NANOMETER PRECISION IN PRACTICE

In 2020, Nobby Assmann won a Zeiss #measuringhero Award for the smallest measured object on a coordinate measuring machine: 0.4 mm x 0.4 mm x 0.03 mm. The next year, he won another award, this time for the smoothest surface, with a surface roughness of R_a 540 pm and R_z 3.1 nm. The surface was finished by lapping, flat polishing and chemical mechanical planarisation; three extremely precise processes. What exactly are these processes and what is it that drives this technician?

Profile of a precision winner

Nobby Assmann (1978) runs a precision toolroom in Zevenbergen (NL); Assmann Verspaningstechniek. The company provides manufacturing processes that go beyond the usual CNC turning and milling. Nobby (Figure 1) is supported by his parents, while the company does not have any employees. Since 1998, he works in the family business that his parents founded in 1985 in the small garage behind their home. Currently, the company covers a 500 m^2 facility for wire-EDM, die-sinking EDM, lapping, honing, cylindrical grinding and surface grinding. The company also has a measuring lab for contract measuring jobs. Nobby holds a bachelor's degree in mechanical engineering.

Nobby in front of his largest lapping machine, with a lapping disk of 1 m.

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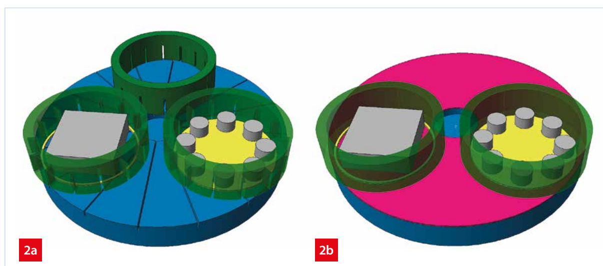
Of all the finishing processes, lapping – rubbing two surfaces together with an abrasive between them – is the most precise, explains Nobby Assmann. "I remember a table about expected tolerances for different techniques from coarse to fine. It began with milling and turning – which was IT (International Tolerance) grade 7 to 10. Then came grinding: IT grade 3 to 7. Lapping was at the very bottom with IT grade 1 to 3. That really drew my attention." A few years later, he bought his first lapping machine.

Back then, the company already performed wire-EDM (electrical discharge machining), die-sinking EDM, grinding and honing. It seemed to be a small step towards lapping. But it wasn't: lapping really is something else. It takes more patience and a whole lot of experience, according to Nobby. "Lapping is a true craft. It might be hard, but it is very rewarding in the end." See Table 1 and Figure 2 for the various finishing processes.

Applications for lapping

Only few people are familiar with lapping and its benefits. What is it for and why? The most common example of lapped surfaces can be found in mechanical seals. Two ring-shaped surfaces are pressed together; one stationary and one rotating. The surfaces must have a superior flatness and surface, or the seal will leak.



Schematic comparison of lapping versus polishing and CMP.
In gray, the workpieces (one large and multiple small); in yellow, the workpiece holders.
(a) Lapping.
Blue: lapping disk.
Green: lapping rings.
(b) Polishing and CMP.
Pink: polishing pad.
Note that the green rings are not serrated.

EDITORIAL NOTE

This article was contributed by Assmann Verspaningstechniek.

Table 1
Properties of various finishing processes.

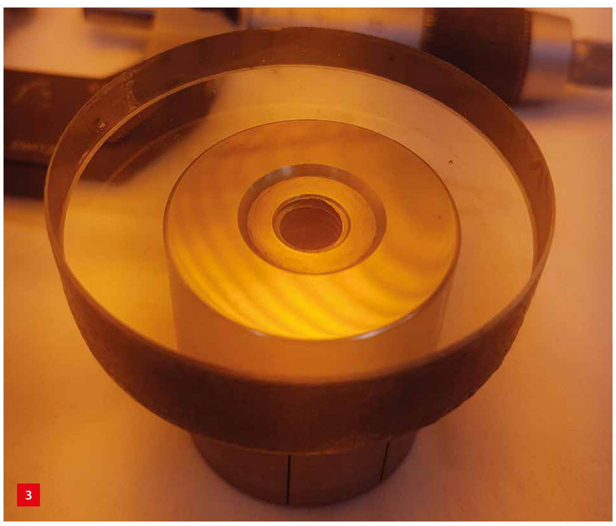
Process	Abrasive	Liquid	Disk
Conventional lapping	1-20 µm corundum	Oil	Cast iron (hardened)
Diamond lapping	1-20 µm diamond	Oil or water	Epoxy mixed with metal particles
Polishing	1-8 µm diamond	Oil or water	Flat carrier disk with adhesive polishing pad
Chemical mechanical planarisation (CMP)	10-100 nm silica	Etchant	Flat carrier disk with adhesive CMP pad

Also, many precision components are lapped. The increasing precision of turning and milling machines cannot keep up with the industry's current hunger for precision. Sometimes grinding and EDM might be a solution. But true precision is only obtained by lapping. Flatness values under 1 µm are common. Surfaces roughness is often below R_a 100 nm.

Measuring extreme flatness

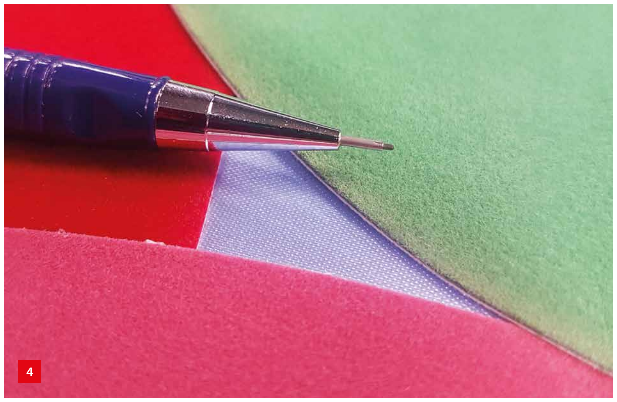
Even the most accurate coordinate measuring machines can not measure the flatness of a lapped plane. Their measuring uncertainty is simply too high. Flatness values under one micron are measured optically – using an interferometer. That compares the flatness of a workpiece to a reference with a known flatness. This reference usually is an optical flat: a glass disc with a flatness under 50 nm. The measurement is taken without contact between optical flat and workpiece.

With lapping, the optical flat is often placed directly on top of the lapped surface. Under monochromatic light, fringes appear (Figure 3): a pattern of lines, alternatingly dark and bright. This is the most basic form of an interferometer. The flatness of the workpiece reads from the straightness of the fringes. The straighter they are, the flatter the workpiece. In order to see the fringes, the surface must reflect light. This occurs below a surface roughness of about R_a 100 nm.



3

Flatness measurement with an optical flat laying on top of a lapped workpiece. The fringes indicate a flatness of 500 nm. The orange colour derives from the 589-nm monochromatic light used in the measurement.



4

Polishing pads come in a large variety: wool, polyurethane, artificial silk and many more. The hardness and thickness of the pad are important parameters. Different types have their own colour for easy recognition.

Another application for lapping is improving the flatness of precision parts that are non-magnetic. Surface grinding machines usually have a large magnet to hold the parts – which is ideal for steel parts. Nobby: "Often clients ask me to improve the flatness of parts of aluminium, titanium or austenitic stainless steels. They expect me to grind their parts. When I tell them lapping is easier, faster and therefore cheaper, the client is happily surprised." Lapping has a unique way of holding the parts: they lie freely on top of the lapping disk. Only roughly held in place by a work holding plate. This way, there are no clamping forces on the workpiece – in contrast with the use of a machine vice or a three-jaw chuck. No clamping forces means no deformation and that is the basis for extreme precision.

Conventional lapping and diamond lapping

When grinding, the abrasive is held by the grinding wheel. With lapping, the abrasive is free, suspended in a liquid. Rubbing two items together with some abrasive lapping fluid in between them, will cut both items. The same happens with a workpiece and the lapping disk. This constantly jeopardises the flatness of the lapping disk.

This flatness is crucial since the workpieces are a 'reflection' of the lapping disk's flatness. If the disk is convex, the workpieces will turn out concave and vice versa. To keep the lapping disk flat during lapping, three or four lapping rings continuously rotate on top of the lapping disk, slowly cutting the lapping disk flat in a controlled manner. In case the lapping disk would turn convex, the operator moves the rings' centres of gravity a few millimeters towards the centre of the disc. In that way the disk turns flat again. Nobby summarises: "The most important thing during lapping is the flatness of the lapping disk. The better it is, the flatter the workpieces will turn out."

The abrasive is usually corundum or silicon carbide. Lapping disks used to be made of metal – often hardened cast iron. A revolution came about 40 years ago: diamond lapping. The ceramic abrasive was replaced by diamond, while the metal lapping disks were now made of epoxy containing metal particles. The epoxy disks are available with different metal particles, such as iron, copper or tin, which results in a different hardness. A lapping disk with high hardness is more wear-resistant and is therefore used for coarse lapping. Softer lapping disks, giving a better workpiece finish, are used for finishing operations.

6

Nobby Assmann placing the winning workpiece on the Zeiss LSM 900.

Both conventional and diamond lapping will give a perfect flatness. Additionally, diamond lapping will give a bright finish. That is because the epoxy disks will hold some diamond grains that will polish the surface. With conventional lapping all the abrasive grains will roll between the lapping disk and the workpieces – just like rolling meat balls. This results in a dull surface. Nobby: "Both have advantages; I use conventional lapping for roughing and diamond lapping for finishing." Cleaning the parts between operations is highly important. Coarse grains from roughing might cause unwanted scratches during finishing.

Flat polishing

Diamond lapping easily gives a surface roughness of R_a 25 nm or better. Further improvement by diamond lapping is often time-consuming and costly. An easier way is flat polishing. The lapping disk is then replaced by a flat carrier disk covered by a self-adhesive polishing pad (Figure 4). This process resembles lapping – apart from the abrasive, which is held by the polishing pad. It is just like polishing a car's paint or your grandmother's silver cutlery.

Flat polishing is a quick and easy way to improve the surface finish. The flatness, however, will not improve and, in fact, can get worse. Since the workpiece is pushed into the soft polishing pad, the edges of the workpiece will round off. It is up to the operator to try and limit the rounding of the edges. Just like with lapping, flat polishing is performed in multiple stages: from coarse to fine. Grain sizes are usually between 10 and 1 μm. After polishing, the surfaces are bright and shiny, but under a microscope cutting marks can still be seen.

CMP for optical surfaces

Improving the surface roughness of a shiny polished surface requires chemical mechanical planarisation (CMP). This is similar to flat polishing, on a polishing pad. The abrasive is suspended in an aggressive fluid that etches the surface while polishing. Grain sizes typically are 10 to 100 nm – often silica or corundum.

The part that Nobby won his second award with [V1], was ultimately polished using CMP – after surface grinding, conventional lapping, diamond lapping and two stages of flat polishing; see Figure 5 for a comparison of the results of the various processes. The surface roughness of R_a 540 pm is extremely low. For optical surfaces, though, this is a fairly common roughness. It is the material that made Nobby's effort extra special, since the complicated structure of hardened tool steel is far from ideal. Homogeneous and single-crystal materials give the best roughness, while glass has an amorphous structure, which makes it ideal for polishing – that is why glass is often used for lenses.

A typical CMP application is polishing wafers for the semiconductor industry. Materials such as silicon, silicon carbide and sapphire have a very high hardness and a homogeneous composition. Surface roughness values below 2 nm are very common.

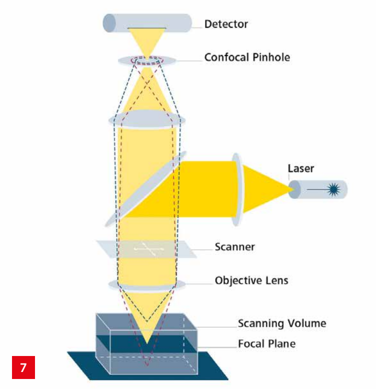

5a


5b


5c


5d

A comparison the results of the various processes.
(a) Conventional lapping. *(b) Diamond lapping.* *(c) Polishing.* *(d) Chemical mechanical planarisation.*



7

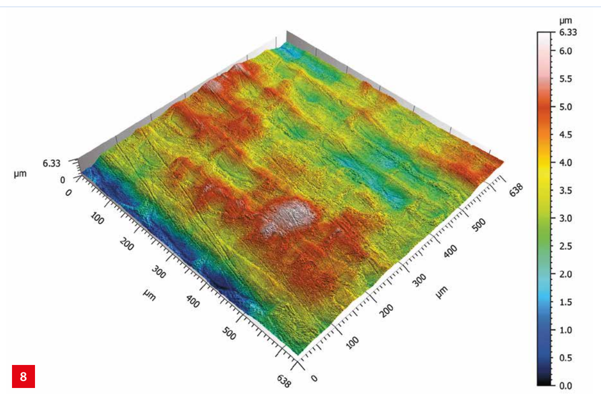
Working principle of the laser scanning confocal microscope Zeiss LSM 900 for materials. (Image courtesy of Zeiss)

Measuring extremely low surface roughness

Many machine shops measure roughness with a surface roughness tester. Such a device scans the surface using a 60° diamond cone with a tip radius of 2 μm or more. It measures milled, turned and most ground parts just fine. For nanometer surface roughness, however, the tip is just too blunt and the resolution of the device is just not good enough.

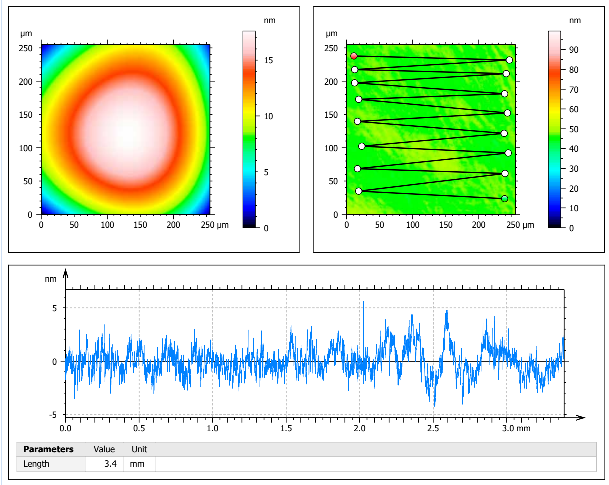
Atomic force microscopy and confocal microscopy are more appropriate to measure polished surfaces. "The roughness had to be measured on a Zeiss device, for the competition," Nobby says. "And by the way, glass was not allowed as workpiece material." He had the surface roughness measured on a laser scanning confocal microscope, the Zeiss LSM 900 (Figure 6). It scans the surface using a laser (Figure 7), taking pictures at several heights with a very small depth of field. Software uses this stack of pictures to reveal the 3D topography (Figure 8).

The Zeiss ConfoMap software easily calculates the roughness of the surface. Since it is an area that is inspected, these are all *S*-type surface roughnesses: S_a and S_z, for instance. Part of the Zeiss competition for the smoothest surface was that R_a and R_z should be calculated along a line of at least 1.25 mm. ConfoMap can also calculate *R*-type roughnesses after a line has been drawn manually on the inspected area. In Nobby's case a zig-zag line of 3.4 mm length was used to calculate the winning R_a and R_z values.



8

3D topography scanned with the Zeiss LSM 900. ConfoMap software can calculate surface roughness from this image. (Image courtesy of Zeiss)



ISO 4287 - Roughness (S-L)				
F: None				
S-filter (λs): Gaussian, 2.5 μm				
L-filter (λc): Gaussian, 0.08 mm				
Evaluation length: All λc (42)				
Amplitude parameters				
Rp	1.5	nm		*Maximum peak height of the roughness profile*
Rv	1.6	nm		*Maximum valley depth of the roughness profile*
Rz	3.1	nm		*Maximum height of roughness profile*
Rc	1.7	nm	*No averaging (single value)*	*Mean height of the roughness profile elements*
Rt	5.4	nm		*Total height of roughness profile*
Ra	0.54	nm		*Arithmetic mean deviation of the roughness profile*
Rq	0.67	nm		*Root-mean-square (RMS) deviation of the roughness profile*
Rsk	-0.059			*Skewness of the roughness profile*
Rku	2.7			*Kurtosis of the roughness profile*
Material ratio parameters				
Rmr	100	%	*c = 1000 nm below highest peak*	*Relative material ratio of the roughness profile*
Rdc	1.1	nm	*p = 20%, q = 80%*	*Roughness profile section height difference*

9

Measuring report of the winning workpiece. Top left: the scanned surface. Top right: waviness filtered out, and a manually drawn zig-zag line included. Middle: roughness profile along the zig-zag line. Bottom: measured surface roughness.

"I am really impressed by the microscope's resolution," Assmann comments on the LSM 900. "With an optional accessory it is even possible to extend the resolution far below one nanometer. This option uses total interference contrast to measure R_a roughness of only tens of picometers. Figure 9 shows the final measuring report.

Lapping: future or history?

Lapping is a very old technique – it looks rather old-fashioned. Is there room for such a labour-intensive classical production method in our digital future? Manufacturing seems to be limited to CNC turning and CNC milling these days. Cylindrical grinding is occasionally replaced by hard turning. Jig grinding seems to be forgotten – precision CNC milling is said to reach the same level of accuracy.

Still, there is not a single finishing method that achieves the form accuracy of lapping. And no other process can achieve the roughness of polishing. Our industry's future will depend on lapping, polishing and CMP. Besides the modern CNC machines with their flashy controls, there will always be demand for craftsmen (male or female) who know the art of lapping and polishing. "The lapper/polisher is a rare species in the metalworking habitat," Nobby concludes. "You might recognise one by the dirty hands and a satisfied smile when the work is done."

VIDEO

[V1] "2021 measuringhero awards", *youtu.be/6YsMfFBQmJM*