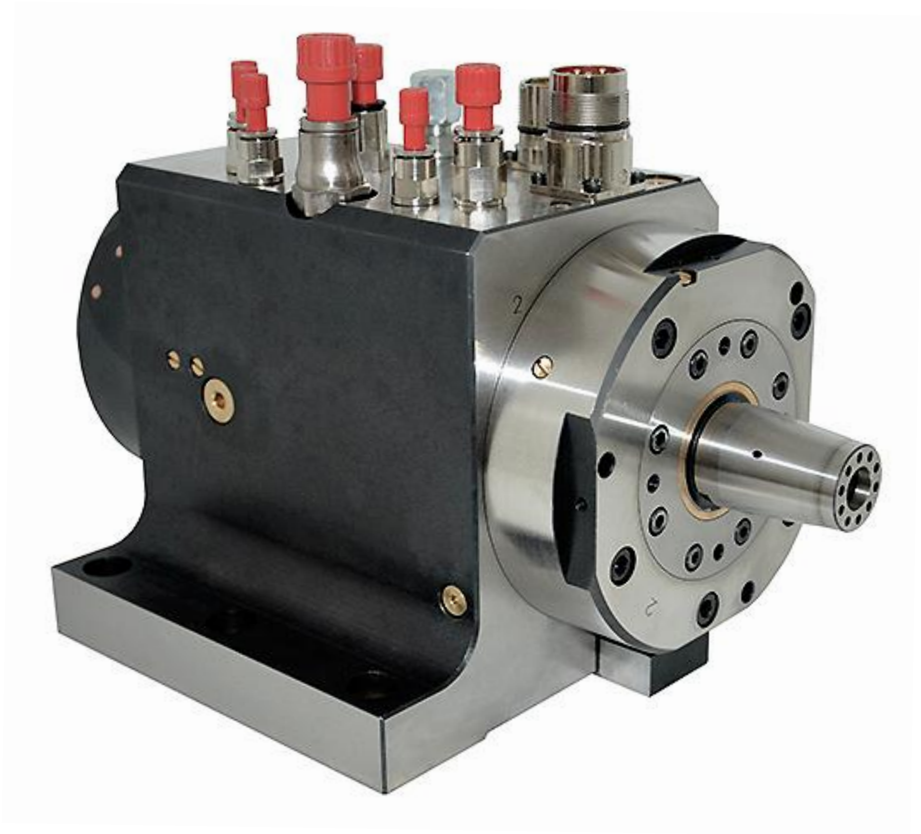
HYDROSTATIC SPINDLES
when to use them and why



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HYDROSTATIC technology

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HYDROSTATIC SPINDLES – WHEN TO USE THEM AND WHY

The goal of this paper is to help manufacturing engineers determine and make the right decision on when it makes sense to use hydrostatic spindles for a particular application. Based on my personal involvement in the development and manufacture of hydrostatic spindles for more than 40 years, I like to share my thoughts about hydrostatic spindles' applications – when they **can** be used and when they **must** be used.

On one hand, hydrostatic spindles effectively combine ultra-high rotational accuracy, high static stiffness and load capacity, extremely high vibration resistance, controlled thermal behavior, moderate thermal expansion and are virtually free of wear.

On the other hand, hydrostatic spindles are usually about 30% more expensive as compared to spindles with rolling elements and require more expensive periphery support equipment, such as hydraulic power unit used to provide high pressure liquid media to hydrostatic bearings, and chiller used to compensate power losses due to the share friction in the bearings as well as power losses caused by the pumping.
As matter of fact, the share friction in hydrostatic bearings is a big problem. Friction power grows very quickly depending on speed – proportionally to speed square if flow in the bearings is laminar, and even faster if flow starts to convert to turbulent regime. Wrongly designed, the hydrostatic spindle will serve as an oven rather than precisely rotating shaft.

The main advantage of hydrostatic spindles is not any one of separate features, but a unique combination of many different features. It gives us a powerful tool that provides for the correct technical and financial decision for particular applications.

Let's investigate some concrete examples that will help clarify the above statement:

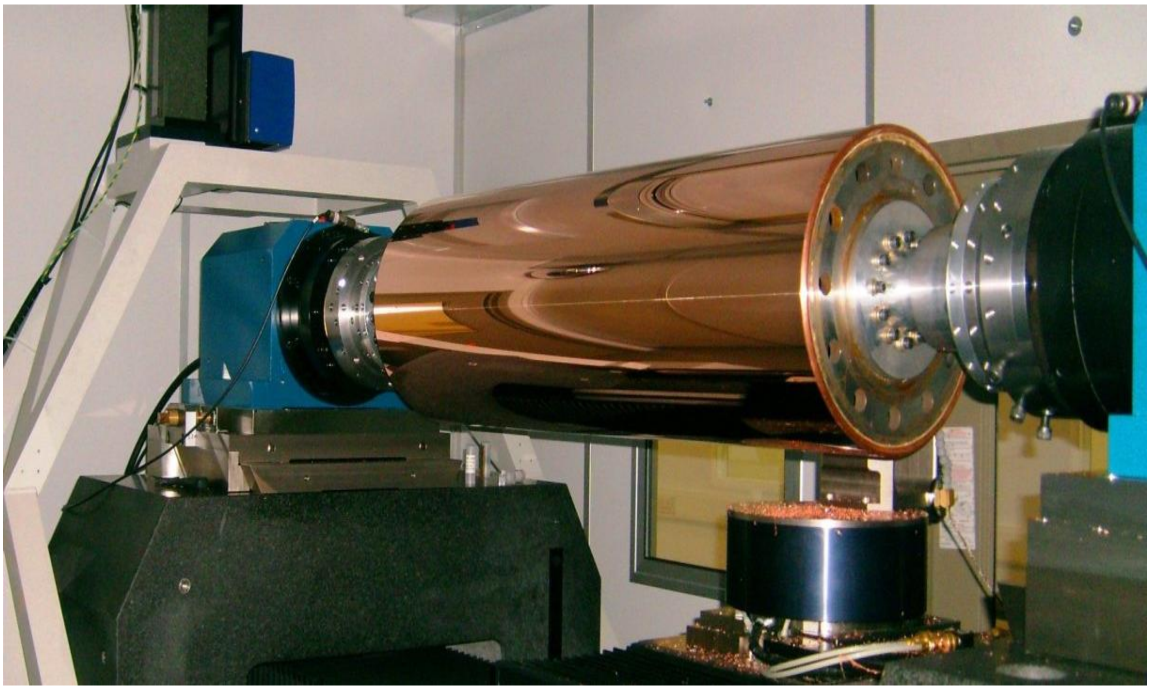
1. Diamond Turning

Diamond turning is a kind of ultra-precision machining with the goal to achieve mirror surface finish by a turning process that for cutting uses a single crystal natural diamond tool. The main feature required from the spindle is the ultra-high rotational accuracy due to the cutting forces being very low. Air static bearings spindles are overwhelmingly used for this operation. They have extremely high rotational accuracy (about the same when compared to hydrostatic spindles); friction in bearings is minimal; no problems with oil leakage and they do not require such an expensive periphery equipment when compared to hydrostatic spindles.

But if a machined part is heavy, the load capacity of the spindle has to be taken into consideration and Hydrostatic Spindles excel.

To reach the same load capacity as hydrostatic spindle, the bearings surface in air static spindles has to be 10-15 times bigger. This makes Air static bearings spindles economically and technically not acceptable and Hydrostatic spindles should be considered.

The good examples are copper drums with mirror surface finish that are widely used in flat screen TV manufacturing with weights varying from 1 to 3 tons. On Picture 1 is shown ultra-precision diamond turning machine with hydrostatic head stock and tail stock developed by TDM engineers.



Picture 1

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2. Hard Turning and hard Milling

Hard Turning is turning of the hardened steel and is often used to replace final grinding. To compete successfully with the grinding process, geometrical accuracy and surface finish after turning have to be close to the results achieved by grinding. Because of hardened steel machining, the cutting forces expected to be relatively high. Because of chips formation while brittle material is machined, cutting force is not steady and has sharp peaks, creating high frequency alternative load applied between the tool and the machined part. Spindles going to be used for hard turning must combine high accuracy, high stiffness and high vibration resistance.

The research conducted by Institute of Production Technology (IPT) located in Aachen, Germany has proven that hydrostatic bearing spindles are the optimal choice for hard turning.

The usage of hydrostatic spindles makes possible to achieve sub-micron geometrical accuracy and excellent surface finish with Ra up to 0.05 microns and sometime even better. Besides that, the life time of the cutting tool is significantly prolonged as a result of the powerful vibration suppression that comes with
Hard Milling is precision milling of hardened steel. One of the most common applications of Hard Milling is finish machining of high precision dies and molds, just before polishing, to compensate parts' distortion caused by heat treatment. Cutting depth is usually small and cutting forces are quite moderate. But because brittle material is machined, the force applied through the cutting tool to the spindle will contain sharp peaks generating wide spectrum of vibrations. It means that spindle used for this application has to be able to effectively suppress vibrations and to smooth sharp peaks in the cutting forces. Besides that, the spindle has to be very accurate and to provide as good surface finish as possible in order to reduce an expensive and time consuming polishing phase.

Only the hydrostatic spindle combines ultra-high accuracy and high effectiveness in vibrations suppression.

3. Ultra-High precision Grinding of Brittle Materials

There is a very wide range of applications related to high precision grinding of components made of brittle materials, one example is optical lenses. The materials like glass, quartz, tungsten carbide and ceramics are very brittle. To reach excellent surface finish from grinding the parts made of these materials is an extremely challenging task. The requirements for the spindle characteristics are even tougher when compared to Hard Turning and Hard Milling applications. In contrast to Hard Milling, the radial run-out of the grinding tool can be reduced by the truing process. The only imperfection left in the tool radial motion is caused by non-repeatable portion in shaft rotation, i.e. totally defined by internal features of the spindle bearings.

The rolling elements bearings would definitely not be the best choice due to having natural limit in rotational repeatability, i.e. after every revolution, the angular position of the rolling elements will be changed. The only spindles can be used are either air static or hydrostatic.

But because of sharp peaks vibrations generated by brittle material removal, the hydrostatic spindle is preferable one featuring significantly more aggressive vibrations suppression when compared to air static spindle.

Surface finish with Ra between 1 nm and 2 nm (!) has been reached in optical components grinding.

There are interesting comparison results obtained during grinding of large size lithography lenses using air static and hydrostatic spindles:

a. Subsurface damages caused by grinding using hydrostatic spindle were substantially smaller when compared to air static one.
b. The time between grinding wheel dressings while hydrostatic spindle was used is about two times longer when compared to wheel dressings when grinding was accomplished using air static spindle.

4. High Precision Internal Grinding in Mass Production

There are two spindles involved in internal grinding process: the work head spindle holding a part to be ground, and the wheel head spindle holding a quill with a grinding wheel mounted on the quill. Generally speaking, the work head spindle is responsible mainly for roundness of the ground opening, while the wheel head grinding spindle is responsible for the surface finish and productivity (i.e. for material removal rate). There is no need in hydrostatic spindles for majority of internal grinding applications – high accuracy work head spindle with rolling elements bearings and internal grinding spindle with rolling elements bearings will provide reasonably good results for surface finish, roundness and productivity.

However the situation changes drastically when the size of the ground opening and the time given for grinding drops. As an example, let's consider the gas fuel injector valve seat.

The small internal taper with average diameter of about 2-3mm has to be ground to very tight tolerances within 6 seconds or less, including in-feed and spark-out portions of the grinding cycle:

a. To remove the material as quickly as possible during the in-feed portion of the cycle, the speed of the wheel head spindle has to be very high in order to reach more or less a reasonable number for the surface speed, especially when CBN grinding wheels are used.
b. To reduce spark-out time, both spindles have to perform with extremely high rotational repeatability because spark-out process by its nature is an averaging process. Which rotation is more repeatable, the shorter will be the averaging process. To achieve required out of roundness statistically (0.1 micron) the rotational accuracy of the work head spindle has to be at least two times better.
c. To reduce danger of chatter, wheel head spindle has to have good vibration suppression features.

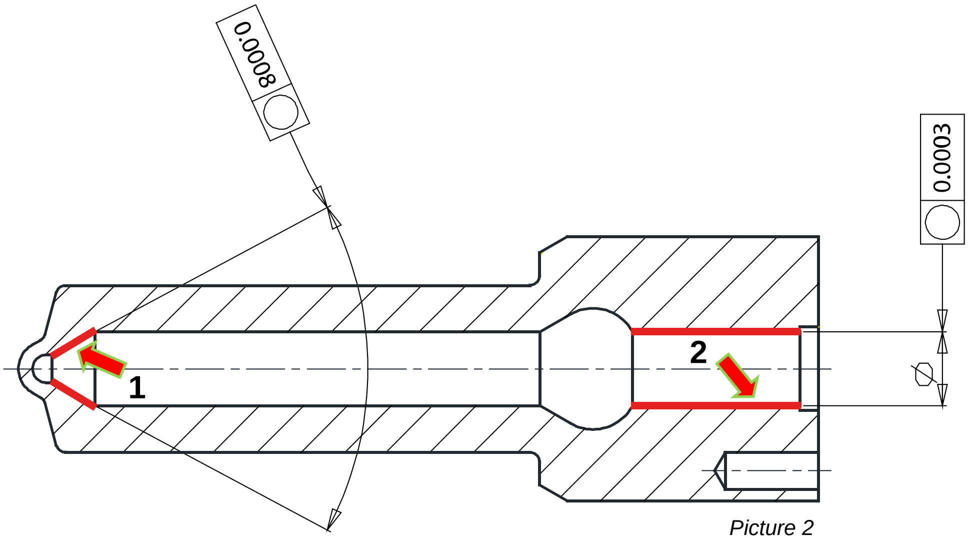
It is easy to estimate that to reach an optimal number for the surface speed while 2mm diameter hole is ground using CBN wheel, the rotational speed has to be about 1,000,000 RPM. To achieve more or less reasonable number for the surface speed, the rotational speed has to be as high as possible. Here the spindle lifetime comes into consideration:

a. When rotational speed is higher than 150,000 RPM, lifetime of rolling elements bearings drops significantly and can be as short as several months only.
b. The average price for repairs of such a spindle is about $4,500. Plus cost of time while expensive grinding machine is temporarily out of production.

It can therefore be concluded that the optimal choice for internal grinding of small precision parts in mass production environment would be combination of two hydrostatic spindles: work head grinding spindle with maximal speed usually up to 6,000 RPM and internal grinding spindle with maximal speed as high as possible (100,000 RPM and higher).

The typical parts are: gas and diesel fuel injector components; bearings rings for the small size precision ball bearings; components for computer hard disc bearings; precision servo valve components; fiber optic connectors etc.

On Picture 2 is shown typical diesel fuel injector. Tapered portion 1 (seat) and cylindrical portion 2 (bore) have to be ground within extremely tight tolerances for surface finish and for geometrical accuracy while the grinding cycle duration has to be as short as possible.



Picture 2

5. High Precision Boring

Boring is a high precision machining process used to generate a cylindrical hole by removing material with single point cutting tool. Preliminary, hole has been made by previous rough operations. Goal of the boring is to improve significantly accuracy of the just existing hole: roundness, straightness and surface finish. In contrast to internal turning, boring process is most commonly used with the workpiece held stationary while cutting tool is rotating and advancing into the workpiece.

As it clear from machining kinematics, roundness of the hole is to a large extent defined by rotational accuracy of the spindle. Besides that, tool material, its geometry as well as cutting conditions can have a certain impact on the hole accuracy and, especially, on the surface finish. The rigidity of the boring bar is very critical for chatter appearance. If the ratio length of the boring bar to its diameter is too high, the radial vibrations of the tool during boring process will be generated.

Ultra-high accuracy of hydrostatic spindles combined with an extremely high vibration resistance makes them an optimal choice for high precision boring applications. Rotational accuracy will allow to machine holes with extremely low out of roundness values, while high damping ratio in the hydrostatic bearings will allow using longer boring bars without getting chatter. Or, alternatively, can be used the shorter boring bar, but for much more heavy cutting conditions as compared to ball bearings spindles.

As a boring application example can be considered machining of the pin holes in Internal Combustion Engines piston shown on the picture 3.

Picture 3

Usage of the hydrostatic spindle with a boring bar equipped with PCD tool will simultaneously increase productivity, surface finish and geometrical accuracy.

6. Truing Process for CBN grinding wheels.

Truing is a process of creating a round wheel concentric to spindle axis of rotation and generating, if required, a particular profile on the wheel. It is also to clean out any material embedded in the wheel.

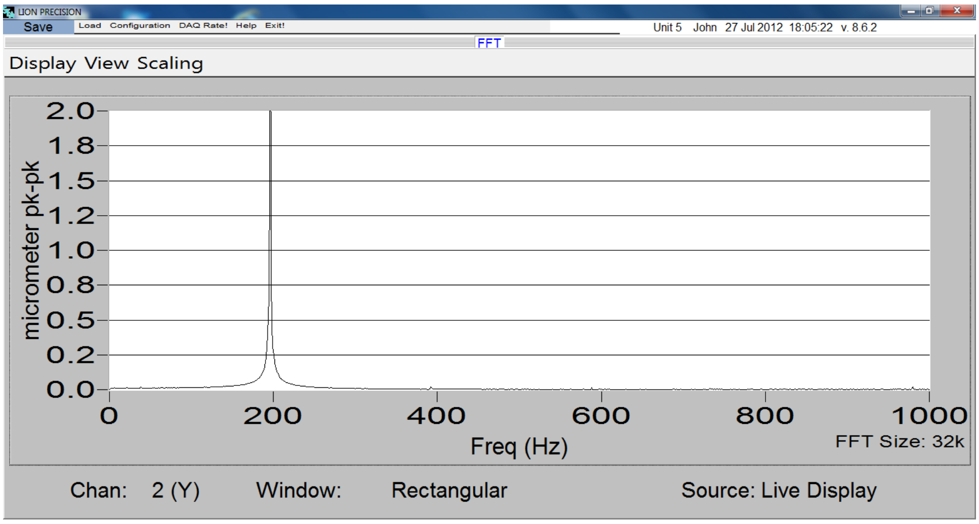
Truing of CBN wheel is made by diamond wheel usually mounted on the separate spindle named as a Truing Spindle. To control and to visualize truing process as well as to minimize material removal from the CBN wheel (which is by the way is very expensive) is used acoustic emission sensor directly mounted into the dressing spindle's rotating shaft.

Truing is an extremely important and critical component of the grinding process. Grinding results and, especially surface finish, to a large extent defined by truing spindle quality. Almost every even small imperfectness during the truing could be seen later on the ground part surface.

Truing spindle has to be stiff enough, has to have excellent damping characteristics, has to have extremely high rotational accuracy and has to perform with vibrations spectrum as clean as possible not to interfere with acoustic emission signal generated by truing process itself.

As it clear from above, hydrostatic spindles without any doubt are absolutely the best choice for truing process, especially if ground part has to meet very high requirements.

On Picture 4 is shown vibrations spectrum. The high peak on the chart is generated by the run-out of the master ball rotational frequency.



Picture 4

7. Ball ad Roller Bearings Inspection.

The same advantage of mechanical noise free rotation can be effectively used for ball and roller bearings inspection.

To test vibrations generated by ball and roller bearings under the load, rolling element is mounted onto the spindle and preloaded axially by pneumatic or hydraulic cylinder with calibrated load. Vibrations are measured by high precision inductive sensors.
If rolling element is mounted onto the ball bearing spindle, the mechanical noise created by the test spindle bearings will interfere with vibrations of tested bearing and will reduce significantly accuracy and reliability of measurement results.

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