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Flexible right sized honing technology for fast engine finishing

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Machine
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ABSTRACT

The paper discusses a flexible honing technology by describing the new prototype machine with its specificity. Three original methods produced by the flexible honing prototype have been studied. A path combines the two contemporary methods of industrial honing: the helical slide honing at 135° at the bottom of the cylinder and the conventional honing at 45° on the upper part. This method of honing shows the effectiveness of specific motion tracking to remove traces of inversions. Circular trajectories with large radii can be traveled quickly without consuming too much energy. The high cutting speed promotes the removal of material thus saving time. Finally, the multi-circle paths can get original textures thus proving the feasibility of all patterns.

The conventional honing process which produces a textured liner surface with a honing angle close to 45° pertains in automotive industry for over 40 years. The evolving of pollution standards in the last ten years has changed the process with the application of a plateau honing technology. This technology removes the running-in of the engine after assembly [1]. Some manufacturers are engaged in helical slide honing (HSH, with a honing angle of 135°) to increase engine performances by reducing friction [2]. However, this process requires over-sized honing machines and a long cycle time. The latest engine developments tend toward crankcase made entirely of aluminum of which only functional cylinder surfaces are coated with shirts deposit extremely hard. This deposit ensures the retention of oil by its porosity; the surface must, however, be honed to be as smooth as possible before an assembly with the piston and rings.

To reduce the manufacturing cycle and get a right-sized honing machine for development, a new prototype of vertical honing machine was designed with high dynamic performances. A digital controller allows the synchronized control of the rotation and stroke axis and allows interpolation of trajectories. The radial expansion can be hence controlled in position or in force. We sought new paths with the aim to increase productivity of the process and to generate new textures.

This paper compares the performance of the prototype with those of conventional machines before presenting some original new methods.

1. The honing machine

The honing operation of cylinder block liners consists of removing material by abrasion inside the cylinders bored to obtain a good quality of the cylindrical surface. This quality is defined at three levels: at the macroscopic level the cylindrical shape must satisfy the dimensional criteria, roughness at the microscopic level is specified by the designers of the engine, at the mesoscopic level, the surface appearance of a texture must be defined in the specification of the surface. To achieve these objectives, the honing operation must implement abrasive stones that are mounted on an expansion honing tool. The honing tool has the feature to push the stones for contacting with the cylindrical surface. The material removed by abrasion requires cutting speed [3]. The cutting speed defined by the relative speed between the abrasive grains and the machined surface is given by the combination of a movement of rotation and translation of the honing tool about its axis. Fig. 1 shows the kinematics of a honing machine with one pin. The *Z*-axis of the pin is the axis of the honing tool and of the cylinder.

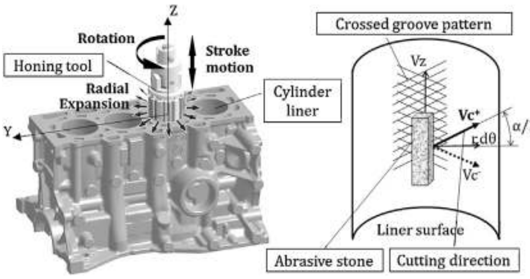

Fig. 1. Honing machine kinematic.

In conventional honing strokes along the *Z*-axis are linear and the rotational speed is constant. Following the trajectory of these movements form helices crossed at the angle $\alpha/2$. The pattern left by the abrasive traces therefore has streaks that cross each other at the angle α, the angle of grinding. To satisfy different levels of quality of honed surface, the honing operation is often divided into several stages. In general one first step, the roughing, is performed with large grains to obtain effective material removal and correcting the shape. Then the finishing steps can combine several

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abrasives to achieve low roughness. The configuration of these conventional operations is optimized empirically to achieve high production rates. The optimization of the parameters can be done with the aid of a simulation [4].

1.1. Characteristics of classical honing

Honing process, like drilling, requires only two axes to fulfill the motion of the tool: rotation and axial translation. Like any machine tool and according to the convention [5], the rotation axis of the tool is designated as the Z-axis. On most machines, the workpiece is fixed and the tool performs the movement. Traditionally, the linear actuator is a hydraulic cylinder controlled in position. The stock removal is obtained by generating a contact pressure between the stones and the cylindrical surface of the cylinder bore. There are two different kind of actuator to perform this movement: hydraulic and electromechanical systems, as shown in Fig. 2. For hydraulic system, the cutting force is given by the hydraulic pressure supply of the actuator.

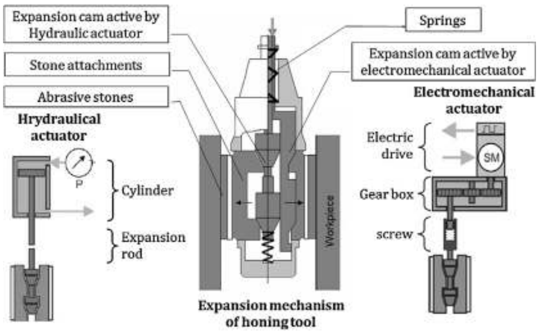
Expansion cam active by Hydraulic actuator
Stone attachments
Abrasive stones
Hrydraulical actuator
P
Cylinder
Expansion rod
Springs
Expansion cam active by electromechanical actuator
Electromechanical actuator
Electric drive
SM
Gear box
screw
Workpiece
Expansion mechanism of honing tool

Fig. 2. Two technologies for expansion axis.

Electromechanical systems are naturally driven in position. The position setpoint is often expressed in microns and corresponds to a diameter that is absolute or relative to advance abrasive stones. Some techniques for detecting the radial position of contacted stones have been patented [6]. The observed diameter of the advance of the expansion is not necessarily identical to the real diameter of the cylinder, because the wear of the abrasive is not taken into account. On the other hand, in-process measurement gives a true measure of the diameter. The control calculates the abrasive wear by comparing the evolution of the actual diameter and the radial feed of the abrasive stones.

The principle of double expansion honing tool was patented in 1986 by industrial company Nagel [7]. A double expansion honing tool has two sets of stones that are separately operable. The superposition of two concentric cams, depicted in Fig. 2, can activate both sets of stones independently. This double expansion allows two successive steps without changing tools in order to save cycle time. On conventional machines, the spindles are frequently equipped with one electromechanical expansion and one hydraulical expansion.

1.2. Characteristics and performance of the prototype

The prototype machine that we designed operates the same type of honing tool as conventional machines.

In order to meet the needs to exceed the dynamic performance of existing machines, we chose an inverted architecture illustrated in Fig. 3.

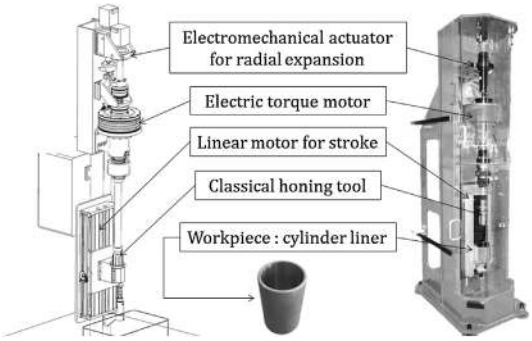
Electromechanical actuator for radial expansion
Electric torque motor
Linear motor for stroke
Classical honing tool
Workpiece : cylinder liner

Fig. 3. Machine with inverted structure/photography.

The liner is clamped in a workpiece holder and is driven in a translation motion. While the rotating tool remains at a fixed height. This solution minimizes the moving masses, prevents vibrations and the jolts in the tool, and can pass on processes requiring high cutting speed and strong momentum. The motion law governing the beat is very dynamic. The reversal of the speed at the end of the stroke involves high acceleration. The integration of a high performance linear motor of 7 kW on the prototype allows achieving high travel speeds (60 m/min) with high acceleration (50 m/s^2). With the integrated incremental rule in the electric motor, the autopilot provides positioning at 5 μm that is much more accurate than hydraulic systems (1 mm).

In general, on conventional machines, the rotation is provided by asynchronous electric motors controlled in speed (50–2500 rpm). The prototype machine is equipped with an electric motor with permanent magnet mounted directly on the spindle axis. This technology controlled in position or in speed ensures a torque greater than 50 N m at a standstill and at very low speed, up to 450 rpm.

Table 1 shows the main characteristics of the prototype machine compared to current machines.

Table 1
Comparison between the prototype and conventional machines.

	Nagel	Gehring	Prototype
Maximal stroke speed	30 m/min	25 m/min	60 m/min
Acceleration of stroke	30 m/s^2	30 m/s^2	50 m/s^2
Rotation speed with torque >50 N m	50–2500 rpm	50–2500 rpm	0–450 rpm
Rotation acceleration	Constant speed	Constant speed	350 rad/s^2

Coupling the linear motor for the stroke and motor torque for rotation enables a synchronized piloting in position of the two axes to track optimal trajectory. As a numerically controlled machine tool, it is possible to interpolate the linear or circular paths described in ISO language G-Code [8].

The axis expansion requires a special performance to meet the specifications of the prototype machine. It must perform both functions of the two current systems. The selected hardware solution is to combine an electromechanical actuator and a force sensor at the end of the rod. The force control is performed by controlling the command on the force sensor. The machine includes a system for acquisition of all the physical data of the axes and the sensors.

2. Honing path with variable angle

In conventional honing, the constant rotation speed during the inversion of translation at the ends of stroke generates a parabolic trajectory of abrasive stones in the cylinder. Paper [9] shows that the acceleration of inversion plays a role in the amount of horizontal traces. The prototype machine is programmed to interpolate rotation – and stroke axes in order to respect a path defined by the user. Through the high dynamic performance of the actuators, this operating mode allows for precise monitoring of the triangular setpoint path to remove inversions traces.

2.1. Definition of the honing path

The path shown below includes a grooves angle change between the upper part of the cylindrical surface and the bottom. This multi-honing angle provides so-called mixed liners which have a pattern typical of HSH at the bottom to facilitate the dynamic flow and a pattern typical of conventional honing on the upper part to limit the back-flow of oil. We want to show here the feasibility of such a process, the best combination of these two patterns optimizing engine performances has still to be designed by means of work in tribology.

2.2. Performance of the process

Linear interpolations for linking two adjacent programmed points are crossed following a ramp rate law to slow down in the vicinity of target points. At the cusp, the cutting speed momentarily cancels inducing a null material removal. On the prototype the phenomenon is not really marked because the ramps of acceleration and deceleration are set to exploit the high performance of the machine. The cycle time by honing multiple angles is identical to the conventional method for the same thickness of material to be removed under the same cutting conditions. Linear interpolation does not affect the performance of the honing process but corrects innate imperfections of conventional systems.

2.3. Surface quality obtained

A series of six liners were rough honed and finish honed with this technique based on the path described in Fig. 4. This finish was produced with identical stones IAS65/100 as finishing abrasive used in Renault conventional three step honing. The path is traversed with a target speed corresponding to the optimum cutting speed of the abrasive, 45 m/min. Like the experiment of article [9], the texture quality was assessed at the top and bottom of the cylinder. From the top, we can compare the quality observed in the liner with the classic honing at 45° equivalent to a conventional machine. Despite the proximity of the reversal point with the measurement zone, the honing method by tracking trajectory leaves almost no trace of inversions. At the bottom of the liner, honing angle of 135° coupled with the speed of 45 m/min cutting puts the linear axis in full use.

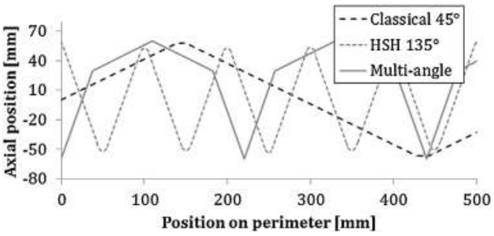

Fig. 4. Classical honing path and double angle.

Table 2 summarizes the data from the classical experiment. The criterion "visible traces" comes from the visual analysis of the entire surface by a process expert. The expert subjectively determines if horizontal traces appear on the surface. The criterion M-turn developed for the analysis of such surfaces was used to quantify the proportion of grooves that did not conform compared to grooves that did conform.

Table 2
Comparison between the conventional and angle controlled honing.

Method	Classical $\alpha = 45^\circ$			Controlled	
				$\alpha = 45^\circ$	$\alpha = 135^\circ$
Stroke acceleration (m/s^2)	5	10	15	Max 50	Max 50
Visible grooves	Yes	Yes	Low	No	No
M-turn criteria	2.1	1.2	0.88	0.30	0.95

The study conducted in [9] showed the influence of the acceleration on the rate of non-conform grooves. The development of the prototype machine provides a way to remedy such non-compliance. Even in the toughest conditions, with a high stroke axis speed, the respect of the setpoint trajectory avoids inversions trace. This mode of operation of the prototype machine improves the quality of textures on the conventional ground surfaces.

3. Sinusoidal honing

Tracking a path with point cusps requires slowdowns and stops, even very short, near these points. Without taking into account the texture that is usually referred, the trajectory can be optimized to travel faster without stops. We propose a trajectory curve based on sinusoidal control laws and following circles.

3.1. Definition of the honing path

This trajectory follows a single circle on the cylinder height and three circles on the perimeter. The large interpolation radius allows a high travel speed. The trajectory shown in Fig. 5 was obtained at the cutting speed of 60 m/min almost constant.

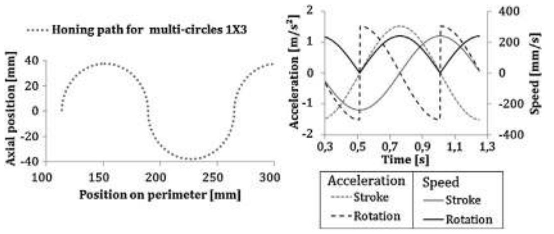

Fig. 5. Sinusoidal honing path with speed and acceleration.

This path does not involve large acceleration or jerk, it reduces energy consumption and machine wear. It can for example be deployed in roughing operation, with very high cutting speed for maximum material removal. It can therefore save cycle time.

3.2. Performance of the method

The comparison between the classic roughing process and sinusoidal honing was established considering five series of tests performed with the same tools and the same diamond abrasive D126. The expansion force is constant for all tests and set to 1200 N on the tool rop. For each series the removal material thickness is measured after a 60 s honing. The energy required for each type of test is calculated by averaging the instantaneous power acquired by the PC. Table 3 presents the overall results.

Table 3
Comparison between conventional and sinusoidal honing.

Method	Classical 45°		Sinusoid		
Cutting speed (m/min)	50	70	50	70	90
Material removal rate (mm^3/s)	0.57	1.34	0.67	1.46	1.83
Average power (kW)	2.5	4	1.8	2.5	3.7

We note that at equivalent cutting speed, conventional honing and sinusoidal honing guarantee almost the same cycle time. The cutting speed of 90 m/min is achievable on the sinusoidal trajectory and reduces the cycle time for roughing. For equivalent cycle time and equal cutting speeds, the electrical power consumed by the machine is greatly reduced by the sinusoidal trajectory. As a conclusion, sinusoidal honing reduces cycle times and consumes less energy than the traditional diamond rough honing.

4. Multi-circles honing

"Multi-circles honing" is a new honing method based on specific honing paths to obtain circular patterns visibly interspersed on the surface texture. These paths have been developed using simulation [4] before being implemented on the prototype machine.

4.1. Definition of the honing path

Multi-circles honing paths are characterized by the number *Nz* of circles over the height of the cylinder and the number *Np* of circles on the perimeter of the cylinder. The radius of the circle is denoted by *x* in mm and the speed of the trajectory *y* in mm/min. A multi-circles path is denoted by the notation: $Nz \times Np\ Rx\ Fy$. *x* is calculated based on the diameter of the cylinder through the relationship:

$$x = \frac{\pi \cdot D}{2 \cdot Np} \qquad (1)$$

There are combinations between *Nz* and *Np* which allow homogeneous coverage of the surface with a minimum number of strokes equal to *Np*, for example, 3 × 7, 5 × 11, 7 × 13, 8 × 15. Fig. 6 shows the plot of the trajectory for a point of the honing tool in multi-circles honing 8 × 15 R7.56 F35000 in the reference frame associated with the cylindrical surface with the height of the cylinder on the *y*-axis and the curvilinear position on the perimeter on the *x*-axis.

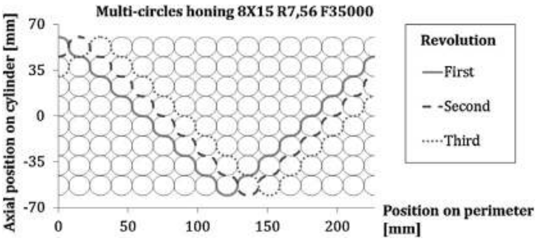

Fig. 6. Multi-circles honing path 8 × 15 R7.56 F35000.

The solid line is related to the first revolution. The following traces are shifted. After 16 revolutions and 15 strokes, one point of the honing tool went all around the pattern. The surface of the cylinder is honed evenly with multi-path circles if a good combination of *Np* × *Nz* is selected and the cycle time is long enough to cover at least *Np* strokes.

4.2. Performance of the method

One characteristic of multi-circles honing paths is the permanently oscillating cutting speed direction. This property can be exploited in the same way as in polishing to obtain very low roughness. A series of tests was conducted to compare the time required in order to reduce the maximum roughness in finish honing with the abrasive IAS65/100 and SC500. At the finishing step, the initial roughness *Ra* was close to 8 μm.

At the end of the finishing, the roughness must be less than 4 μm to be reduced to 2 μm during the final step of super finishing. The evolution of the surface roughness as a function of time for different honing methods is shown in Fig. 7. Each point represents six measured liners. The cutting speed and expansion force are identical for each abrasive: finish IAS 65/100 *Vc* = 45 m/min, *Fexp* = 800 N, super finishing SC500 *Vc* = 40 m/min, *Fexp* = 600 N. We note that the measurement uncertainties reduce with time as the roughness converges to its stable value.

In finishing the multi-circle method 5 × 12 reduces roughness Ra to less than 2 μm in about 30 s while 45 s are required with the conventional method. With fine abrasive, during super finishing, the minimum roughness is reached within 24 s with multi-circles method 8 × 15, compared to more than 50 s with classical honing. We note that the multi-circles paths guarantee a much more effective reduction in roughness. Multi-circles path gives the polished appearance as expected.

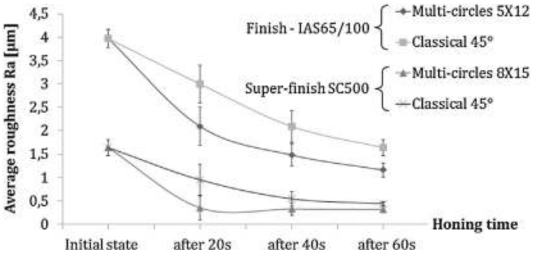

Fig. 7. Roughness evolution in function of honing method.

4.3. Surface quality obtained

Multi-circles honing gives a surface entirely new. Fig. 8 shows the pattern observed with naked eye and a preview of the 3D micro geometry observed with an interferometer.

Depending on the abrasive used, the pattern of the intermingled circles may be more or less pronounced. The scope of such a micro geometric structure of grooves is still under investigation. The results show the feasibility of a texturing process using abrasion to produce almost every type of pattern.

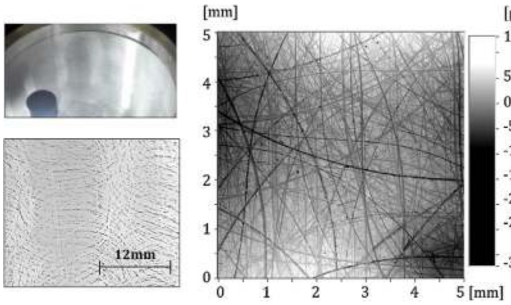

Fig. 8. Obtained texture photography and 3D digital.

5. Conclusion

This paper proposed the design and implementation of a prototype of honing machine with high dynamic actuators and efficient numerical control. The definition of the trajectory of the abrasive enables to achieve new honing techniques with a better control of the resulting surface. The three original methods presented have special features allowing the extension of the range of applications of abrasive process. Future work will focus on the best choice of abrasives for texturing.

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