped with one honing stone and two guiding stones for bores with small diameters (less than 20 mm). When working with bores of such small diameters, a direct measurement of the process forces with an integrated sensor is usually difficult to realize. Therefore, a theoretical model will be used to calculate the process forces within the honing tool. Missing coefficients of friction or tangential force coefficients (TFC) within the system will be determined with the help of an external test bench. Moreover, guiding stones made of hard metal with two different types of surfaces will be investigated and then compared with conventional guiding stones. The following measurement results are based on a MATLAB® simulation calculating the forces of the honing and guiding stones.

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Keywords: Precision honing, Cutting force, Textured surface, Hard metal, Tangential force coefficient

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1. Introduction

In the future, production engineering will have to face new challenges concerning production accuracy which calls for a continuous optimization and advance of research. Honed bores applied in high-pressure injection pumps and the valve spool used in hydraulic systems are both examples where a high surface-finishing geometrical accuracy is needed in order to avoid an excessive system pressure. An important contribution can be made through the use of abrasive machining processes as they are able to create the smooth and precise surfaces required. Honing is an example of such an abrasive machining process. It is implemented in the precision machining of cylinder bores. The surface of a honed part is functional and ready for use. High-precision, cylindrically honed bores obtain a high exactness in form and dimension as well as a very low roughness, namely less than 1 µm. [1, 2]

The essential components of the honing tool are the honing stone and the two guiding stones which are made of super-hard composite materials. These components are then used together in accordance with the machining requirements. These super-hard composite materials are expensive as they usually include CBN or diamond abrasives. Honing stones serve to remove the materials of their counterpart, whereas guiding stones are applied to guarantee the stable rotation of the feeding cone. Within this context, the guiding stone should not have any cutting effect and should be only used as a supporting component. Hence, it is useful to find an alternative material in order to replace the super-hard composite materials as long as the new material can also meet the requirements of the mechanical properties. Taking into account the function of the guiding stone, the modification of surface structures could change the frictional performance of the guiding stones. The aim is to analyze the force distribution on the honing tool under different surface conditions, including the honing stone and guiding stones.

Hard metal is a material widely used for the fabrication of the cutting tools in the manufacturing industry. It combines adequate hardness and significant toughness, and its mechanical properties can be varied by different compositions of its hard phase (carbide) and its matrix (the binder) [3-5]. Laser machining, especially when using ultra-short pulse lasers, has been proven to be an efficient technique for the high-precision surface modification of hard metals in the micron range [6, 7]. Therefore, it is feasible to modify the hard metal surface using laser surface texturing to then use it as a potential supporting component in the honing process. Furthermore, this paper focuses on the investigation of a stable honing process regarding the forces on honing and guiding stones in order to optimize the honing tool and improve the machining process.

2. State of the Art

2.1. The honing process

Honing is a precise abrasive machining process. During the workpiece manufacturing, it is particularly used at the end of the process chain. It finishes surfaces so that they become functional and ready for use. During the mechanic workpiece load, the tasks of the functional surface are gliding, sealing and guiding. Therefore, high demands regarding form, dimension, and surface quality must be fulfilled. Mostly, the production tolerances lie within the submicron range with a high repeatability at the same time. The honing process is basically characterized by the following four features:

- Hole filling tool
- Cutting pads with bound abrasives
- Self-regulating system for coaxial machining
- Process kinematics [8]

The following paragraph refers to the long-stroke honing. The honing process includes the overlap of three movement components that take place simultaneously. The first one is the rotation movement in tangential direction, the second one an oscillating movement in axial direction and the third one a feed motion in radial direction. Figure 1 depicts the kinematic movements exemplified by a single honing tool with an abrasive honing stone and two guiding stones.

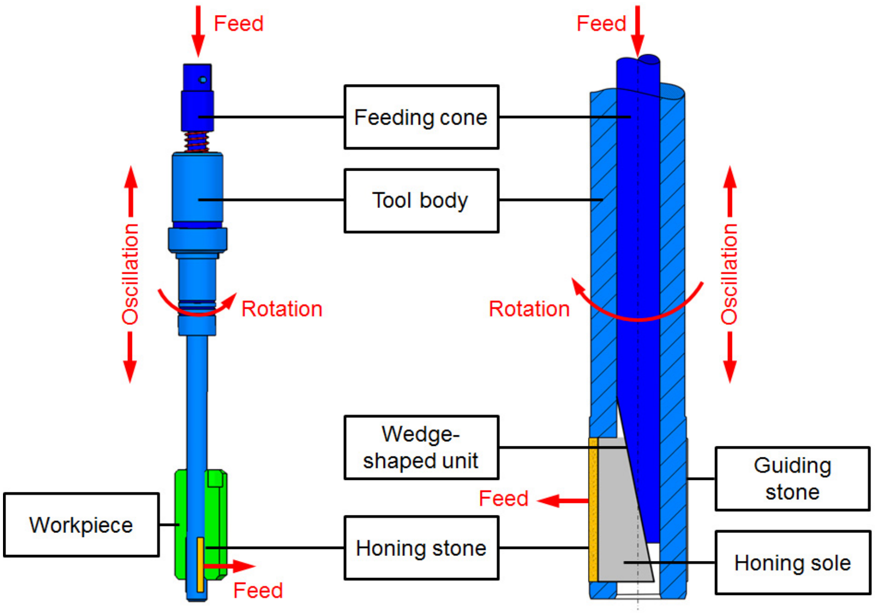

Fig 1. Single honing tool with one honing and two guiding stones [9]

As a result of the kinematic conditions a typical crosshatch with defined roughness properties appears on the honed surface. It needs to be stated that the material and contact ratio values are exceptionally good compared to other precision machining processes. [8]

2.2. The Honing Tool and the Description of System Forces

In addition to the process kinematics, figure 1 shows a setup of a single honing tool equipped with one honing stone and two guiding stones. Both consist of a steel base with an abrasive layer on top. The guiding stones have finer abrasive grains in a higher concentration as they are only supposed to guide the tool into the bore and not to contribute to the material removal process. Depending on the machined material, the concentration of the abrasive grains and the binder has to be adjusted on a special application. The concentration of the binder has a high influence on the cutting behavior as it fixes the cutting grains and releases them as soon as they are blunt. Generally, it can be distinguished between conventional (e.g. silicon carbide; SiC or corundum; Al_2O_3) and high hardness (e.g. Diamond or Cubic Boron Nitride; CBN) abrasives. In the process the metallic, ceramic and resinoid binder are usually used. The feed motion of the honing stone results in the material removal. The axial input force which is generated by the electro-mechanical feed motion control system is forwarded through the wedge-shaped contact surface in radial direction towards the honing stone. Typical removal thicknesses lie within 10-150 µm per honing operation. [8].

In the following the interaction of the honing stone and the two guiding stones will be explained. Figure 2 shows the honing system for a single honing tool in regard to the occurring radial and tangential forces. The honing stone and the two guiding stones are arranged in angles ε and δ.

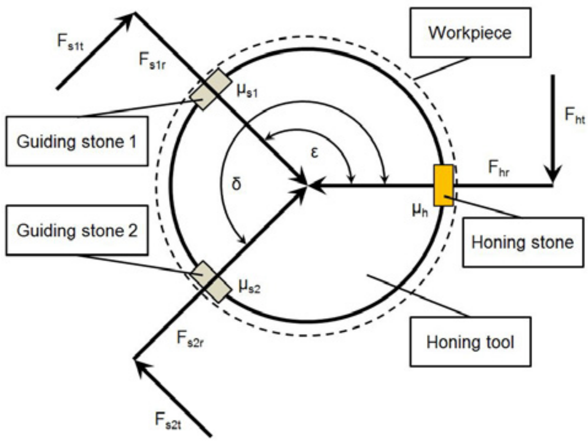

Fig. 2. The honing system for a single honing tool equipped with one honing stone and two guiding stones [10]

The tangential force components F_{ht}, F_{s1t} and F_{s2t} exhibit a certain ratio to the radial force components F_{hr}, F_{s1r} and F_{s2r} [10].

Scientific studies have shown that there is a proportional correlation between the tangential and radial force components. Wanninger [11] describes this ratio as coefficient of friction, whereas von Saljé and von See [12] refer to it as tangential force coefficient (TFC). This constant coefficient is said to depend on the characteristics of the honing stone, the workpiece as well as the used cutting fluids. The mathematical equation for the honing stone is the following [10]:

$$\mu_h = \frac{F_{ht}}{F_{hr}} \tag{1}$$

The same correlation can be assumed for the two guiding stones [10]:

$$\mu_{s1} = \frac{F_{s1t}}{F_{s1r}}, \quad \mu_{s2} = \frac{F_{s2t}}{F_{s2r}} \tag{2, 3}$$

In case of two identical guiding stones, the TFC would be the same ($\mu_{s1} = \mu_{s2} = \mu_s$). In addition, all tangential and radial force components can be estimated through the balance of forces in the honing tool. The radial direction is defined as [10]:

$$F_{hr} = -F_{s1r} * \cos(\epsilon) + F_{s1t} * \sin(\epsilon) - F_{s2r} * \cos(\delta) + F_{s2t} * \sin(\delta) \tag{4}$$

The tangential direction is defined as [10]:

$$F_{ht} = -F_{s1r} * \sin(\epsilon) - F_{s1t} * \sin(\epsilon) - F_{s2r} * \sin(\delta) + F_{s2t} * \cos(\delta) \tag{5}$$

In order to solve the system of equations of forces, one equation still needs to be identified. This is why the following paragraph will focus on the power transmission from the feeding cone to the honing stone. A simple geometrical model described by Flores [13] is based on the transfer ratio. The radial force component of the honing stone F_{hr} is defined as the quotient of the cone force F_k and the cone angle φ:

$$F_{hr} = \frac{F_k}{\varphi} \quad (6)$$

Moreover, Zettel [14] and Mushardt [15] consider the amounts of friction in the power transmission system between feeding cone and honing stone and add the coefficient of friction μ_{tool} to the equation system. The calculation of the balance of forces, the power transmission system in regard to the cone force F_k and cone angle φ is defined as:

$$F_{hr} = \frac{F_k * (\cos(\varphi) - 2\mu_{tool} * \sin(\varphi))}{\sin(\varphi) + \mu_{tool} * \cos(\varphi)} \quad (7)$$

2.3. Guiding Stones with Different Surface Structures

The guiding stones used in the honing process are also composites of fine super-hard abrasives and mainly applied to support the rotation of the feeding cone. Hence, the materials of the guiding stone should possess an adequate hardness and significant toughness. Low friction and high wear resistance are considered to be two significant factors to evaluate the performance of guiding stones. Sometimes it can be observed that the split grain particles damage the machined surface of workpieces. In regard to cost function, hard metal often referred to as cemented carbide, can be an alternative material for guiding stones since it meets not only the economical, but also the performance requirements.

Cemented carbide is a refractory material often used for cutting tool fabrication which combines excellent hardness and toughness, and usually consists of the hard phase and the binder. It may refer to tungsten carbide (WC), titanium carbide (TiC), or tantalum carbide (TaC). Tungsten carbide (WC), however, is most commonly used in the manufacturing industry. The mechanical properties of hard metal can be adjusted by changing the composition of the mixtures. In this study, a cemented carbide grade was implemented as a potential alternative for the guiding stone [16]. The used WC-CoNi cemented carbide has the grain size of 20 µm. WC grains account for about 72 wt% of the material, whereas the binder accounts for 28 wt% of the material, as shown in table 1. The hardness of this cemented carbide grade is 610HV30, and is therefore considered as a soft hard metal in the cemented carbide family.

Table 1. WC-Co hard metal properties

Material	**WC Grain Size (µm)**	**Co (wt%)**	**Ni (wt%)**	**Density (g/cm^3)**	**Hardness (HV30)**
VN77	20	14	14	12.82	610

During the experiments two types of structures, namely polished and dimpled ones, were produced on the cemented carbide surfaces, as can be seen in figure 3. The dimples on the cemented carbide were fabricated on the cemented carbide surfaces using an ultra-short pulse laser [16]. The Nd:YVO_4 picosecond laser system is integrated in a high-precision 5-axis laser micromachining system which has a movement accuracy of ±1µm and a maximum axis speed of 2m/s. The used laser beams have the wavelength of 532 nm, the pulse duration of 10 ps, and the fluence of 0.5 J/cm². The produced dimples are arranged in an array with identical distances of about 500 µm and have a diameter of 50 µm and a depth of 3.8 µm. Meanwhile, a conventional guiding stone made of diamond composite was also tested as reference case.

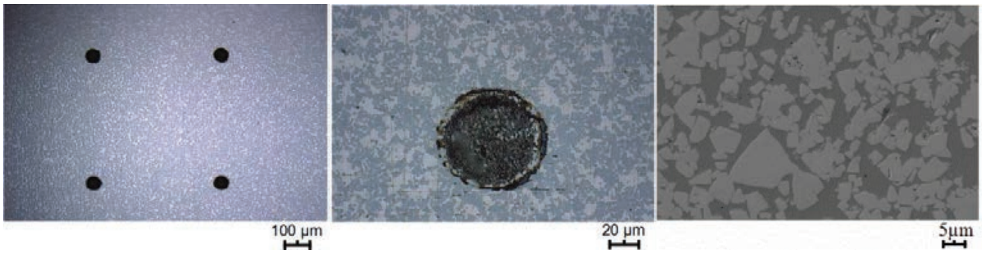

Fig. 3. LSM images and cross-sectional plots of geometrical properties of cemented carbide surface patterns: (a) arrangement of dimples, (b) single dimple, (c) polished surface

3. Experimental Results

In order to systematically analyze the different parameters and their impact on a single honing tool within the abrasive processes, an in-house test bench was constructed [17]. The concept, design, and application of the test bench are based on the conditions occurring during the process of external honing. This test bench is generally employed for the analysis of the influencing parameters during the abrasive machining process. It measures the process forces, and can also be implemented as a tribometer to evaluate the frictional performance of functional surfaces (Figure 4 (a)).

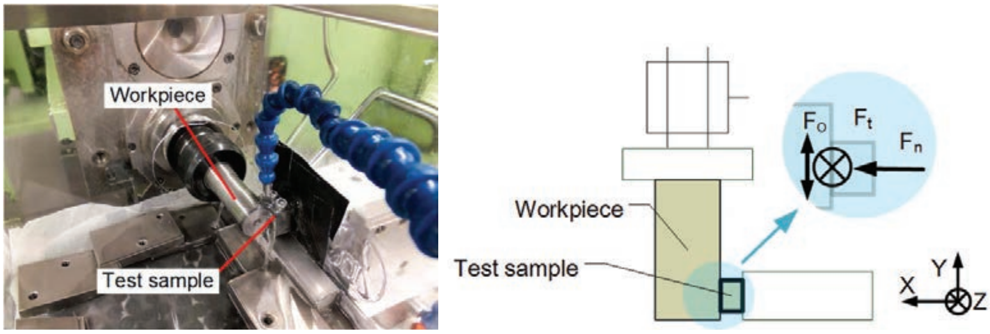

Fig. 4. (a) In-house test bench for abrasive machining processes, (b) Kinematics in the abrasive machining process

The testing processes consist of three independent movements: the rotation movement, the oscillation movement of the workpiece, and the longitudinal feed motion of the tool. The three independent movements generate the cutting force between the test tool and the workpiece. The latter can be decomposed via three orthogonal forces corresponding with the movements mentioned above (Figure 4 (b)):

F_n: Normal force along the x-axis produced by the tool feed
F_t: Tangential force along the y-axis produced by the workpiece rotation
F_o: Oscillation force along the z-axis produced by the workpiece oscillation

Knowing the normal force F_n and the tangential force F_t, TFC can be calculated with the following equation (8) [12, 18]:

$$TFC = \mu = \frac{F_t}{F_n} \quad (8)$$

Two different surface patterns with determined geometrical properties on the micrometer scale (dimpled and polished surface) were tested under the conditions displayed in table 2. The test tools are made of WC-CoNi hard metal with the dimensions of 20×3×4.95 mm³. The counterpart (workpiece), which is made of steel, has a rotation speed of 500 r/min (i.e. 40 m/min), and an oscillation speed of 1000 mm/min. The working surfaces of the test counterparts had been pre-machined to meet the required roughness (R_a < 0.1 µm). Kadiol 50 with the viscosity of 5 mm²/s was used as lubricant.

Table 2. Machining parameters set for the workbench

Rotation speed (r/min)	**Oscillation speed (mm/min)**	**Oscillation number**	**Feed (µm)**	**Lubrication viscosity (mm^2/s)**
500	1000	10	2	5

The tests on these two surface structures were then conducted with a standard force of 70 Newton. The results have shown that the dimpled surface obtained a TFC of 0.17, whereas the polished surface had a TFC of 0.19. The tangential force coefficient for the combination of the honing stone, workpiece material and cutting fluid, respectively used with conventional guiding stones, had been determined in previous experiments [10].

4. Simulation Results

The MATLAB® Version R2016a from MathWorks was used to create the simulation. The aim of the simulation is to calculate the mathematical formulas with the help of a computer. This measurement technique allows recording the cone force F_k as a matrix with two column vectors. The first column vector indicates the time steps and the second vector the corresponding cone forces. Formulas (6) and (7) describe the correlation between the feeding cone and the honing sole. The following calculation includes the friction within the power transmission system. By using formulas (7) and (1), the vectors F_{hr} and F_{ht} can be added to the solution matrix. The formulas (2)–(4) describe a mathematical system with four equations and the four unknown forces F_{s1r}, F_{s2r}, F_{s1t} and F_{s2t}. The solutions of the linear system of equations are completed by this specific solution matrix.
The following calculation is based on a generated cone force vector F_k with eleven different values from 0 to 200 N (see x-axis in Figure 5) presenting a standard honing process.
The coefficient of friction μ_{tool} as well as the geometrical parameters of the honing tool such as ε (angle of the first guiding stone), δ (angle of the second guiding stone) and φ (cone angle) are fixed. The focus of this paper is the characterization of three different guiding stones. First, the simulation begins with conventional guiding stones, and is followed by the two hard metal guiding stones with defined surface textures characterized in section 2.3. The list of parameters used during the MATLAB® Simulation is shown below in table 3.

Table 3. Parameters of the MATLAB® Simulation

Parameter	Value
Cone force [N]	0 … 200
Cone angle [°]	2.5
Coefficient of friction μ_{tool}	0.11
Angle ε [°]	125
Angle δ [°]	225
TFC of the honing stone	0.192
TFC of the conventional guiding stone	0.101
TFC of the polished guiding stone	0.19
TFC of the dimpled guiding stone	0.17

The following figure 5 illustrates the radial and tangential forces of the honing system for the honing stone and the three different guiding stones. The radial and tangential forces of the honing stone are defined by the cone force, cone angle and coefficient of friction (μ_{tool}).

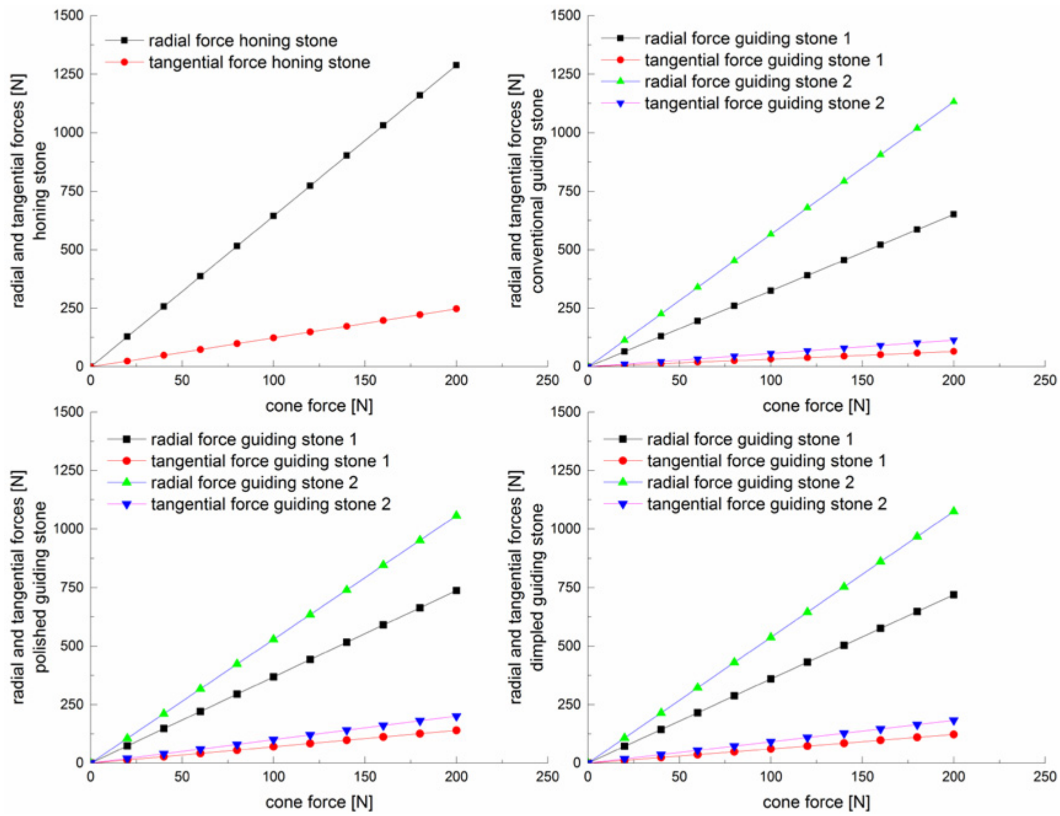

Fig. 5. Calculated forces of the MATLAB® simulation

The radial force is five times higher than the tangential force (top left). This outcome should be paid close attention to as it is an important factor in the control of the removal process during honing. The higher the cone angle is, the more the radial force decreases, whereas the tangential force increases given a constant cone force. In general, the MATLAB® simulation shows that, in the honing system, the tangential forces are lower than the radial ones in regard to the honing and guiding stones. The three remaining figures characterize forces of the conventional guiding stones (top right) as well as the forces of the two hard metal guiding stones (bottom left and right). The force ratio between guiding stone one and two of the honing tool shows different force values. In all three cases, the force values of the guiding stone two are twice as big as the force values of guiding stone one. This is due to the geometrical setup of the honing tool. The industrial production confirms the fatigue limit of guiding stone two. The basic goal is the investigation of the force ratios within the tool system in order to improve the duration of the forces relating to the honing stone. By using hard metal guiding stones, the maximum forces on the second guiding stone can be reduced. However, the difference between the polished and dimpled guiding stones is insignificantly small.

For further investigations, the radial and tangential forces of the three different guiding stones were examined separately (figure 6). Both figures show the force difference between the guiding stone one and two with respect to radial and tangential force components. By using hard metal guiding stones, the force difference in radial direction can be reduced in order to adapt the friction and lubrication between the honing and guiding stones as well as the workpiece. Additionally, the comparison of the polished and dimpled guiding stones reveals slight differences in the force values. In contrast to the radial force component, the tangential force component increases using hard metal guiding stones in order to adjust the balance of forces in the honing tool. Generally, the force differences of the tangential components are smaller than the ones of the radial components.

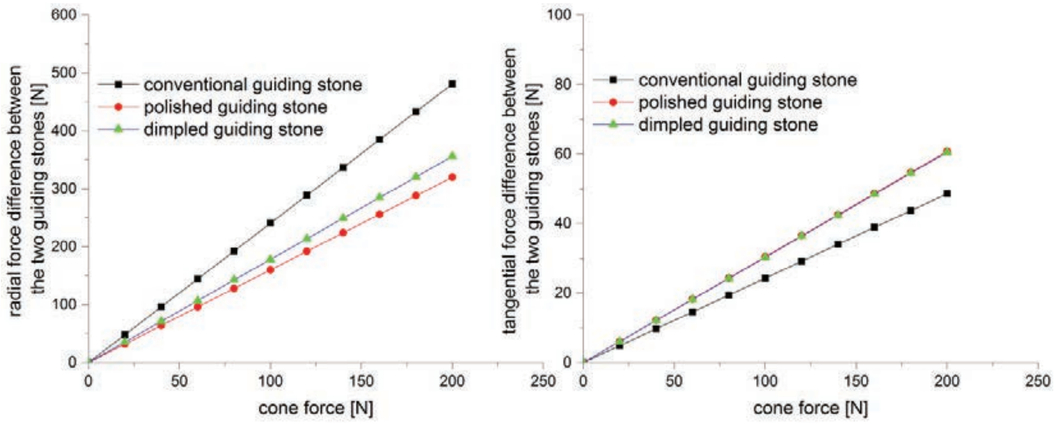

Fig. 6. Force differences between the two guiding stones (left: radial; right: tangential); nearly identical tangential force paths for the two hard metal stones

5. Conclusion and Outlook

In this paper a dynamic theoretical model of the honing process has been implemented to investigate the force distribution on the honing stone and two guiding stones. Three different types of guiding stones, namely a conventional guiding stone, a hard metal guiding stone with a polished surface, and a hard metal guiding stone with a laser textured surface, were compared in regard to their force distributions on the two cooperating guiding stones, aiming towards the optimization of stability in the honing process. It has been found that:

- The hard metal guiding stones can effectively improve the stability of the honing tool compared to the conventional guiding stone. This is due to the fact that the difference of the radial forces between the two hard metal guiding stones is much smaller than the one between the conventional guiding stones.

- Only slight radial force differences were observed between the polished and textured hard metal guiding stones. This suggests that both the polished and dimpled hard metal guiding stones can achieve similar results in regard to process stability.

The results of the simulation regarding the polished and dimpled hard metal guiding stones are similar, which will enable us to further improve the honing system in the future. However, other tribo-mechanical properties of hard metal surfaces need to be investigated more closely in order to evaluate their performances. Especially the surface integrity and wear resistance of the laser-produced surface structures should be assessed with regard to the long-term system stability.

References

[1] Bähre D. and Schmitt C., 2010. Analysis of Forces and Process Behaviour During the Honing of Bores. In: Proc. of the *CIRP Conference on High Performance Cutting*.

[2] Schmitt C. and Bähre D., 2013. An Approach to the Calculation of Process Forces during the Precision Honing of Small Bores. In: Proc. of the 46th *CIRP Conference on Manufacturing Systems*.

[3] Wolfe T. A., Jewett T. J. and Singh Gaur R. P., 2014. Powder Synthesis. In: *Com-prehensive Hard Materials.*

[4] Casas B., Wiklund U., Hogmark S. and Llanes L., 2008. Adhesion and Abrasive Wear Resistance of TiN Deposited on Electrical DischargeMmachined WC-Co Cemented Carbides. In: *Wear, Vol. 265, no. 3–4.*

[5] Exner H. E., 1979. Physical and Chemical Nature of Cemented Carbides. In: *Int Met Rev, Vol. 24, no. 1.*

[6] Li T., Lou Q., Dong J., Wei Y. and Liu J., 2001. Selective Removal of Cobalt Binder in Surface Ablation of Tungsten Carbide Hardmetal with Pulsed UV Laser. In *Surf Coat. Technol*. 145.

[7] Dumitru G., Lüscher B., Krack M., Bruneau S., Hermann J. and Gerbig Y., 2005. Laser Processing of Hardmetals: Physical Basics and Applications. In: *Int. J. Refract. Met. Hard Mater 2.*

[8] Klink U.,2016. Honen Umweltbewusst und Kostengünstig Fertigen. Carl Hanser Verlag, München, Germany (only avaible in German, translated title: "Honing Environmentally Conscious and Cost-Effective Manufacturing").

[9] Klein S., Forsch K., Maier R., Brandstetter J., Klein H., Bähre D., 2016. Untersuchung des Kinematischen Verhaltens beim Präzisionshonen von Bohrungen. In: Jahrbuch Schleifen Honen Läppen und Polieren, 67. Ausgabe , Vulkan Verlag, Essen (only avaible in German, translated title: "Investigation of the Kinematic Behavior During the Precison Honing of Bores, In: Yearbook Grinding, Honing, Lapping, and Polishing").

[10] Schmitt C. and Bähre D., 2014. Analysis of the Process Dynamics for the Precision Honing of Bores. In: Proc. of the 47th *CIRP Conference on Manufacturing Systems*.

[11] Waninger G., 1952. Bewegungsvorgänge und Kraftgrößen beim Feinhonen und die Entwicklung der Geräte. *Ph.D Thesis*, TU Aachen. (only avaible in German, translated title: "Movements and Force Components of the Fine Honing Process and the Development of the Devices").

[12] Saljé E. and von See M., 1987. Process-Optimization in Honing. In: *Annals of the CIRP*, Vol. 36/1.

[13] Flores G., 1992. Grundlagen und Anwendungen des Honens. Vulkan Verlag, Essen (only avaible in German, translated title: "Basics and Applications of the Honing Process").

[14] Zettel H.-D., 1974. Abtragssteigerung und Formverbesserung beim Langhubhonen. *Ph.D Thesis*, Universität Karlsruhe. (only avaible in German, translated title: "Increase of Material Removal and Form Improvement for Long-Stroke Honing").

[15] Mushard H., 1986. Modellbetrachtungen und Grundlagen zum Innenrundhonen. *Ph.D Thesis*, TU Braunschweig. (only avaible in German, translated title: "Model Analysis and Basics for Long-Stroke Honing").

[16] Fang S., Herrmann T., Rosenkranz A.,. Gachot C., Marro F. G., Mücklich F., Llanes L. and Bähre D., 2016. Tribological Performance of Laser Patterned Cemented Tungsten Carbide Parts. In: *Procedia CIRP, vol. 42.*

[17] Bähre D., Fang S., Gliche J. and Trapp K., 2014. Set-Up of a Test Bench for the Investigation of Single Parameter Effects in Abrasive Processes by Force Measurements In: *Adv Mater Res, Vol. 1052.*

[18] Hoffmeister H. W. and Menze B., 2004. Einsatz von Sensorik beim Honen und Regelung von Honprozessen. In: Jahrbuch Schleifen Honen Läppen und Polieren, 61. Ausgabe, Vulkan Verlag, Essen (only avaible in German, translated title: “Use of Sensors for Honing and Control of Honing Processes”, In: Yearbook Grinding, Honing, Lapping and Polishing”).