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METHOD OF THE ENVIRONMENTALLY FRIENDLY DRY SINGLE-PASS HONING WITH USE OF THE SUPERIMPOSED LOW FREQUENCY OSCILLATIONS

Single-pass honing is used as a finishing process to meet high demands regarding form and dimensional accuracy of drilled holes. The disadvantages of single-pass honing compared to the conventional long-stroke honing are high process forces and torques as well as an increased risk of chip space clogging of the abrasive stones. Following this, the oscillation-superimposed single-pass honing without cutting fluid has been conducted in this work, which is promising when it comes to the environmentally friendly improvement of machining processes. It was shown that the omitted lubrication and flushing effect of the contact zone between the tool and the workpiece could be compensated with the aid of the superimposed oscillations. The process forces of the dry honing process are up to 37% lower compared to the conventional process, the height of the surface profile Rz decreases by 33% and the form deviations decrease up to 47%. Hence, the new method allows the saving of resources, while improving the work results.

1. INTRODUCTION

The use of cutting fluids in machining processes provides cooling and lubrication of the workpiece and the tool as well as the removal of the chips. Compared to other machining processes, honing requires the use of high volume flows for flushing and lubrication, while the cooling effect is less important due to low cutting speeds [1]. However, cutting fluids are a pollutant for health and environment. Apart from that, the application of cutting fluids is accountable for up to 17% of the machining costs [2]. Therefore, recent developments in research and industry aim for minimizing or eliminating the use of cutting fluids. In turning and milling of cast iron, steels, aluminium alloys and non-ferrous metals, it is already state of the art to dispense the cooling lubrication in many process windows. Sarikaya et al. emphasize the need for sustainable cooling and lubrication systems like Minimum Quantity Lubrication (MQL), nanofluids-MQL, Ranque-Hilsch vortex tube (RHVT) + MQL, and

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cryogenic-MQL as alternatives to flood cooling for cutting light-weight materials, offering improved heat transfer, lubrication, and sustainable implementations [3]. Krolczyk et al. analysed ecological trends in machining difficult-to-cut materials and propose sustainable approaches such as dry cutting, MQL, cryogenic cooling, high-pressure coolant, and biodegradable vegetable oils. The aim was to reduce pollution and improve machining processes, considering factors like cost reduction, lower cutting force, energy consumption, temperature, enhanced surface quality, material removal, and tool life, while considering qualitative aspects like human health, atmospheric impact, and chip removal, providing valuable insights for future research on machining sustainability [4]. Singh et al. examined various cooling and lubrication methods and summarizes the advancements in eco-friendly and cost-effective machining, including the use of nano-fluids, ionic liquids, and biodegradable oil, as well as hybrid machining, to efficiently process harder materials at higher speeds [5]. Weinert et al. reviewed modern cutting technologies using dry machining and MQL with regard to the workpiece material application of tool coatings as well as adapted tool designs and machining strategies [6].

Nomenclature

Aa	Amplitude in axial direction
$A_{a,max}$	Maximum amplitude in axial direction
$aa,_{max}$	Maximum acceleration of the machine axis
di	Inner diameter of the workpiece
e_c	Specific honing energy
f_a	Oscillation frequency in axial direction
f_G	Straightness deviation
f_R	Circularity deviation
$F_{t,m}$	Mean tangential force
f_Z	Cylindricity deviation
V_w	Volume of removed material
$v_{a,const}$	Constant velocity in axial direction
v_c	Cutting speed
$v_{\mathrm{cf,const}}$	Constant velocity in circumferential direction
w	Width of honing stones
W_a	Work performed in axial direction
W_t	Work performed in tangential direction
Rk	Core roughness depth
Rpk	Reduced peak height
Rvk	Reduced valley depth
Rz	Maximum height of the surface profile
sa(t)	Time dependent path in axial direction
t	Processing time
zc	Workpiece circumference
zh	Height of workpiece
zu	Unrolled cylinder periphery
α	Cross hatch angle
α_{dyn}	Dynamic cross hatch angle
β	Cone angle of the honing tool
Δd	Diametral stock allowance
$\tilde{\nu}_{\mathrm{a,dyn}}$	Dynamic wavenumber in axial direction
φ	Volume concentration

Chinchanikar et al. explored nanofluids in minimum quantity lubrication (MQL) machining and their effect on process performance, showing that certain nanofluids and hybrid nanofluids impart superior lubrication and cooling effects [7].

In turning and milling operations, the process parameters are primarily determined by considering the thermal load of the workpiece and the tool. By that, the lack of cooling capacity does not have a critical effect on tool life and machining accuracy [1]. Due to the lower importance of cooling during honing, it can be expected that negative effects resulting from thermal load are negligible within this machining process. In contrast, due to the use of a multi-bladed, bore-filling tool, a sufficient chip removal from the contact zone between the tool and the workpiece has to be ensured during the honing process. Especially in the single-pass honing which is characterized by the use of a honing tool with a diameter fixed to the desired dimension before machining, the material removal rates are higher compared to the common longitudinal stroke honing. Hence, cutting fluids with high volume flows are necessary to remove the chips.

Superimposed oscillations in ultrasonic frequency regions are commonly used for single-pass honing processes. Initially an increase of the maximum cutting speed v_c and thus, the increase of the removal rate was the aim of superimposing ultrasonic oscillations for single-pass honing processes [8, 9]. Furthermore, superimposed ultrasonic oscillations facilitate the guidance of removed material along the tool surface which improves the surface quality of the machined workpiece [10].

Mansori et al. investigated the impact of dynamic effects during the honing process on engine cylinder bore surface textures, demonstrating that higher stone accelerations can improve form quality and reduce cycle time while maintaining dimensional accuracy, facilitated by a micro scale regeneration mechanism of abrasive stones [11]. Baby et al. conducted experiments on the impact of varying honing angles on cylinder liner surface performance under boundary lubrication, revealing that using a linear reciprocating tribometer at sliding conditions of 0.2 m/s and 0.3 m/s establish an optimal cross hatch angle of $\alpha = 40°$ through assessment of tribological traits including coefficient of friction and wear [12]. The research of Bo et al. covered the ultrasonic ductile-regime honing of ZrO_2 engineering ceramics using a new-type machine and compared results with conventional honing, revealing shallower grooves in ultrasonic grinding, wider grooves at the bottom close to ultrasonic wave amplitude, shallower and layered fractures on ultrasonically honed surface, concentrated fractures at groove boundaries in ultrasonic honing but at groove bottoms and boundaries in conventional honing, minimal chap cracking on ZrO_2 surface for both methods but more in conventional honing, occasional extensive trans-crystalline rupture cracks at the periphery of the damage area in ultrasonic honing [13]. Ultrasonic assisted honing however demands tools, which fulfil the resonance condition [14].

For single-pass honing, it has recently been shown that chip removal is improved by superimposing low frequency oscillation and that machining forces are significantly reduced as a result, without causing a decrease in the quality of the work results regarding cast iron EN-GJL-250 [15] and long-chipping steel E295 [16]. Based on the preceding findings, the main purpose of the presented research is to assess the feasibility of a dry single-pass honing process through superimposing low frequency oscillations as well as the evaluation of the resulting process parameters and work results on an industrial scale.

2. SUPERIMPOSING LOW FREQUENCY OSCILLATION

During the single-pass honing process, a cylindrical guideway section secures the insertion of the tool into the workpiece. The material removal V_w is primarily performed by the conical cutting section. A smoothing of the machined surface is achieved by the cylindrical calibration section. The conventional single-pass honing process yields helical honing marks on the workpiece surface which result from the combination of a constant velocity in axial direction $v_{a,\mathrm{const}}$ and a constant velocity in circumferential direction $v_{cf,const}$. Superimposing low frequency oscillations by adding a dynamic velocity component in axial direction changes the pattern of the honing marks. Depending on the applied set of oscillation parameters, a cross hatched surface like a longitudinal stroke honing process can be observed [17]. This surface pattern increases the oil containment potential of the surface and hence improves tribological properties of functional surfaces [18].

To implement the oscillation within the machine control, the tool motion is explicitly defined via the addition of the constant velocity in axial direction $v_{a,const}$ with a dynamic term as shown in Eq. 1 [15].

$$s_a(t) = v_{a,const} \cdot t + A_a \cdot \sin\left(2 \cdot \pi \cdot f_a \cdot t\right) \tag{1}$$

The time dependent path in axial direction $s_a(t)$ is influenced by the oscillation amplitude in axial direction A_a and the oscillation frequency in axial direction f_a. The range of the possible combinations of the oscillation amplitude in axial direction A_a and the oscillation frequency in axial direction f_a is limited by the machine specifications. Depending on the executing machine axis, its maximum acceleration $a_{a,max}$ must be considered. For choosing a specific oscillation frequency in axial direction f_a, the maximum acceleration $a_{a,max}$ is used to derive the corresponding maximum amplitude $A_{a,max}$ as presented in Eq. 2 [15]. Therefore, the choice of high frequencies f_a allows only a small maximum amplitude $A_{a,max}$ and vice versa.

$$A_{a,max}\left(f_a\right) = \frac{a_{a,max}}{\left(2 \cdot \pi \cdot f_a\right)^2} \tag{2}$$

To further characterize the process, the dynamic wavenumber in axial direction $\tilde{\nu}_{a,dyn}$ and the dynamic cross hatch angle α_{dyn} are introduced. The dynamic cross hatch angle α_{dyn} describes the range of the cutting vector angles acting on an individual grain and is similar to the cross-hatch angle α of the conventional longitudinal stroke honing, Fig. 1a. Within this range, the distribution of the directions regarding the forces acting on an individual grain for one oscillation period depends on the set of process and oscillation parameters.

A more regular distribution of force directions acting on an individual grain increases the removal of workpiece material adhering to that grain at the contact zone [15]. Referring to the conventional cross hatch angle α, a high dynamic cross hatch angle α_{dyn} can increase the tool wear [1].

Equation 3 defines the dynamic wavenumber in axial direction $\tilde{\nu}_{a,dyn}$ as a function of the workpiece circumference z_c, the oscillation frequency f_a and the constant velocity in circumferential direction $v_{cf,const}$ [15]. It describes the number of oscillation periods per full rotation of the honing tool due to the proportionality to the oscillation frequency f_a.

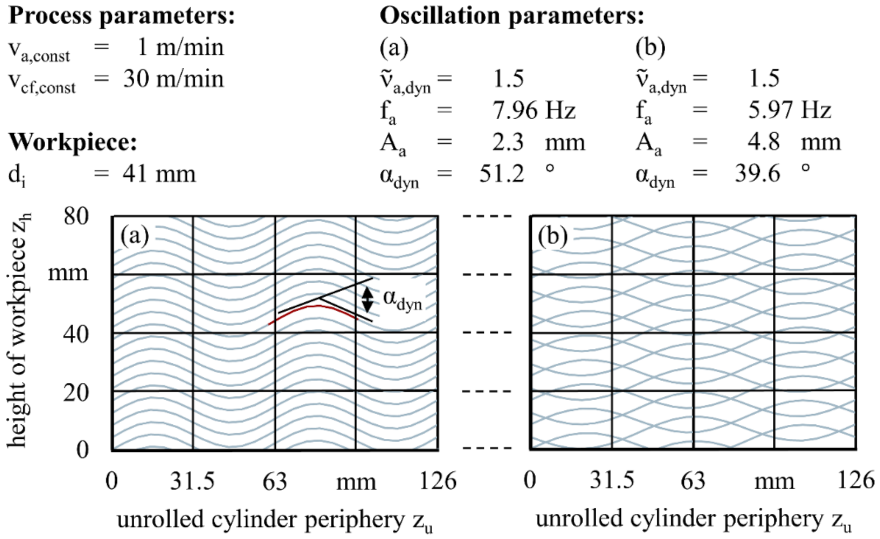


Fig. 1. Path of a single grain on the unrolled surface of a workpiece for different dynamic wavenumbers in axial direction $\tilde{v}_{a,dyn}$; (a) integer value of $\tilde{v}_{a,dyn}$; (b) decimal value of $\tilde{v}_{a,dyn}$ [15]

$$\tilde{v}_{a,dyn} = \frac{f_a \cdot z_c}{v_{cf,const}} \tag{3}$$

Depending on the constant velocity in circumferential direction $v_{cf,const}$, the axial frequencies f_a can be chosen in order to set the dynamic wavenumber in axial direction $\tilde{v}_{a,dyn}$ as an integer value. Hence the trajectories of an individual grain are running parallel on the workpiece surface, Fig. 1a. Frequencies corresponding to decimal values of the dynamic wavenumber in axial direction $\tilde{v}_{a,dyn}$ however cause trajectories to overlay each other, Fig. 1b. A higher rate of overlaying trajectories can have a subsequent influence on process behaviour, surface quality and form accuracy [17].

In contrast to the conventional single-pass honing process, superimposing oscillations cause a fluctuation of the process forces. Therefore, the methodology of former research is followed, and the investigation uses the mean values of the process forces [15]. On that account, the specific honing energy e_c is introduced which gives a simplified representation of the time dependent process forces. As depicted in Eq. 4, the specific honing energy e_c corresponds to the work performed in axial direction W_a, the work performed in tangential direction W_t and the removed material V_w.

$$e_c = \frac{W_a + W_t}{V_w} = \frac{\int_0^{s_a} |F_a ds_a| + \int_0^{s_u} |F_t ds_u|}{V_w} \tag{4}$$

3. EXPERIMENTAL SETUP

To investigate the influence of oscillation parameters on the process behaviour, the surface quality as well as the form accuracy for cast iron, series of experiments are conducted. In each series, the grain size D151, regarding the FEPA standards, in a metallic bond are used.

Honing stones with a width of $w = 4$ mm and a cone angle of $\beta = 0.06°$ are selected for the test series. Each experiment is carried out three times. The investigations are conducted solely for the initial working stroke. Therefore, the used single-pass honing tool, TH41-0/125-330-VH from PWG Präzisions-Werkzeugbau Geißler GmbH, Leutkirch, Germany, have no cylindrical calibration section, Fig. 2. Workpieces made of cast iron EN-GJL-250 with a maximum height of the surface profile $\mathrm{Rz} = 6.8$ µm, an inner diameter of $d_i = 41$ mm and a height of $z_h = 75$ mm are used.

Fig. 2. Single-pass honing tool TH41-0/125-330-VH from PWG Präzisions-Werkzeugbau Geißler GmbH, Leutkirch, Germany

The experiments are performed on the 5-axis milling machining center LPZ 900 from MAP Werkzeugmaschinen GmbH, Magdeburg, Germany. It is equipped with highly dynamic linear drives and is therefore suited for superimposing low-frequency oscillations. The CNC control system is a Sinumerik 840D sl from Siemens AG, München, Germany. The performance data of the machining center relevant to the investigations are listed in Table 1.

Table 1. Performance data machining center MAP LPZ 900

Linear drives (Direction X, Y, Z)	Unit	Value	
Maximum Speed	m/min	120	
Maximum acceleration	m/s^2	12	
Main spindle			
Maximum rotational speed	1/min	18.000	
Maximum acceleration	U/s^2	300	
Maximum output	kW	28	

As coolant, an emulsion with a volume concentration of $\varphi = 5$ vol.% of Adrana A 401 is applied via internal cooling through the tool. Process forces are measured with the 6-component dynamometer K6D110 from ME Meßsysteme GmbH, Hennigsdorf, Germany, while the matching displacement signals of the machine axes are recorded, Fig. 3. If the maximum torque of the machine spindle is exceeded for a parameter set, the series of that parameter set will be aborted.

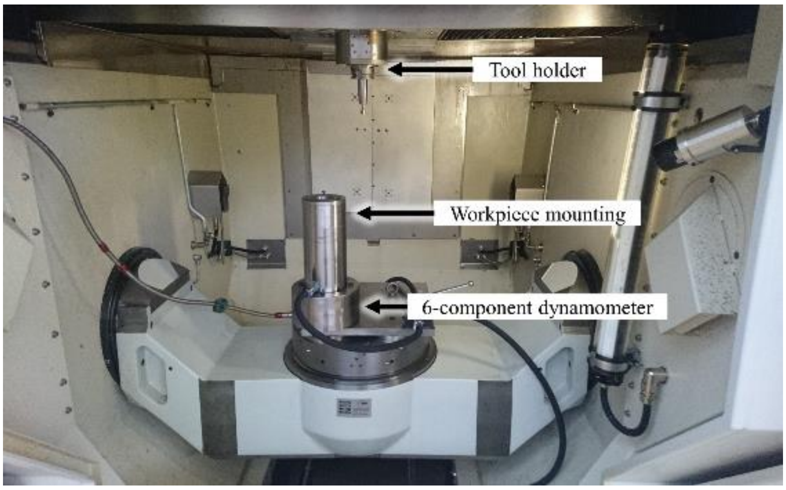


Fig. 3. Experimental setup within the milling machining center LPZ 900 from MAP Werkzeugmaschinen GmbH, Magdeburg, Germany

4. RESULTS

The displayed results of the comprehensive investigation focus on two key aspects. At first, the impact of superimposed oscillations in axial directions on honing ledge topography and tool wear is analysed, revealing a significant reduction in specific honing energy and improved cutting capability. Microscopic analysis confirms the effectiveness of oscillations in minimizing workpiece material accumulation. Subsequently, the characteristics and benefits of dry honing processes, including process behaviour, surface quality, and form accuracy. These findings highlight the potential of superimposed oscillations and dry machining techniques in honing operations. is explained how the effects enable dry honing processes.

4.1. INFLUENCE OF SUPERIMPOSED OSCILLATIONS IN AXIAL DIRECTION

In order to analyse the influence of the oscillation on the honing ledge topography and the tool wear, several workpieces are machined in succession with the same process parameters. The development of the specific honing energy e_c with increasing material removal V_w in processes with and without superimposed axial oscillations are shown in Fig. 4. It can be observed that the specific honing energy e_c for the process with superimposed oscillations is between 50 and 67% lower than the conventional process with a mean value of $e_c = 44.2\ \frac{\mathrm{J}}{\mathrm{mm}^3}$, which is consistent with previous results [10, 11].

Furthermore, the specific honing energy e_c of the conventional process without superimposed oscillations predominantly rises from $e_c = 29.6\ \frac{\mathrm{J}}{\mathrm{mm}^3}$ to $e_c = 50.1\ \frac{\mathrm{J}}{\mathrm{mm}^3}$with increased material removal V_w. In addition, by exceeding a material removal of $V_w = 730\ \mathrm{mm}^3$ fluctuations up to 11% can be observed. After the consecutive machining of a material removal of $V_w = 2828\ \mathrm{mm}^3$, the maximum torque of the machine spindle was exceeded, which meant that this series of tests had to be aborted. In contrast, the specific honing energy e_c of the process with superimposed oscillations remains almost constant with increased material removal V_w and only marginal fluctuations at a material removal of $V_w = 504\ \text{mm}^3$ and $V_w = 1710\ \text{mm}^3$ occur.

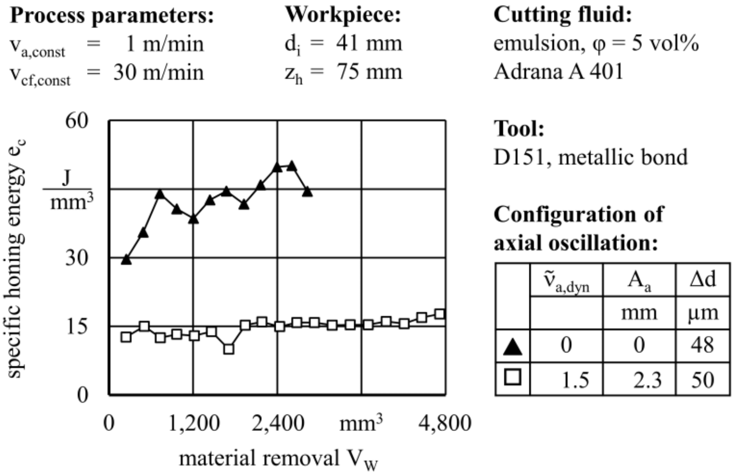


Fig. 4. Influence of the material removal V_W and oscillation parameters on the specific honing energy e_c

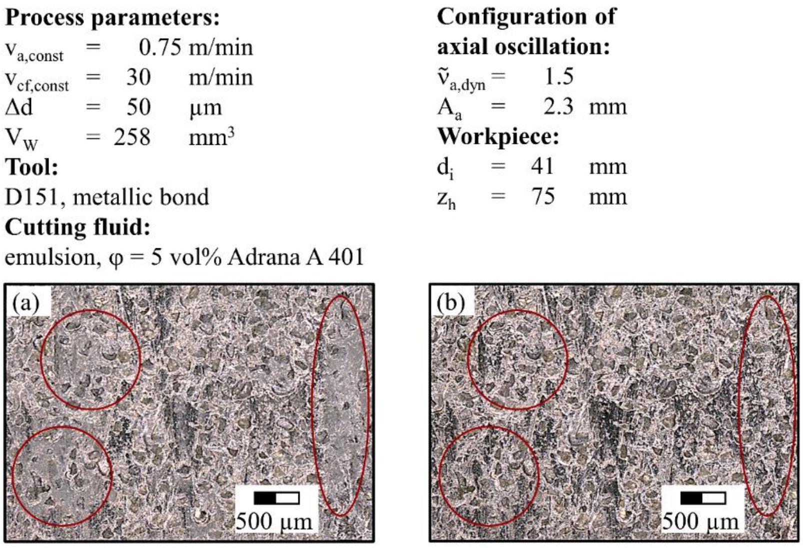


Fig. 5. Comparison of honing ledge surfaces after the single-pass honing process; (a) without superimposed oscillations; (b) with superimposed oscillations

After the execution of single-pass honing processes with and without superimposed oscillations, the honing ledge surfaces have been investigated with the VHX 5000 digital light microscope from Keyence Deutschland GmbH, Neu Isenbrug, Germany, with a magnification of 160×, Fig. 5. During the single-pass honing process without oscillations, large areas of the honing ledge surface become clogged with separated workpiece material, Fig. 5a (red markings). Within these areas, the cutting grains are persistently clogged by removed material and cannot fully participate in further machining. Thus, the cutting ability of the tool is reduced which can be assumed to be the reason for the increasing specific honing energy e_c with the increase of material removal of V_w, Fig. 4. The material accumulation is caused by adhesion processes [19, 20].

Depending on the process conditions, the accumulated material is temporarily separated from the honing tool surface, causing the cutting capability of the tool to increase again. Consequently, large fluctuations of the specific honing energy e_c can be observed due to these conditions, Fig. 4. In contrast, little remaining workpiece material can be seen on the honing ledge surface after a single-pass honing process with superimposed oscillations, Fig 3b. Even with increasing material removal V_w, the tool remains capable of cutting and operates in a self-sharpening behaviour. Hence, the development of the specific honing energy e_c, Fig. 4, can be explained based on the microscopic analysis of the honing ledge surfaces. Based on these findings, it is concluded that due to the removal of chips induced by superimposed oscillations, the process forces and torques are sufficiently reduced to enable dry honing processes. However, the amount of clogged surface area as well as the resulting reduced grain protrusion has not been quantified within these investigations and is subject to current projects.

4.2. DRY HONING

Figure 6 shows the tool and the workpiece after a honing process without a cutting fluid. From the distribution of the removed workpiece material on the tool, Fig. 6a, it can be observed that the tool first came into contact with the workpiece surface at a height of approximately one third of the honing tool length. This results from the conical shape of the honing tool. At a height of approximately one half of the honing tool length, it is almost completely in contact with the workpiece surface.

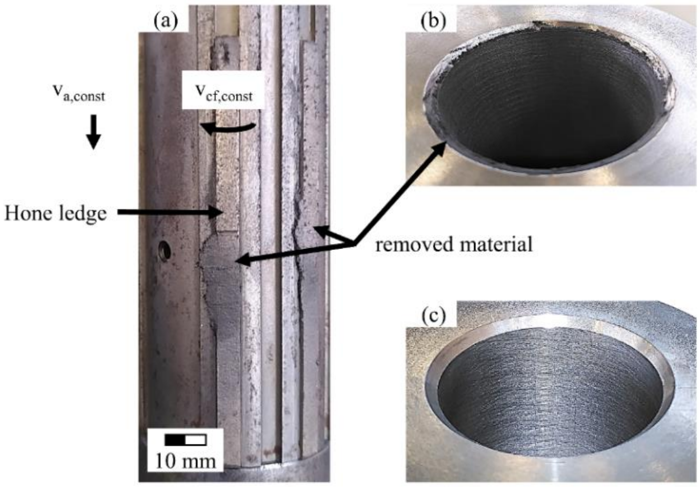
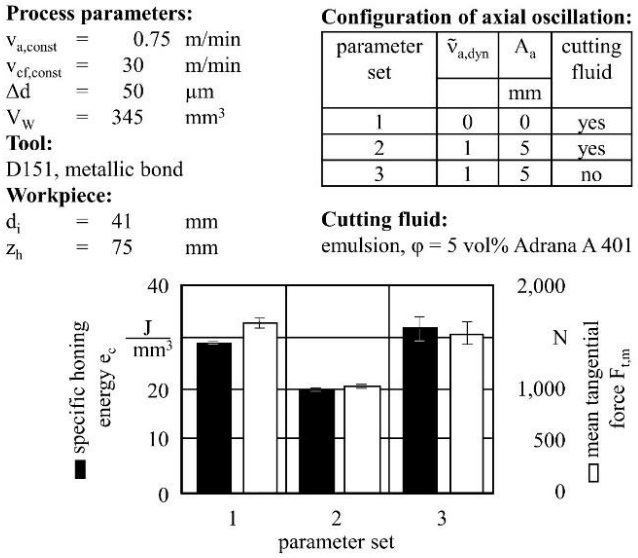


Fig. 6. Honing tool and workpiece after the dry honing process; (a) honing tool with remnants of removed material; (b) workpiece with remnants of removed material; (c) cleaned workpiece

A large amount of the material is pushed into the space between the hone ledges, while smaller amounts remain on the honing ledge surfaces. In contrast to single-pass honing processes without oscillations and with the use of a cutting fluid, in which material adheres to the honing ledge, Fig. 5a, the workpiece material does not adhere during the dry honing process and can be removed almost completely with compressed air. Furthermore, removed material remains on the workpiece surface, Fig. 6b, which can be cleaned with compressed air as well, Fig. 6c.

To further analyse the influence of the cutting fluid, additional technological investigations are carried out. The influences of the cutting fluid and the superimposed oscillations on the specific honing energy e_c and on the mean tangential force $F_{t,m}$ are shown in Fig. 7. It can be observed that the use of superimposed oscillations and cutting fluid i. e. parameter set 2 results in a decrease of 30% in the specific honing energies e_c and a decrease of 37% in the mean tangential force $F_{t,m}$ compared to the conventional process, i. e. parameter set 1. With the conventional parameter set, a specific honing energy of $e_c = 29.2\ \frac{\mathrm{J}}{\mathrm{mm}^3}$ and mean tangential force of $F_{t,m} = 1663$ N is measured, which is consistent with previous results [10, 11].



Process parameters:
$v_{a,const}$ = 0.75 m/min
$v_{cf,const}$ = 30 m/min
Δd = 50 µm
V_W = 345 mm^3
Tool:
D151, metallic bond
Workpiece:
d_i = 41 mm
z_h = 75 mm

Configuration of axial oscillation:

parameter set	$\tilde{v}_{a,dyn}$	A_a	cutting fluid
		mm	
1	0	0	yes
2	1	5	yes
3	1	5	no

Cutting fluid:
emulsion, φ = 5 vol% Adrana A 401

Fig. 7. Influence of the use of cutting fluid and oscillation parameters on the specific honing energy e_c and mean tangential force $F_{t,m}$

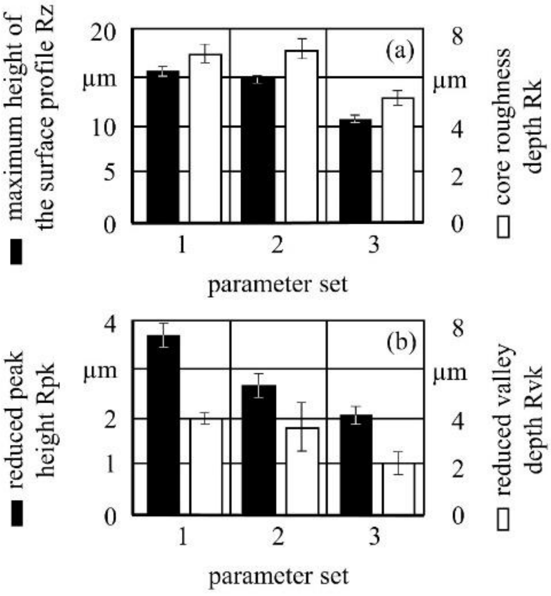
The reduction of specific honing energy e_c and the mean tangential force $F_{t,m}$ when comparing parameter set 1 and 2 is due to the improved material removal V_w by superposing the oscillations. In comparison, using superimposed oscillations without a cutting fluid, i. e. parameter set 3, the specific honing energy e_c and mean tangential force $F_{t,m}$ are in the range of conventional single-pass honing process with parameter set 1. It can be observed that the flushing and lubrication effects of the coolant is compensated by the superimposed oscillations.

The influences of the cutting fluid and the superimposed oscillations on the surface quality is shown in Fig. 8. The comparison of the maximum height of the surface profile Rz shows only minor differences between parameter set 1 and 2 with a 7% lower value for the single-pass honing process with oscillations and the use of cutting fluid by applying parameter set 2, Fig. 8a. Compared to single-pass honing processes with the use of a cutting fluid regarding parameter set 1 and 2, the dry honing process with parameter set 3 results in a lower maximum height of the surface profile *Rz* with a decrease of 33% compared to the conventional process, i. e. parameter set 1, with a maximum height of the surface profile of *Rz* = 16.0 µm.

When comparing the use of superimposed oscillations and cutting fluid i. e. parameter set 2 to the conventional process, i. e. parameter set 1, in regard to the core roughness depth *Rk*, the deviation is smaller than 1% with a core roughness depth *Rk* = 6.94 µm for parameter set 1, Fig. 8a. In contrast, using superimposed oscillations without a cutting fluid, i. e. parameter set 3, exhibits a core roughness depth *Rk*, which is 29% smaller compared to the conventional process, i. e. parameter set 1.

The utilization of superimposed oscillations and cutting fluid, i. e. parameter set 2, results in a 26% decrease in reduced peak height *Rpk* compared to the conventional process, i.e. parameter set 1, with a reduced peak height *Rpk* = 3.62 µm. This is illustrated in Fig. 8b. When examining the impact of superimposed oscillations without cutting fluid, i. e. parameter set 3, on the reduced peak height *Rpk*, a 46% decrease is observed compared to the conventional process, i. e. parameter set 1.

With the conventional parameter set, i.e. parameter set 1, a reduced valley depth of *Rvk* = 3.98 µm is measured, Fig. 8b. Compared to the conventional process, i.e. parameter set 1, the reduced valley depth *Rvk* yields a 9% decrease in single-pass honing processes with the use of superimposed oscillations and cutting fluid, i. e. parameter set 2. In contrast, the reduced valley depth *Rvk* of single-pass honing process with the use of superimposed oscillations and cutting fluid, i. e. parameter set 3, yields a 47% decrease compared to parameter set 1. The reason for the decrease in surface roughness might result from a change of the chip formation mechanisms caused by an increase in temperature which lowers the ductility of the workpiece material [17].



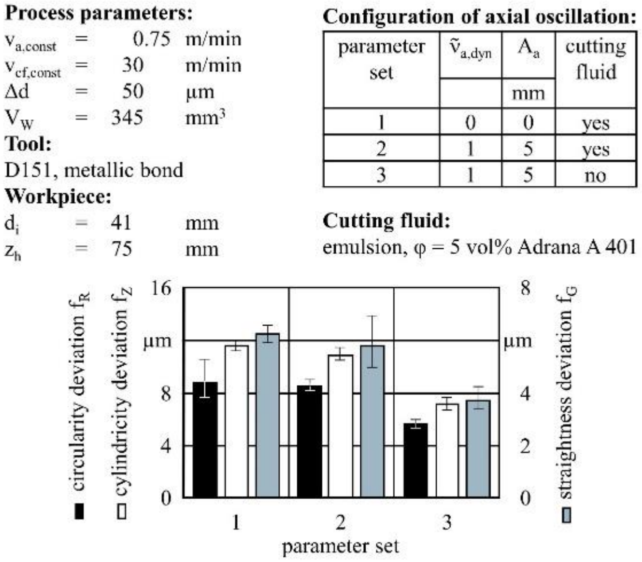
Process parameters:
$v_{a,const}$ = 0.75 m/min
$v_{cf,const}$ = 30 m/min
Δd = 50 µm
V_W = 345 mm³
Workpiece:
d_i = 41 mm
z_h = 75 mm
Tool:
D151, metallic bond
Cutting fluid:
emulsion, φ = 5 vol% Adrana A 401
Configuration of axial oscillation:

parameter set	$\tilde{v}_{a,dyn}$	A_a mm	cutting fluid
1	0	0	yes
2	1	5	yes
3	1	5	no

Fig. 8. Influence of the use of cutting fluid and oscillation parameters on the surface quality; (a) maximum height of the surface profile *Rz* and core roughness depth *Rk*; (b) reduced peak height *Rpk* and reduced valley depth *Rvk*

Furthermore, the change of the hone ledge topography which is less clogged by removed workpiece material due to the superimposed oscillations and hence has more active grains, might explain the improved surface quality for the dry honing. However, the reasons for the improved surface quality for the dry honing process are not fully known and are the subject of future investigations.

The influences of the cutting fluid and the superimposed oscillations on the circularity deviation f_R, the cylindricity deviation f_Z and the straightness deviation f_G are shown in Fig. 9. The comparison of the circularity deviation f_R shows only minor differences between parameter set 1 and 2 with a 4% lower value for the single-pass honing process with oscillations and the use of cutting fluid by applying parameter set 2. Compared to single-pass honing processes with the use of a cutting fluid regarding parameter set 1 and 2, the dry honing process with parameter set 3 results in a lower circularity deviation f_R with a decrease of 38% compared to the conventional process, i. e. parameter set 1, with a maximum height of the circularity deviation of f_R = 8.7 µm.



Process parameters:
$v_{a,const}$ = 0.75 m/min
$v_{cf,const}$ = 30 m/min
Δd = 50 µm
V_W = 345 mm^3
Tool:
D151, metallic bond
Workpiece:
d_i = 41 mm
z_h = 75 mm

Configuration of axial oscillation:

parameter set	$\tilde{v}_{a,dyn}$	A_a	cutting fluid
		mm	
1	0	0	yes
2	1	5	yes
3	1	5	no

Cutting fluid:
emulsion, φ = 5 vol% Adrana A 401

Fig. 9. Influence of the use of cutting fluid and oscillation parameters on the circularity deviation f_R, cylindricity deviation f_Z and straightness deviation f_G

Regarding the cylindricity deviation f_Z, it can be seen that the use of superimposed oscillations and cutting fluid i. e. parameter set 2 results in a decrease of 11 % compared to the conventional process with parameter set 1 with a cylindricity deviation of f_Z = 11.6 µm, Fig. 9. In comparison, using superimposed oscillations without a cutting fluid by applying parameter set 3, the dry honing process has a decrease of 42 % in the cylindricity deviation f_Z compared to the conventional process with parameter set 1.

With the conventional parameter set, i.e. parameter set 1, a straightness deviation of f_G = 6.27 µm is measured, Fig. 9. Compared to the conventional process, i.e. parameter set 1, the straightness deviation f_G yields a 8% decrease in single-pass honing processes with the use of superimposed oscillations and cutting fluid, i. e. parameter set 2. In contrast, the straightness deviation f_G of single-pass honing process with the use of superimposed oscillations and cutting fluid, i. e. parameter set 3, yields a 41% decrease compared to parameter set 1. Again, the main reason for the form deviations f_Z, f_R and f_G might be the change in ductility due to increased temperature and changes of the hone ledge topography which are the subject of future investigations.

5. CONCLUSION

By superimposing low frequency oscillations, single-pass honing can be carried out without the use of a cutting fluid leading to improved work results compared to the conventional single-pass honing process. To implement the dry honing process, no additional equipment is necessary and no resonance condition has to be fulfilled. It can be assumed that specific surface structures, which also occur during conventional long-stroke internal cylindrical honing, can contribute to an enhanced functionality of the workpiece surface. It was shown that the omitted lubrication and flushing effect of the contact zone between the tool and the workpiece could be compensated with the aid of the superimposed oscillations. That is reflected in the specific honing energy e_c and mean tangential force $F_{t,m}$ of the dry honing process which is in the range of the specific honing energy e_c and the mean tangential force $F_{t,m}$ of conventional single-pass honing. The reasons for the improved work results might result from a change of the chip formation mechanisms caused by an increase in temperature which lowers the ductility of the workpiece material and are the subject of future investigations. In essence, the advantages can be utilized to decrease the required energy during the processing of workpieces, increase the workpiece allowance or maximum axial velocity, and thus overall enhance the material removal rate to improve the cost efficiency of honing processes. Furthermore, the development of a basic understanding of the dependencies between the process behaviour and the work results as a result of the absence of a cutting fluid offers the potential of enhancing other dry manufacturing processes. A systematic investigation of these interdependencies, in particular the influence of the axial velocity component $v_{a,const}$, is required for a comprehensive evaluation of the dry honing process. The transferability to other, more widespread honing processes such as longitudinal stroke honing is subject to current research.

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