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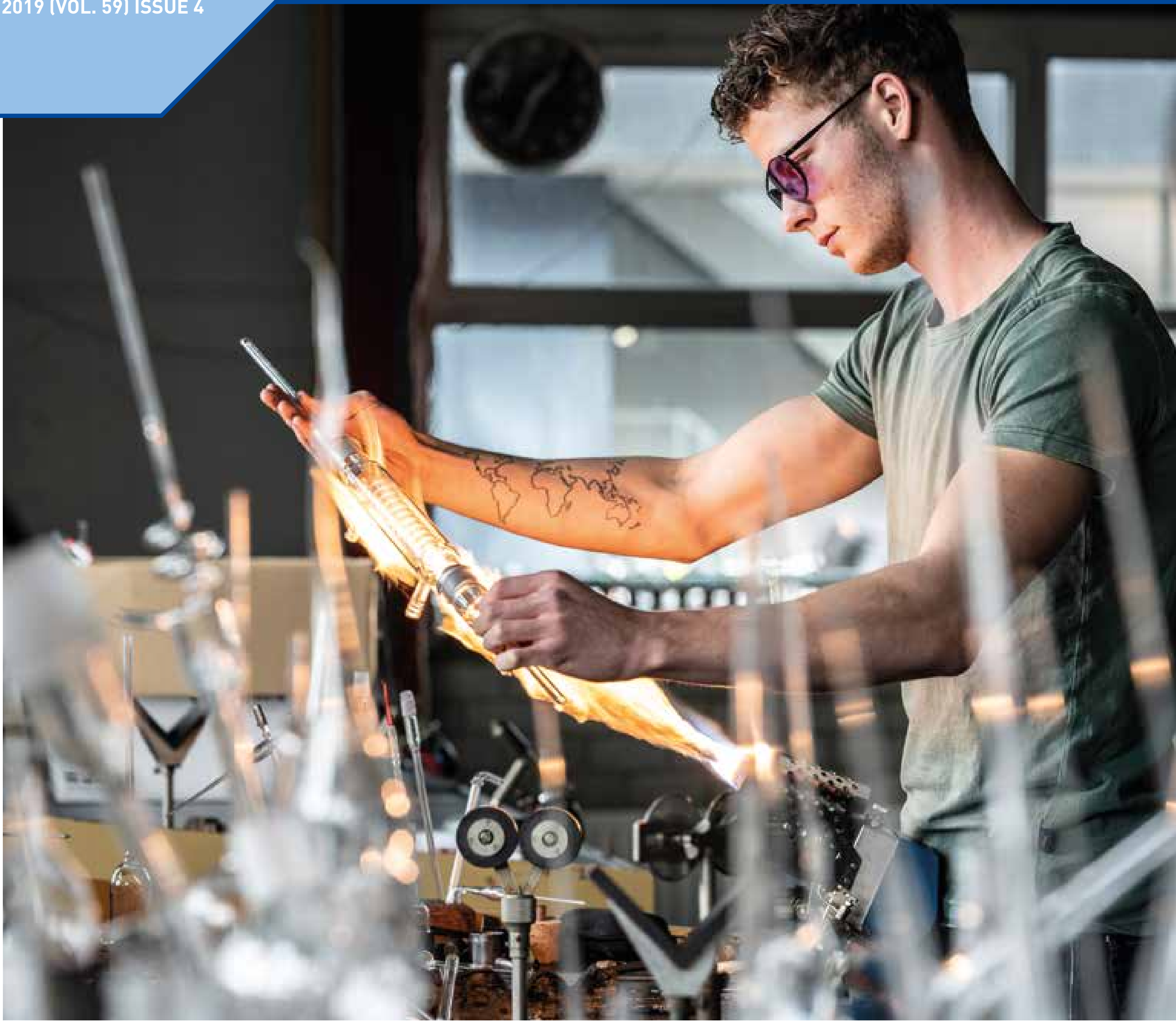

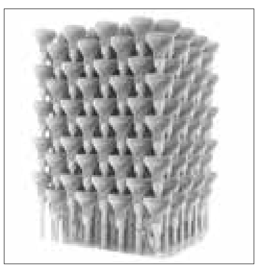

- THEME: MANUFACTURABILITY
- LIS: MAINTAINING HIGH STANDARDS, TAKING NEW DIRECTIONS
- VALUE ENGINEERING IN HIGH-TECH
- EUSPEN CONFERENCE REPORT

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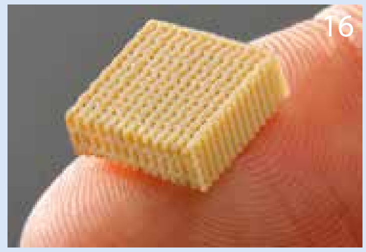
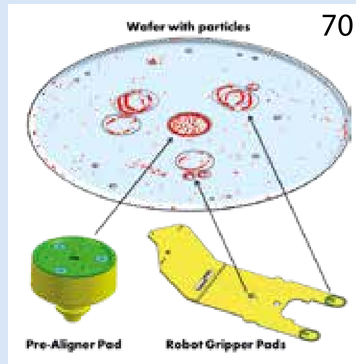
THEME: MANUFACTURABILITY





FEATURES

SMART PARTS, SMART MANUFACTURE...

The sophisticated machines and equipment of the Dutch high-tech industry contain many complex parts. As early as during the development phase there is close contact with suppliers in order to safeguard the manufacturability of these parts with respect to cost price, delivery time and quality. Integration of design, manufacturability and production process is crucial, and software is the connecting factor.

“First time right” is key, so no mistakes. This is only possible if the entire production process is controlled and there are design guidelines available that make this possible. A trend in this respect is ‘digital twins’; precise software simulations during all stages of the design and production process ensure that the final physical product fully meets the functionality requirements that the designer had in mind.
Production processes must be capable of processing digital product information and delivering predictable quality. The most important processes are CNC machining (subtractive) and 3D printing (additive manufacturing). The combination of these two main categories (hybrid production technology) is fully in the spotlight. Machining operations are carried out on 3D-printed parts, for example for the application of precisely defined interface surfaces or for achieving the desired surface roughness.

Some of the unique selling points of 3D printing are:

- the rapid manufacture of prototypes and mock-ups (rapid prototyping);
- the great design freedom (both external and internal complex shapes), enabling the manufacture of complex, unique products (e.g. medical implants);
- the optimisation of parts for the desired mechanical properties (strength, rigidity, mass, natural frequency, thermal and fluid properties);
- the integration of components in a monolithic structure (less assembly, more compact construction, elimination of play);
- the combination of various materials in the same part (multi-material printing).

These USPs of 3D printing enable the Dutch high-tech industry to strengthen its competitive position. Examples of existing applications in the Netherlands are microreactors (Shell STCA), miniature heat exchangers for temperature control in precision devices (ASML), integration of cooling channels in moulds for operational efficiency improvement (RiZZ Plastics, VMT Products), topology-optimised components for the high-tech industry (ASML) and the aerospace industry (Airbus Space), lightweight complex components for aerospace applications (Airbus Space), monolithic adjustment mechanisms for optical instruments (NTS Optel, VDL ETG), and implants for medical applications, such as dental implants (Oceanz), vertebra (BAAT medical, FMI Instrumed), skull implants (Xilloc), and prostheses and ortheses for orthopaedic applications (Buchrnhornen).

A special application of 3D printing is the reverse engineering of machine parts whose product documentation has been lost, such as spare parts for older trains and defence equipment. A CAD model of the desired part is first made using a 3D scan of an existing part, which can be modified if desired. 3D printing is then used to create a lost-wax casting mould based on this model, which is then used to rebuild the ‘old’ part using casting technology and post-machining (Castlab).
Developments in the field of high-grade production technology, in particular additive manufacturing, are taking place at breakneck speed. Unfortunately, the Dutch high-tech industry is still insufficiently aware of the possibilities of this. The design must take into account the possibilities, features and limitations of the production technology. In collaboration with High Tech Institute, Fontys Centre of Expertise HTSM has developed the “Design for additive manufacturing” course for this purpose.

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DIRECT CONTACT BONDING

SRON has produced a set of immersed gratings for ESA's Sentinel-5 mission. Manufacturing them involved the direct bonding of a silicon prism to a thin silicon wafer with etched grating lines. For space mission hardware like this, product assurance and quality assurance requirements are especially stringent. After manufacturing the immersed gratings and integrating them into a support structure, a comprehensive campaign to test the performance of the immersed gratings and their resilience to launch conditions and space environments was organised to qualify the product.

RENÉ WANDERS, PHILLIP LAUBERT AND RALF KOHLHAAS

Direct contact bonding is a remarkable process in which two surfaces are pressed against each other and – under the conditions of perfect parallelism and low roughness of the two surfaces – become a single component by intermolecular forces. For the Sentinel-5 mission, a flagship satellite mission for the measurement of greenhouse gases from the European Space Agency (ESA), special optical components called immersed gratings were needed (Figure 1). Their integration should considerably reduce the instrument size and therefore the cost of the mission.

SRON took the challenge to produce and qualify such immersed gratings for this mission, involving the crucial step of direct bonding of a bulk silicon prism to a thin silicon grating for the first time [3]. This article describes the difficulties encountered, with special emphasis on the space mission aspects.

For the detection of greenhouse gases from space, sunlight reflected from earth is detected with a spectrometer which splits incident light in different wavelengths. From the absorbed light at different wavelengths the abundance of different gases in the atmosphere can be inferred.

The heart of a spectrometer is the grating. A silicon immersed grating, shown in Figure 2, consists of a silicon prism (supplied by Thales SESO) with a grating surface on one side containing a series of equally spaced grooves. In the wavelength range of interest (1.6-2.4 μm), silicon is transparent. Light can enter the prism from an entrance surface and hit the grating surface, which subsequently splits the light in different wavelengths. Upon leaving the prism again through the entrance surface, the ability of the grating to resolve different wavelengths is increased by the refractive index of silicon (n = 3.4), which acts as the immersive medium. Due to the increase in resolving power the size of the spectrometer can be reduced.
In order to meet the stringent requirements on the prism (such as an angular accuracy of 90 arcsec between surfaces and a surface flatness of 10 nm rms) and the grating (such as a line periodicity of 2,070 ± 5 nm) a bonding approach was chosen. This allowed to separately produce the prism and the grating pattern on a 150-mm-diameter wafer, unlike the monolithic immersed grating for the Tropomi instrument [4, 5]. For the grating, standard lithography equipment could be used and the best gratings were chosen after production.

AUTHORS' NOTE

All authors work for SRON Netherlands Institute for Space Research; René Wanders as a mechanical design engineer, Phillip Laubert as a product assurance manager and Ralf Kohlhaas as an instrument scientist and MAIT (manufacturing, assembly, integration and testing) manager for immersed gratings.

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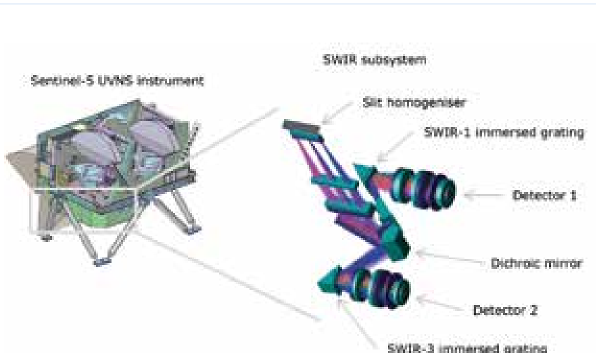

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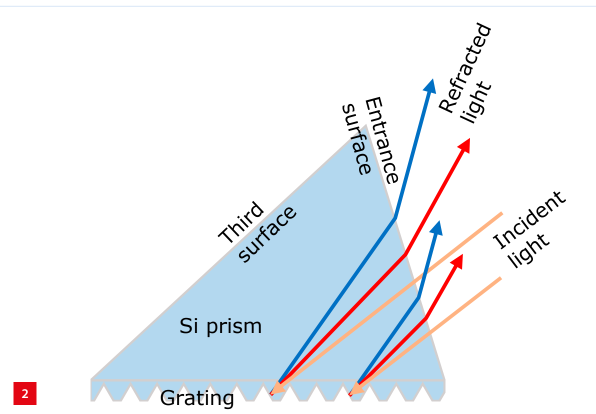
Sentinel-5 UVNS (Ultraviolet Visible Near-Infrared Shortwave) instrument [1] and optical design by Leonardo [2], including the SWIR-1 grating and the SWIR-3 grating (SWIR stands for short-wave infrared).



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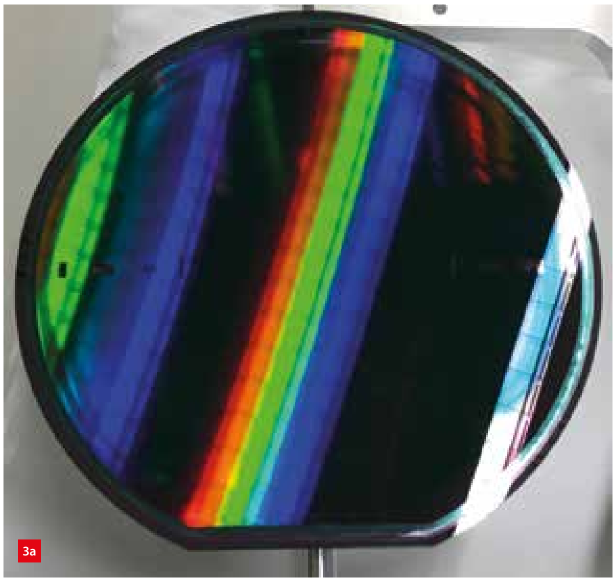
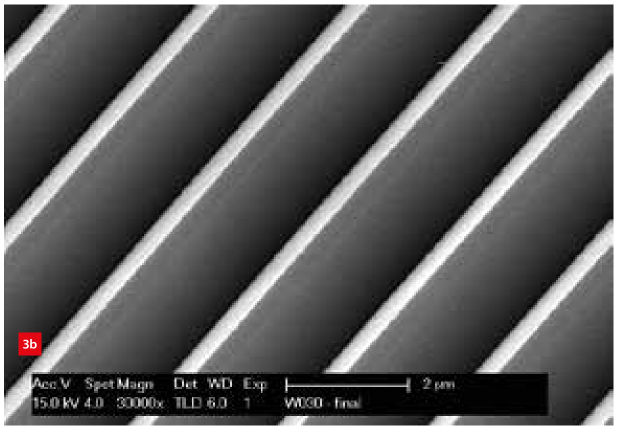
Working principle of an immersed grating. The incident beam is wavelength-dispersed by the grating and the prism.





Example of a grating.
(a) Photograph.
(b) SEM image of grating lines.

Figure 3 shows an example of a grating. The groove pattern was produced at Philips Innovation Services by KOH etching, which yields a very low roughness of the surface along the atomic crystal planes of silicon. Direct bonding of silicon wafers is a standard process in the semiconductor industry.

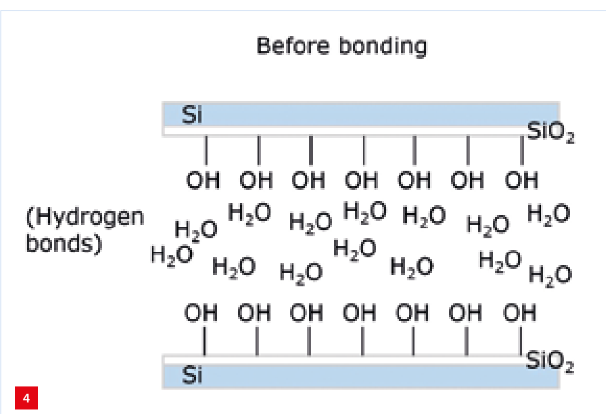
A simplified description of the chemical process taking place in the direct hydrophilic bonding of silicon is shown in Figure 4. After cleaning and plasma activation, silicon reacts with water in ambient air to form Si-OH groups. When two such surfaces are pressed against each other and annealed at high temperature, Si-O-Si bonds are formed. The high chemical bonding strength makes the two components inseparable.

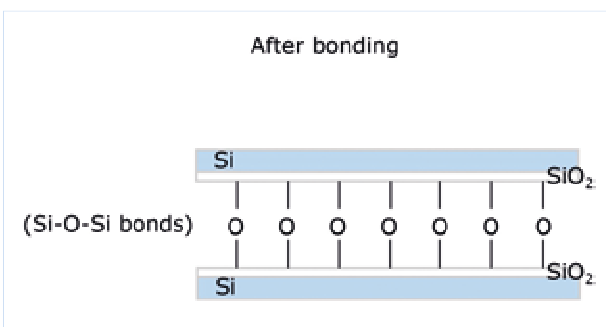
The void-free bonding of a grating with a bulk silicon prism is more challenging than the bonding of two wafers. Only the grating is flexible in this case, which can lead to gaps between the grating and the prism in the bonding process (voids). Furthermore, standard wafer bonders are not equipped to accommodate a bulk prism and are too unstable to fulfil the ±6 arcmin requirement on the orientation of the grating with respect to the prism. For this reason, a standard wafer bonder from AML was modified by SRON (Figure 5).

The bonding procedure

Firstly, the prism was placed in a prism holder structure. The orientation of the prism with respect to the holder was measured in a coordinate measuring machine. Then the prism holder was placed in the bonder and actuators were used to compensate for the measured differences. The grating was clamped to the inside of the lid of the bonder. The prism holder and the grating contain alignment marks and their respective orientations were measured under vacuum through a camera system in the lid of the bonder. Adjusters on the lower stage of the bonder were used to make sure the prism and grating were aligned properly after evacuation of the bonder. An added rotation stabilisation system in the bonder minimised rotational errors during bonding.

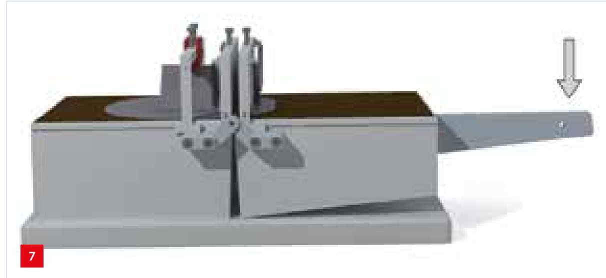
The prism and grating were removed to allow cleaning and surface activation, which had to be done within 10 minutes before the actual bonding for a successful outcome. Both were placed back in the bonder and the surface was inspected one last time for cleanliness.





Hydrophilic bonding of silicon.

Bonder with the prism in the vessel and the grating on the lid.



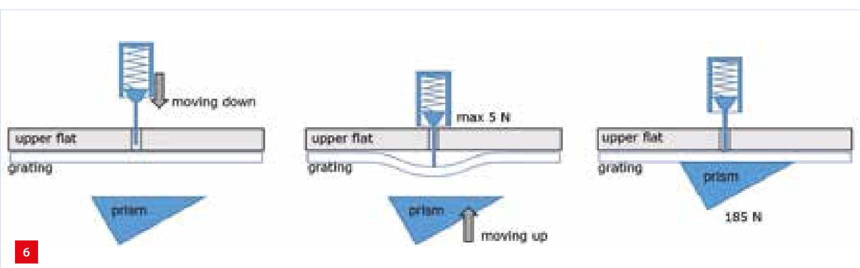
CAD model of the break table. The immersed grating with overhanging wafer parts is clamped onto the table. A handle is pressed down to break the wafer along a groove previously cut with a diamond scribe.

Then the actual bonding took place, a schematic description of which is shown in Figure 6. The grating is bent by pressure of a pin connected to a spring in the centre. The prism on the lower stage is moved upwards and pushed against the rear end of the grating, pushing back the pin. The process takes place in vacuum to allow for the evacuation of air and most of the water from the bonding surfaces.

The newly made immersed grating was then checked with an infrared camera for the presence of voids between grating and prism. The perpendicularity between grating lines and prism sides was checked with an overlay tool that was pushed to the prism while overlaying the grating. From the overlay tool and the alignment marks in the grating, the perpendicularity could be measured. Finally, the grating was fused together in an oven, 16 hours at 150 °C in a nitrogen-rich environment.

The grating is larger than the surface of the prism. After successful bonding and annealing, overhanging grating parts were therefore removed by a scribe-and-break process. An illustration of the break table is shown in Figure 7. A diamond scribe cuts a groove in the rear end of the grating, the break table is then used to break off the overhanging wafer piece along the cut on the wafer.

As a last step in the immersed grating production process, SRON applied a high-reflection coating and a protective coating on the grating surface. At SILAS in France an antireflective coating was placed on the entrance surface and an absorptive coating on the third surface. For these coating processes heritage within SRON existed from earlier projects. Early in the project, coating samples were produced and were tested in a full environmental test programme including adhesion/abrasion testing.



Schematic description of the bonding process. First the wafer is bent by pushing down a pin, then the prism is pushed onto the wafer.

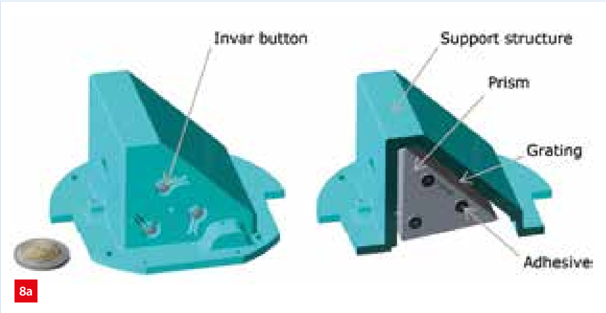
The immersed gratings were fitted into a titanium support structure by VDL ETG (Figure 8). Invar buttons with adhesive channels inside were glued to the support structure and the prism. Flexures in the titanium accommodate the thermal expansion and contraction differences between silicon and titanium, to prevent overstressing the assembly.

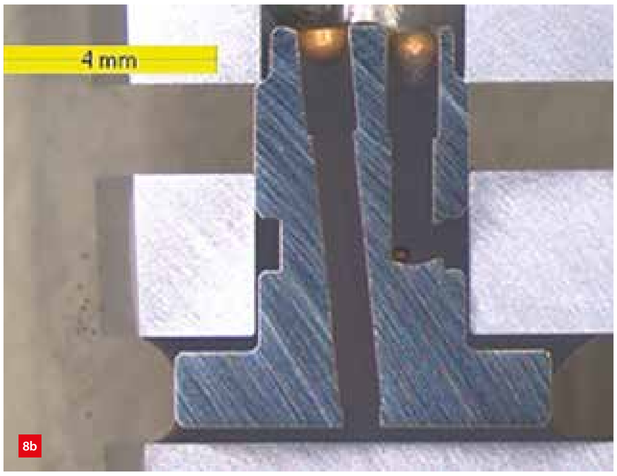
For the adhesive joints a test campaign was conducted already in 2014 to qualify this process. For this purpose, a large number of simplified test items (dummy buttons, dummy prism, dummy mechanical support) were created, assembled and stressed in an accelerated lifetime test to verify the reliability of the mechanical connections under extreme mission conditions. This is an example of how product and quality assurance guided the project already in early stages of the project.

Product and quality assurance

Contributions to ESA programmes are typically guided by a vast set of ECSS standards. ECSS is the European Cooperation for Space Standardization, touching engineering, management and quality disciplines. Following ECSS throughout Sentinel-5, periodic reviews were conducted to discuss the hardware status, its problems and deviations from those requirements that could not be met.

Early in the project, the preliminary design review took place, where the high-level architecture was being finalised and where plans were made for procurement and qualification. Later in the project, in the critical design review, the key elements of the design were finalised based on the results obtained in the previous phase. Other reviews declared readiness for manufacturing or readiness for testing, among other things.





Support structure for SWIR-3 immersed grating.
(a) Overview (left) and cross-section (right).
(b) Cross-section of a test sample of the Invar button (blue) with adhesive (black).

Product assurance has a key role when it comes to negotiating with the customer about what can be achieved and what not. Compliance with requirements must be substantiated by heritage (past performance), analysis or test results. Quality assurance focuses on the quality of the finished product.

Special attention was given to materials and processes that had to be qualified for this particular application. This posed a challenge for product and quality assurance because an immersed grating's performance can only be confirmed on a finished product. It depends on two factors, the quality of all constituents and the processes that connect them.

As for the constituents (prism, grating element, coatings, mechanical support structure, adhesive bonds), the requirements in Sentinel-5 were so challenging that the verification of the quality of each item touched the capabilities of the verification method. For the assembled products (results of the connecting processes), similar difficulties were experienced, regarding zero voids, minimal surface defects and cleanliness levels almost beyond measurement accuracies. Preventing failure on these requirements was a real challenge for quality assurance.

Throughout the whole process dedicated cleanliness monitors confirmed the cleanliness levels of the hardware, invoking cleaning operations where needed. Two different types of monitors were used: particle deposition monitors and molecular contamination monitors. Particle deposition monitors detect the number of particles deposited on a CD-sized glass witness plate; particles of less than 8 µm are scanned and counted by means of contrast imaging. The requirement for particles at delivery was 30 ppm surface coverage.

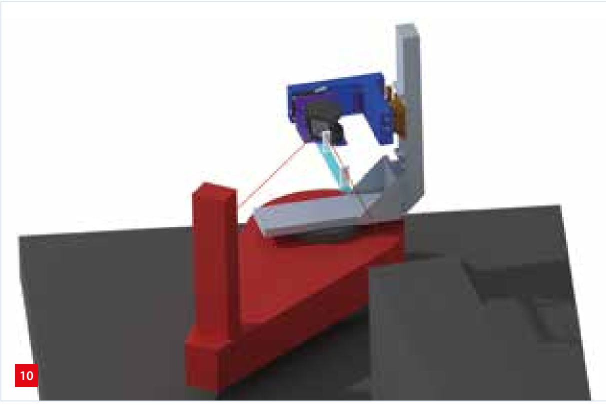
Apart from this, visual inspections took place in a dedicated inspection area with blackened walls and various lighting conditions including black light, confirming the absence of visible particles.

Molecular contamination measurements were more complex due to the high level of uncertainty of the measurement, which itself was close to the project requirement: max 50 ng/cm^2. The measurements were similarly taken by transmission measurements on 1-inch-sized contamination sample plates. In some cases, even the freshly cleaned test sample revealed a result close to the requirement. An important lesson is to use 'fresh' samples to minimise a contaminating side-effect of packing, handling and storage.

In-process control assured keeping the product clean and traceable during a vast number of packing, handling and shipment steps to numerous subcontractors and test facilities. The following of established procedures and a thorough documentation discipline were key to meet cleanliness and traceability requirements for the simultaneous production and testing of six flight models (two for each of the three Sentinel-5 satellites) and two flight spares.

Finally, effects of long-term storage of the immersed gratings are verified by dedicated coating witness samples.

Storage container with an immersed grating bolted onto an internal platform together with a witness sample holder in the bottom right.



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Stray-light measurement. Laser light from the black box is scattered by the immersed grating and collected by the detector (red). The central stage allows 6-DoF manipulation of the grating.

These samples are stored together with the finished immersed grating in the same storage container (Figure 9) – to be extracted and verified in periodic intervals.

Test campaign

A rigorous test campaign was organised for validation of the early prototypes, qualification of the qualification model and acceptance of the actual flight models and flight spares. These tests can be subdivided into performance tests and environmental tests. Performance tests measure the optical performance like optical efficiency and stray-light characteristics, while the environmental tests assure the immersed gratings will not degrade in the operational environment.

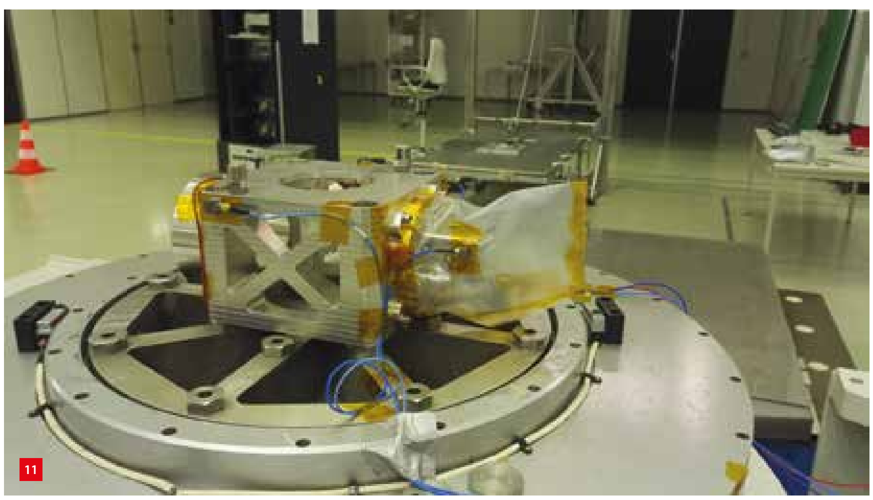
The immersed grating's optical efficiency was measured with a photospectrometer over the complete operational spectral range. An integrating sphere detector captured all the light refracted by the immersed grating. The average optical efficiency was about 60%, more than the required 55%. The sensitivity to polarisation, strongly dependent on wavelength, was well below the required ±0.17. This measurement was performed at TNO.

Also, the stray-light characteristics of the immersed gratings were measured. For this measurement the immersed gratings were placed in a converging infrared laser beam (Figure 10) using a 6-DoF stage (DoF = degree of freedom). A motorised detector scanned the light intensity around the immersed grating in the dispersion plane. To measure in other planes, the 6-DoF stage was used to change the orientation of the immersed grating, upon which the detector performed another scan. The immersed gratings were within specifications for stray light [1]. This measurement was performed at the ESA-ESTEC optical lab.

The wavefront error of the immersed grating surface was constructed from Fizeau interferometer measurements. The errors were about three times smaller than the 900 nm rms required for the total wavefront error. With the defocus subtracted this was less than the required 180 nm rms. The largest contributions to the wavefront error were found to be wafer thickness variations and lithographic inaccuracies since the prism surfaces were polished down to a typical surface shape error of < 10 nm rms.

The environmental tests simulated the harsh conditions of a rocket launch and the vacuum of space. For the vibration tests the immersed grating was mounted on an electro-dynamic shaker at ESA-ESTEC (Figure 11) and subjected to sinusoidal vibrations of up to 44 g and random vibrations of up to 52.6 g rms for qualification. For shock testing the immersed grating was mounted on a metal ringing plate, which was excited by a falling pendulum hammer calibrated to provide shocks with instantaneous accelerations of up to 500 g.
To test for structural damage the grating was subjected to a low-level sine sweep before and after high-level vibrations and shocks. This test generates a before and after frequency response and by comparing the peak locations and peak values between these, it can be inferred whether structural damage occurred. This procedure and visual inspections confirmed that no damage had occurred. The bonding between wafer and prism survived.

The optical performance and mechanical integrity of the immersed grating should not be degraded by the cold vacuum of space. In a dedicated cryostat (Figure 12) built by SRON with an optical read-out system, the rotation of the prism was measured during various temperature cycles with respect to a solid mirror block inside the cryostat. For qualification the temperature ranged from +57 to –103 °C. Using a flat reference, an autocollimator measured that the prism rotation was < 50 arcsec and the repeatability was < 5 arcsec. The interferometer detected no deformations of the immersed grating surface.



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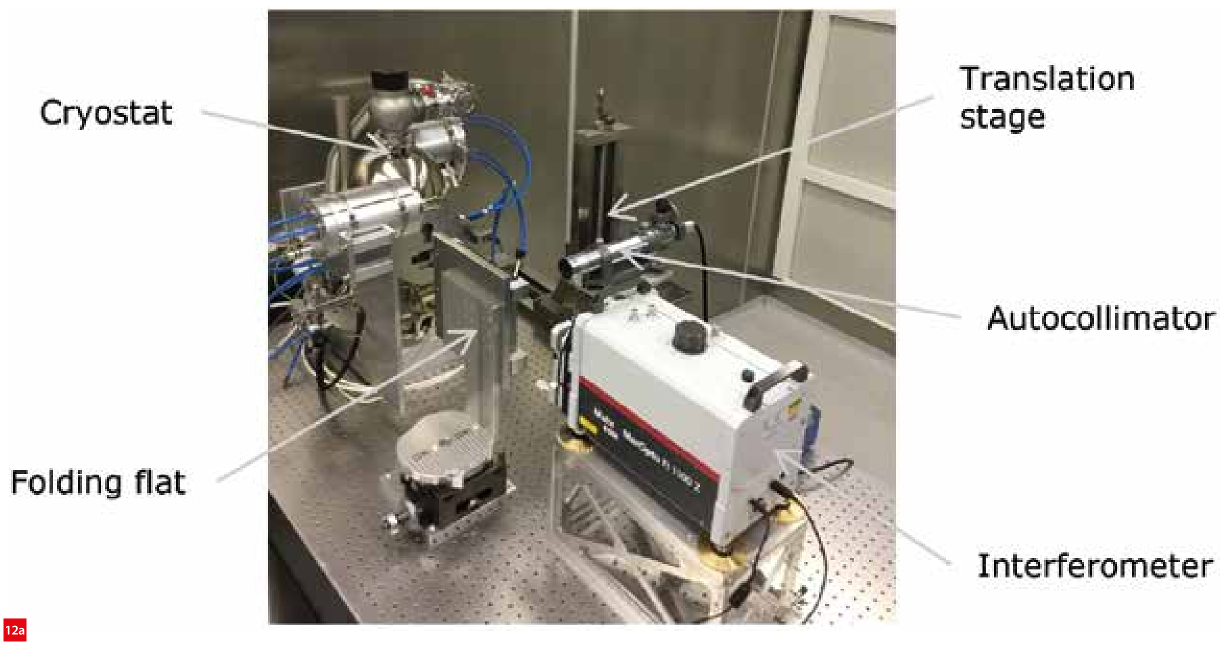
Sentinel-5 immersed grating in a plastic enclosure on the shaker of the ESA test centre operated by ETS (European Test Services). In the background, the shock bench can be seen.



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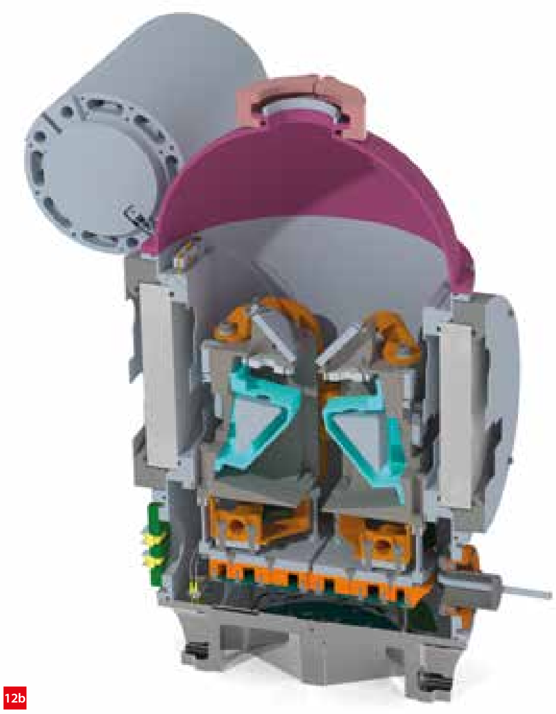
Dedicated cryostat for testing optical performance and mechanical integrity of two immersed gratings (seen in the middle).
(a) Set-up at SRON; the folding flat outside the cryostat acts as a reference for the immersed grating.
(b) Schematic cross-section of the cryostat.

Before and after all the environmental test steps the position and rotation of the prism was measured with respect to the support structure using a coordinate measuring machine. At no time had the prism measurably been shifted or rotated by environmental testing.

To conclude

SRON has built and delivered all six flight models and two flight spares. By virtue of SRON's space mission heritage, its precision engineering expertise and an innovative manufacturing process, the immersed gratings will contribute to Europe's earth observation programme, monitoring the health of our planet. Launch of the first Sentinel-5 is scheduled for 2021. Thanks go out to all of the immersed gratings team members within SRON and SRON's project partners.



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SENSOR-BASED ADAPTIVE LASER MICROMACHINING

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Within the Horizon 2020 project Adalam, a novel depth sensor has been successfully integrated into a laser micromachining system. This new sensor allows the machine to get feedback on the real machined depth, which is used to automatically adapt the micromachining process. The process results in an increased depth accuracy of the machined structures. This article describes briefly the novel depth sensor, its integration into an existing laser machine, and the results obtained when using this adaptive laser micromachining system.

ALBERT BORREMAN, LÉON WOLDERING, ERIK-JAN DE HOON, MAX GROENENDIJK, MANUEL ZENZ, ROUWEN KUNZE AND ROBERT SCHMITT

Introduction

The inline topography measurement concept (Figure 1) [1] integrates a depth sensor based on a frequency-domain low-coherence interferometer (FD-LCI) [2] into the beam path of a laser micromachining system [3]. The integrated depth sensor can be used to:

- measure the surface topography before machining, to scan for existing surface deviations that can be removed in an automatically generated machining process;
- measure complexly shaped objects prior to machining, to precisely align the machining pattern to the workpiece;
- measure the surface topography while machining a part, in order to adapt the micromachining process, leading to highly increased machining accuracies and no defects;
- quickly validate results after machining.

Sensor concept

The sensor uses the optical interference effect between a reference path and signal path to derive the optical path length difference between these two branches, see Figure 2. The longer the optical path length difference between reference and measuring branch is, the higher the resulting modulation frequency will be. The calculation of the Fourier transformation of the acquired spectrum provides a spectral intensity as a function of the depth. Therefore, for each scanned position, an intensity peak is derived at the distance that represents the depth of the sample [4].

An advantage of the FD-LCI measurement principle over other optical measurement principles is that it can be developed to work in different wavelength ranges. This enables the adaptability to different application requirements.

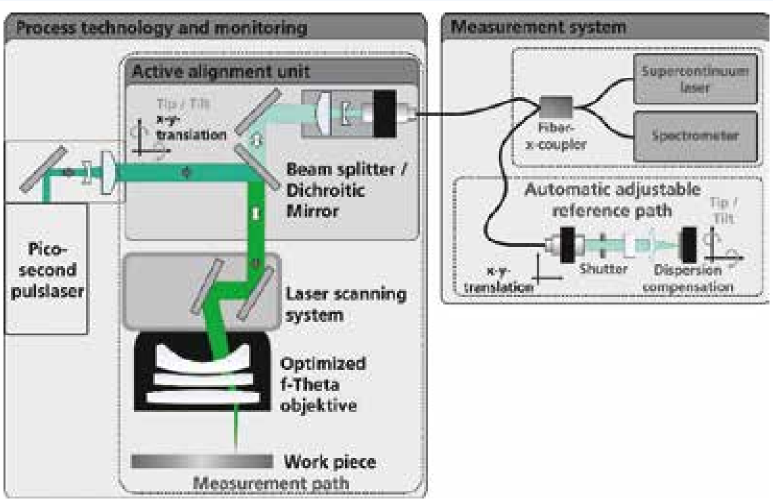
The axial resolution for topographic measurements and the measurement range of an FD-LCI system using a Gaussian-shaped light spectrum are given by Tomlins et al. [5]:

$$Depth_{resolution} \approx 0.44 \frac{\lambda_0^2}{\Delta\lambda}$$

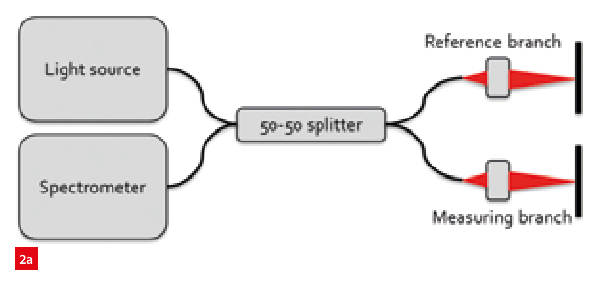
$$Depth_{range} = \frac{N}{4n} \frac{\lambda_0^2}{\Delta\lambda}$$

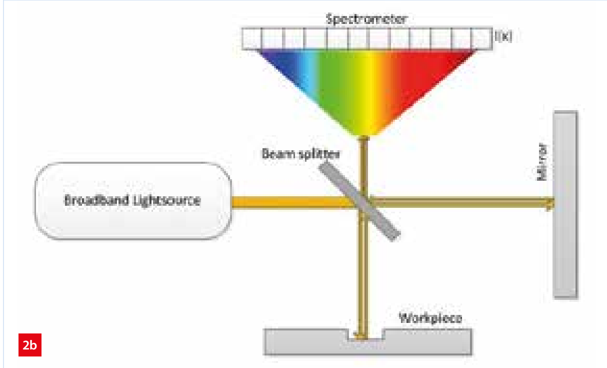
Here, λ_0 is the centre wavelength, and $\Delta\lambda$ the FWHM (full width at half maximum) of the light source. N is the number of pixels of the detector, and n is the assumed average sample refractive index.

To maintain an optimal interference signal while scanning a sample with varying reflectance, the reference path has to be adjusted such that it matches the varying reflected light from the surface. Within the Adalam project [1, 2] an automatically adapting reference path module with a bandwidth of 400 Hz has been successfully developed [6]. Furthermore, the sensor was designed such that it operates at wavelengths near the laser milling wavelength of 532 nm. To be precise, the wavelength range of the sensor beam was



1 Overall system concept including the laser milling modules (picosecond-pulse laser, 2-mirror galvo-scanner laser-scanning system, F-theta lens) and the depth sensor (measurement system, active alignment unit).





Spectral-domain low-coherence interferometer.
(a) Schematic set-up.
(b) Schematic of the light paths.

selected to be 540-595 nm. By doing so the optical path of the sensor and of the laser milling system can be combined in the final part of the optical axis of the machine [6].

The sensor has been successfully developed and tested by Fraunhofer IPT and Demcon. The measurement reproducibility was found to be ±1.5 µm, the measurement range is 900 µm. The initial measurements showed that at the darkest pockets the exposure time is near 1 ms, while at shiny pockets the exposure time is about 0.4 ms [7]. The laser milling beam and the sensor beam have a common path through the F-theta lens.

To avoid aberration of the measurement spot, the F-theta lens had to be optimised for a minimum lateral colour error as well as a minimum chromatic focal shift for the whole wavelength range. Within the Adalam project, Sill Optics successfully developed a colour-corrected F-theta lens that covers 515 nm up to 595 nm with a lateral colour error of less than 5 µm and a chromatic focal shift of less than 30 µm [8].

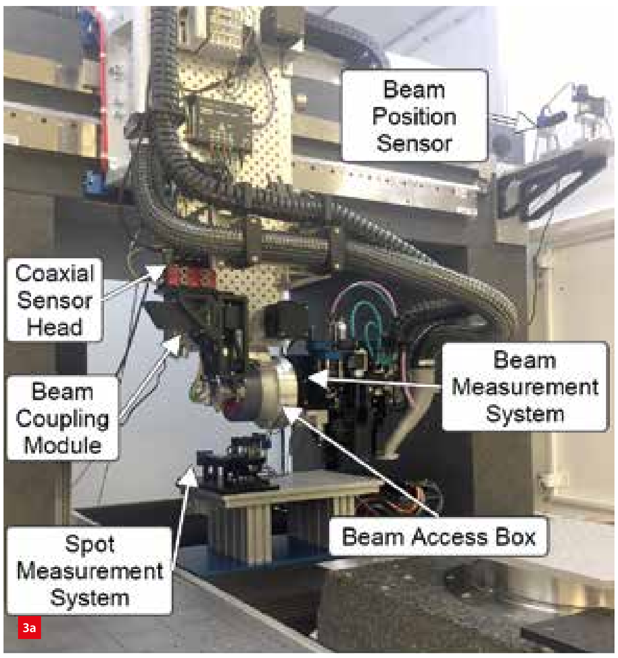
Integration

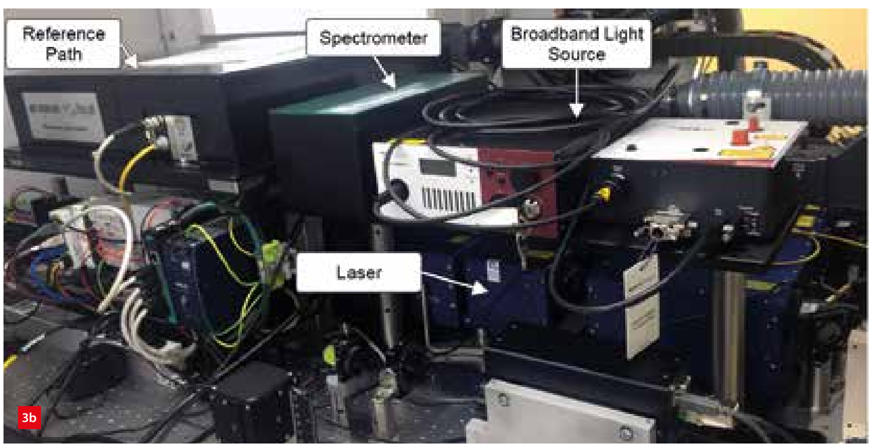
In order to be able to integrate the sensor into the milling machine, three additional measurement tools have been developed:

1. A coaxial sensor head for the alignment of the sensor beam, which is also called the active alignment unit.
2. A beam measurement system that can measure both the laser milling beam and the sensor beam to allow proper alignment and overlap of these two beams.
3. A spot measurement system to measure and compensate for changes over the entire scan field. This system is also used to determine the location of the scan field relative to the machine.

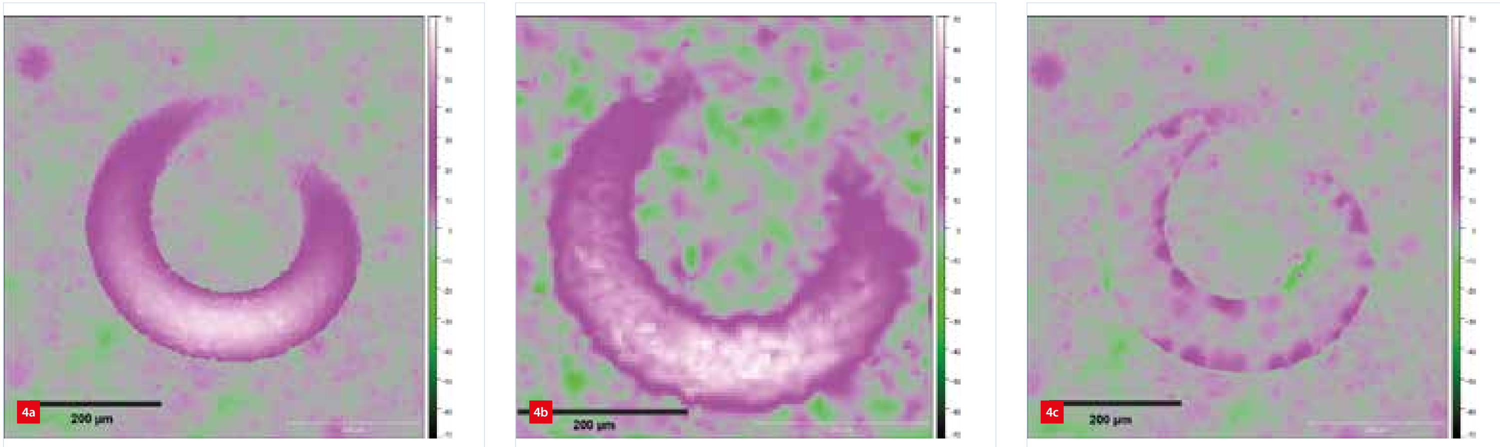
The different components of the measurement system have been successfully integrated into the 5-axis laser micromachining system of Lightmotif; see Figure 3.

To be able to perform depth measurements in machine coordinates, the depth measurement system needs to be calibrated. In particular, the depth and the depth offset have to be calibrated, as well as the centre position and the lateral dimensions.





Overview of the measurement system.
(a) The integrated modules in the 5-axis laser micromachining system.
(b) The relevant components for the depth measurements.



Colour maps of the depth measurement. The height scale ranges from –70 µm to + 70 µm.
(a) Before removal, using a confocal microscope.
(b) Before removal, using the Adalam inline depth sensor (which has lower resolution than the confocal microscope).
(c) After removal, using a confocal microscope.

Results

The inline measurement system makes it possible to perform depth measurements using the same galvo scanner that is also used for machining. An advantage of this solution compared to available off-axis sensor systems, is that measurements can be performed during the machining operation without moving the machining head, and with the same large working distance. The sensor developed in the Adalam project was used to demonstrate two applications:

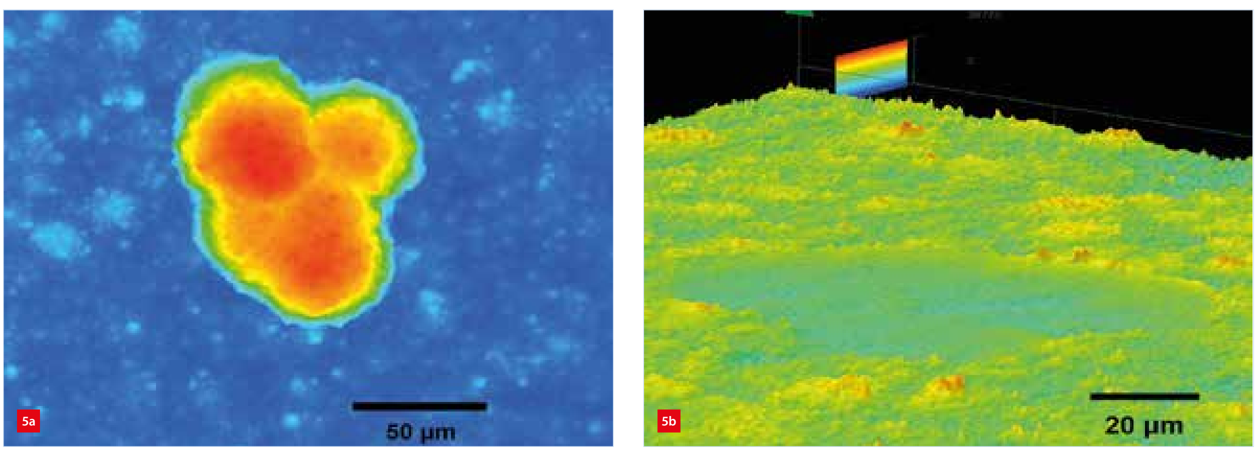
- Measurement of surface defects/elevations followed by automatic removal.
- Adaptive micromilling, where the depth measurements are used to correct the machining process for deviations in order to increase the depth accuracy of milled structures.

One of the applications of the system that is of interest to industry is to measure the surface deviations on ceramic carriers and subsequently using the laser milling system to remove such deviations. Figure 4 shows a typical colour map of a deviation.

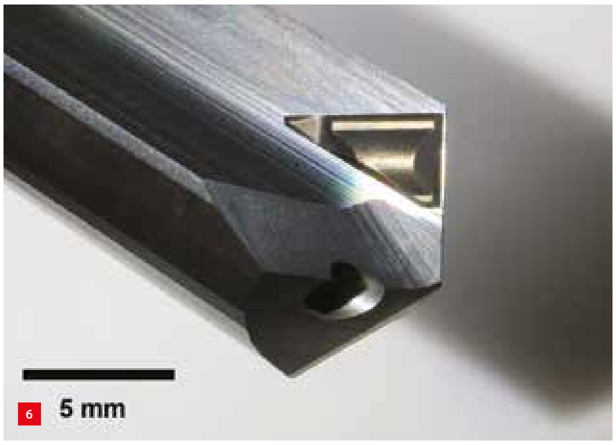
Figure 4a shows the height that has been measured offline using a laser-scanning confocal microscope. Figure 4b shows the measurement performed by the integrated depth sensor. This measurement has been used to automatically determine the volume of the deviation and generate the required laser milling programme for the removal of the deviation. The resolution of the integrated depth sensor is lower than the resolution of the offline scanning confocal microscope, resulting in a lower-resolution image.

Figure 4c shows a laser-scanning confocal microscopy measurement of the same location after laser machining of the defect. The defect has been significantly reduced, and the only elevated regions are at the edges of the defect, where the inline depth sensor did not perform well due to the comparatively low numerical aperture (NA) of the laser-scanning system.

The measurement of a single deviation using the inline sensor took around 200 seconds, acquiring 47 points/second. This is rather slow, mainly caused by the fact that the reflection is diffused and very low due to the nature of the carrier. The laser



Confocal microscopy measurements of a 50-µm-high defect.
(a) Before applying the adaptive removal process (top view; no side view available).
(b) After applying the adaptive removal process (side view).



6 A chip breaker pocket machined into a cemented tungsten carbide drill.

milling process to remove the defect took about 1 minute. To demonstrate how well the defect removal works given a more accurate depth measurement, the same adaptive process was performed on a different defect using an off-line measurement performed by a laser-scanning confocal microscope. Figure 5 shows the 50-µm-high defect before and after laser removal.

The second application targets improving the depth accuracy during micromilling, a process used to machine accurately shaped structures and pockets into any material. Although machining with ultrashort-pulse lasers is an accurate and reproducible process, variations in the process conditions can lead to depth errors of a few per cent of the machined depth. For pockets that are hundreds of micrometers deep these errors may become significant. By using adaptive micromilling this problem can be solved: depth measurements performed during machining provide feedback on the actual material removal, which then is used to correct the process. The result is a highly improved depth accuracy, which is now mainly limited by the accuracy of the measurements.

Within the Adalam project an adaptive micromilling process was developed and tested using the inline measurement system. The demonstrator application was the machining of a chip breaker structure on a drill (Figure 6). Using the adaptive process, it was possible to reduce the depth error by a factor of about 5.

Conclusion

A novel depth measurement sensor that was integrated into an existing laser micromilling machine, has been successfully developed and tested. The sensor is a promising tool for measuring topography offline and inline. Using an automatic reference path allows the sensor to measure objects with different reflectivity. It was proven that rough and highly diffusing materials, like the tested ceramic carriers, can be measured inline, although the measurement time is not optimal and the signal-to-noise ratio (SNR) is limited.

The adaptive application has been successfully demonstrated by removing surface deviations on ceramic carriers. Objects with steep edges are challenging and the NA of the sensor needs to be improved to be able to measure steep edges. Inline topography measurements on a drill reduced the depth error of a chip breaker structure on a drill by a factor of 5.

Outlook

The developed inline sensor system is a promising tool for various applications of adaptive micromachining. The current prototype system however has some drawbacks that require improvement with respect to NA, SNR and reliability before it is ready for the industry.

The development of adaptive micromachining is ongoing. Lightmotif is now developing a machine for industrial production in collaboration with the German high-precision machining centre manufacturer Kern. From this collaboration a new company was founded beginning of 2019, KLM Microlaser. KLM Microlaser and Lightmotif are now developing a laser machining system specifically for high-accuracy micromilling, which amongst others involves further development of adaptive micromachining.

A typical application for this machine is micromilling of stamping or coining tools (Figure 7). Such tools are often made of very hard materials like cemented tungsten carbide (hard metal) and require accurate machining of small features. Laser machining can improve the tool lifetime and the process can be significantly faster than competing technologies. This is a perfect match for laser micromilling, but the high demands for shape accuracy require adaptive machining. KLM Microlaser and Lightmotif expect that the machine will be introduced to the market in 2020.

Acknowledgment

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7 *A typical application of laser micromilling; the machining of an insert stamp tool.*

PRESSURE-CONTROLLED VOIDLESS PEEK PRINTING

High-performance polymers such as PEEK are difficult to print; it is hard to ensure that the properties of printed parts approach those of bulk material. Dutch start-up Bond High Performance 3D Technology, however, has succeeded in developing a unique 3D-printing technology – including system mechatronics, software, slicing technology and process validation – for producing high-end functional parts from PEEK. A recent investment by UK-based Victrex, a leading manufacturer of PEEK, is now helping Bond 3D to bring its technology to the market. Among other things, one of the key elements of Bond 3D's technology, 'bondability', is facilitated by pressure-controlled voidless printing.

PEEK, polyetheretherketone, the best-known member of the PAEK (polyaryletherketone) family of high-performance thermoplastic polymers, finds applications in high-end markets such as semiconductor, medical, aerospace, energy and automotive because of its combination of qualities: lightweight, high strength, chemical resistivity, thermal stability (–50 to +150 °C) and biocompatibility.

Printing challenge

Exploiting the design freedom of 3D printing can further increase the application scope of PEEK, on the condition that the favourable properties of bulk material (certified for markets such as aerospace) are preserved in the 3D-printed parts. That they should do so is not self-evident, as standard 3D-printing using FDM (fused deposition modelling) results in a lower density of the material, as compared to bulk material.

This has to do with the transverse orientation of subsequent layers, each composed of small parallel strands, as ejected by the print nozzle. This transverse lattice-like structure achieves adequate strength in the (horizontal) xy-plane, but has a relatively small contact surface between the neighbouring layers; see Figure 1. The resulting products are anisotropic in their mechanical properties.

As a result, when compared to bulk material, conventionally printed PEEK products have a drastically reduced strength in the (vertical) z-direction and their density is only some 85 per cent. Figure 2 shows the cross-section of a printed product produced by either standard FDM technology or Bond 3D's technology (as explained below), the latter showing a virtually voidless result (density > 99 per cent). This is not only relevant for the mechanical strength of products, but also for their liquid and gas transport properties. For example, manifolds can benefit from 3D printing because of the design freedom it offers, allowing for efficient and complex solutions, but these have to be absolutely leak tight.

Therefore, Bond 3D's challenge was to develop a printing technology for the voidless printing of isotropic products that retain the bulk properties of their base materials. Adding to the equation, PEEK is difficult to print because of its high viscosity in the molten state and its semi-crystalline nature; upon solidification, part of the material will recrystallise, leading to shrink, which will affect the mechanical properties (due to build-up of internal stresses) and dimensional accuracy of the printed products.

Bond 3D

Bond High Performance 3D Technology (Bond 3D for short), founded in 2014 and based in Enschede (NL), delivered a 'proof of concept' 3D printer in 2016. Following further investment that same year, and with the support of high-end technology supplier Demcon, Bond 3D then realised functional models and prototypes, based on its patented technology (12 patent applications thus far). Using the 2019 investment from Victrex, Bond 3D now aims to hit the market next year, offering design capabilities and printing capacity for high-end PEEK products (a sort of 'print factory'). They are also developing 3D printing for other high-tech polymer materials. At the moment, Bond 3D is not planning to sell printers.

WWW.BOND3D.COM

EDITORIAL NOTE

Input was provided by HenkJan van der Pol (CTO), Ton Koster (senior system engineer) and Gerald Holtvlüwer (CEO), all from Bond 3D.

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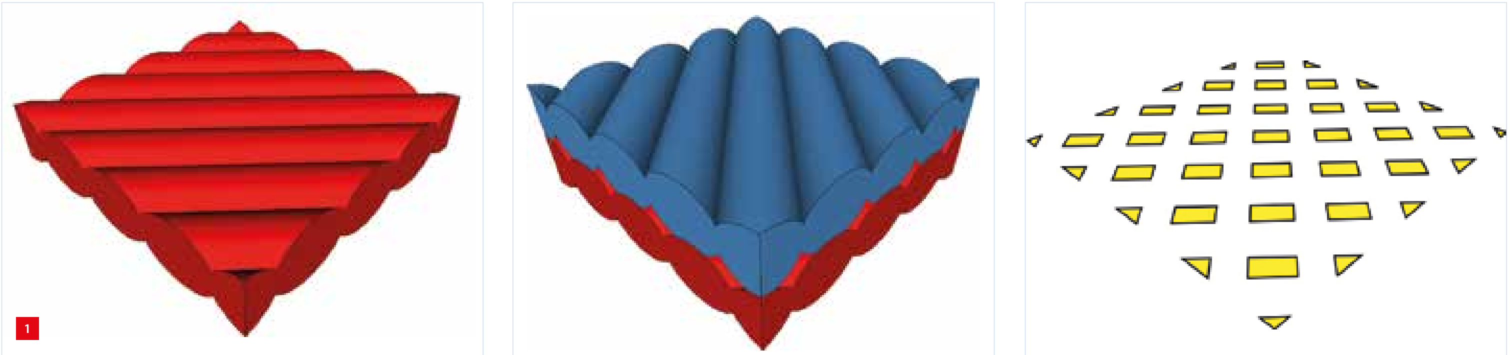


Transverse orientation of neighbouring layers of printed material for adequate strength in the (horizontal) xy-plane leads to a relatively small contact surface (indicated by the yellow areas on the right), resulting in a reduced strength in the (vertical) z-direction.

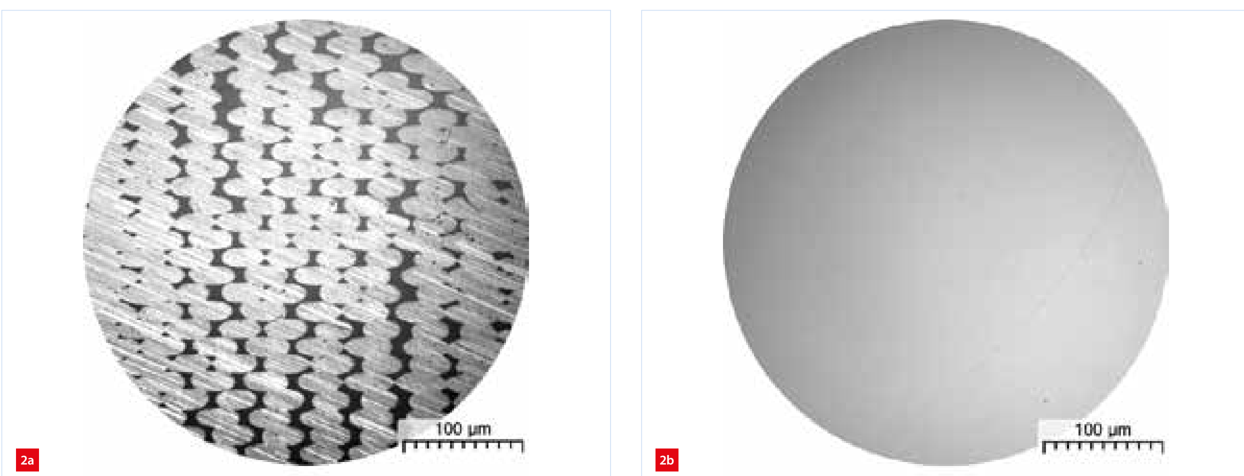
Pressure control

The Bond 3D printing technology is an extrusion process. Bulk material is fed to the print head where it is heated to around 400 °C, upon which the molten material is pushed through the print nozzle and deposited on the print table, then subsequently onto the previously deposited layers.

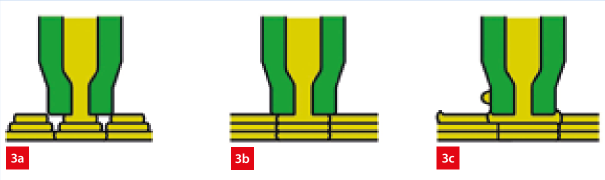
The conventional extrusion process proceeds in a flow-controlled manner: material is fed at a rate that is proportional to the distance the nozzle travels. Inevitably, there are errors. For example, variations in the filament diameter and fluctuations in the temperature of the compressible molten material will affect the flow rate of the highly viscous material through the nozzle. As a result, perfect extrusion cannot be achieved; either more or less material than required will be deposited and the distance between the print nozzle and the top layer of the print will vary. This may lead to an inhomogeneous distribution of the printed material, by either under- or overextrusion (Figure 3). In the latter case, the moving print head causes a kind of bow wave and 'ploughs' through the deposited, solidifying material (solidification only takes seconds, so interaction forces will be high).

Overextrusion results in the accumulation of residual material at the side of the nozzle, which will quickly degrade under the influence of the hot print head, as polymers can only withstand temperatures beyond their melting point for a short time. The degraded material might flake off in black specks and contaminate the printed product, deteriorating its aesthetic and mechanical properties. Moreover, the increasing forces between the 'ploughing' head and the product being printed may eventually lead to the print being ripped off the build plate. The properties of the build plate (for example steel) are chosen as a compromise regarding the adhesion force with the printing material; i.e., high enough to hold the print, but low enough to facilitate removal of the finished product from the build table.

As overextrusion can end disastrously, underextrusion is generally preferred and the process control is set accordingly. This, however, creates voids in the printed product (Figure 3a). Bond 3D's solution is pressure-controlled printing (Figure 4), where the molten material flows to completely fill the gap between previously printed lines; material flow continues until the pressure in the 'melt pool' below the print nozzle starts to exceed the setpoint, indicating that no more material can be added. Then



Cross-section of a printed PEEK product, showing the printed strands coming out of the plane.
(a) Regular FDM technology.
(b) Bond 3D technology.



Flow of the molten polymer (yellow) out of the nozzle of the print head (green) under flow control, resulting in a potentially inhomogeneous distribution of the material. The direction of the moving print head is perpendicular to the plane of the drawing.
(a) Underextrusion.
(b) Perfect extrusion.
(c) Overextrusion.

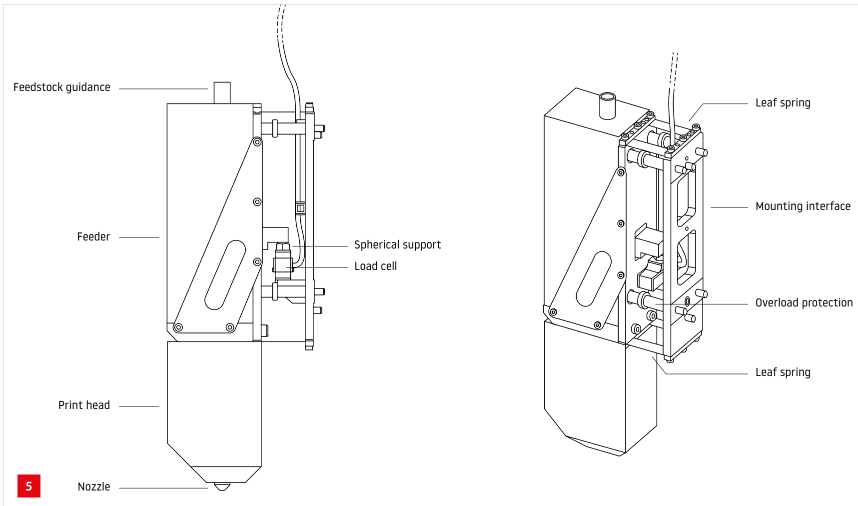
the gap has been filled and adjoining lines have bonded completely – this is what Bond 3D calls 'bondability' from where the company derives its name.

The pressure can be derived from the upward force exerted on the print nozzle at the bottom of the print head by the printed material in the melt pool below. As a first implementation, this force was derived from the motor current required for driving the extruder that delivers print material to the nozzle. This motor current, however, provides a rather noisy signal, so filtering is required, which makes feedback control slow. As an accurate high-bandwidth control alternative, Bond 3D designed a flexure-based, friction- and hysteresis-free mounting of the print head on the gantry to which sensitive force sensors are attached; Figure 5 shows a schematic design.

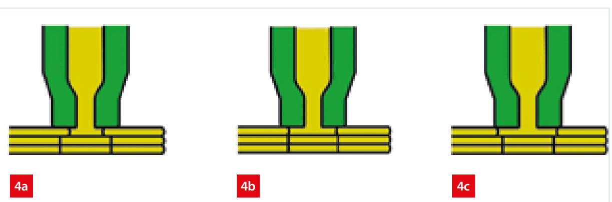
Slicer

In practice, Bond 3D applies a mix of flow and pressure control. Metaphorically this can be compared to the use of an electrical power supply: either setting the current, which yields a certain voltage, or setting the voltage to generate a certain current. Contour lines of shapes to be printed can simply be created using flow control. Here, pressure control does not make sense, as there is no line yet to which the new line has to be seamlessly matched; it's only in the next step that the gap in between is filled up using pressure control.
In 3D printing, the patterns to be printed are generated from a 3D model by a so-called slicer; it partitions the model into layers, or slices, that are to be printed one on top of another. Each layer is a set of 2D shapes, and the slicer determines the paths that need to be printed (similar to the 'tool path' for other CNC machines) and the amount of material to be extruded.
When pressure-controlled printing is used, the slicer does not need to dictate how much material has to be extruded, but rather to which pressure the extruder has to be driven.

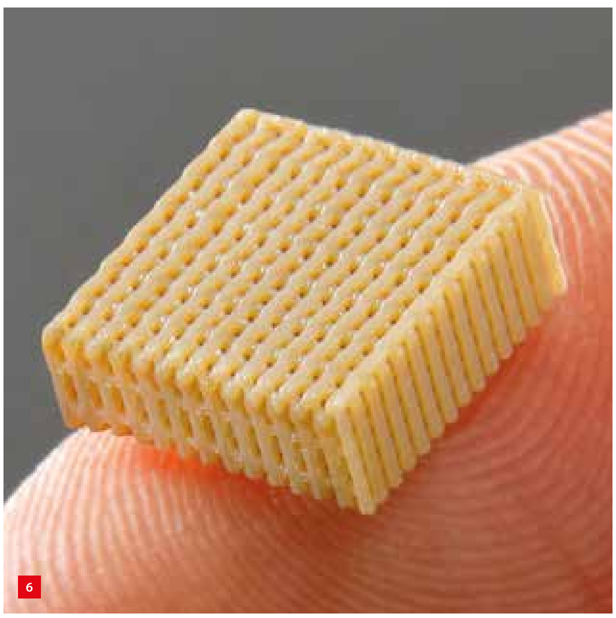
Commercially available slicers cannot distinguish between flow and pressure control, so Bond 3D decided to develop its own slicer that adds information to the slicing profile, indicating whether flow or pressure control is appropriate for the printing step at hand. The additional advantage of a proprietary slicer is that it greatly increases the flexibility in process development; new slicer options can be added almost instantaneously, further improving the quality of the printed products.



Schematic design of the flexure-based mounting of the print head.



Flow of the molten polymer out of the nozzle of the print head under pressure control, as developed by Bond 3D, resulting in a homogeneous distribution of material regardless of the width of the gap that has to be filled.
(a) Small gap.
(b) Moderate gap.
(c) Large gap.



Porous PEEK structure printed with Bond 3D technology (under flow control); internal channels are only 300 µm wide.

Printed manifold-like PEEK part (1.3 mm wall thickness) successfully subjected to a gas pressure test up to 100 bar.

The current three functional model printers in Bond 3D's lab.

Mechanical properties

Bond 3D printing technology can produce both highly detailed, accurate porous structures (Figure 6) and voidless products. Resolution is below 0.3 mm and mechanical properties are excellent. Measurements on printed tensile specimens revealed a yield strength of 99 MPa, which compares favourably to the 98 MPa guaranteed by Victrex for its bulk material and exceeds the yield strength of flow-controlled printed specimens by more than a factor of two.

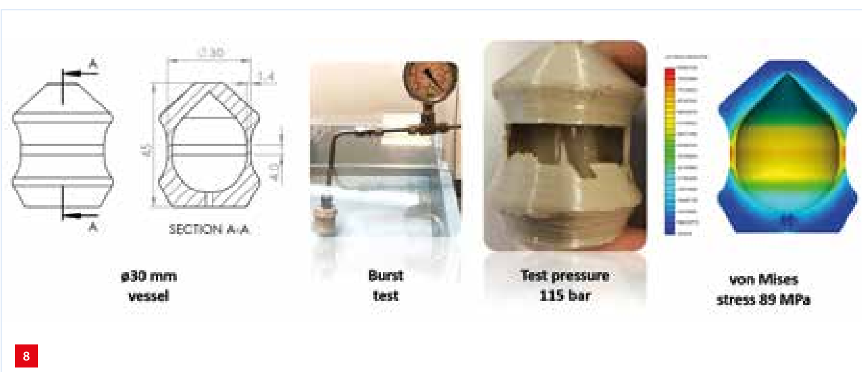
A gas pressure test on a printed manifold-like part with 1.3 mm wall thickness (Figure 7) showed no failure up to 100 bar; the leak rate was below the detection limit of $3 \cdot 10^{-6}$ mbar·l/s. Another part, a vessel designed to have a well-defined stress concentration at the location with least wall thickness (1.4 mm), withstood up to up 115 bar pressure before bursting, equivalent to a Von Mises stress of 89 MPa in the outer wall (Figure 8).

The challenge now is to prove that the fatigue strength of printed parts is on par with that of bulk products. For this, voidless printing is crucial, because even the smallest voids can generate micro-cracks that propagate through the part, eventually leading to fatigue failure. Micro CT scans are used to prove the absence of voids.

Conclusion

Voidless printing is one of the key performance indicators in Bond 3D's technology roadmap. Current development at Bond 3D is performed using three functional model printers (Figure 9). A first batch of eight production-ready printers is scheduled (Figure 10) for this autumn.

Bond 3D's patented technology is capable of printing complex, functional parts made of PEEK with excellent mechanical properties, including in the z-direction. This enables the additive manufacturing of high-strength, isotropic parts with properties comparable to those of conventionally moulded or machined PEEK parts, while allowing for freedom in design and complex structures that are not possible using conventional techniques.



Strength proven in a vessel-like part. Bursting occurred at 115 bar, the stress concentration (red) at the position of least wall thickness (1.4 mm) was calculated to be 89 MPa, which is only 10 per cent below the bulk yield strength of 98 MPa.

Eight production-ready printers are scheduled for autumn 2019.

AS FAST AS LASER, AS PRECISE AS EDM

Laser MicroJet® (LMJ) is a hybrid technology that guides a laser beam within a hair-thin water jet enabling a long working length. While it remains a thermal technology, the coupling with the water jet enables better local cooling and cleaning. Swiss company Synova is the pioneer in exploring and commercialising this cool technology. In the Netherlands, Ter Hoek is a service provider exploiting this technology, next to its main expertise in EDM technology, for the high-tech manufacturing industry across Europe and beyond.

JUN WANG AND GERRIT TER HOEK

AUTHORS' NOTE

Dr. Jun Wang, a Laser MicroJet process engineer at Ter Hoek Vonkerosie Rijssen (NL), did his Ph.D. research on micro-EDM technology at KU Leuven, Belgium. Gerrit Ter Hoek is the founder of Ter Hoek and has been the director since 1990.
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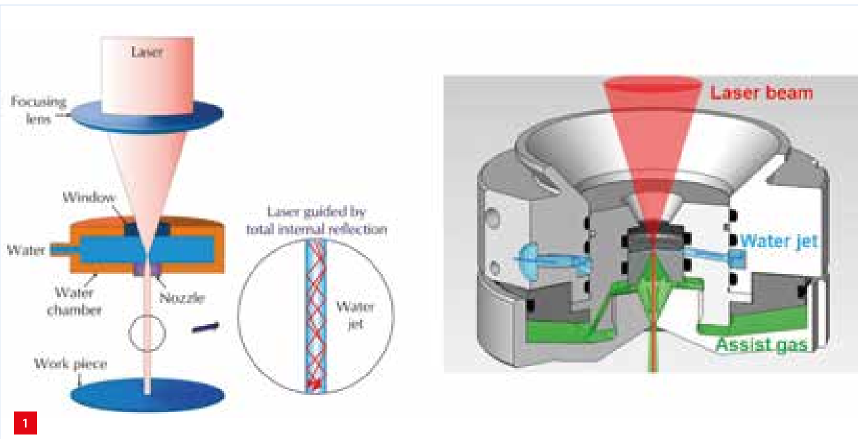
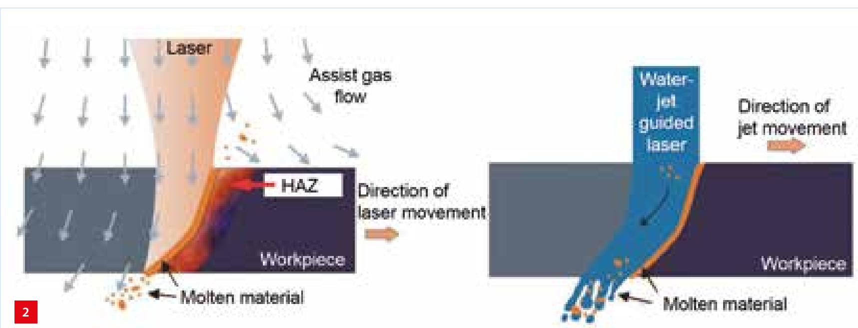
Introduction

In the manufacturing industry, laser technology has been applied in various processes including welding, cutting, drilling, grooving, surface treatment, and ablation deposition. Laser cutting is among them the most widely applied. Compared with mechanical cutting, laser cutting is a contact-free process, which can make smaller and cleaner cuts, with less material contamination, physical damage, and waste. As there is in principle no tool wear, laser cutting is highly reproducible and requires less intervention.



LMJ principle (left) and the coupling of laser and water jet (right). (Image credit: Synova)



Comparison of the heat-affected zones (HAZ) for conventional dry laser and water-jet guided laser (LMJ) processing, respectively [1].

The Laser MicroJet (see the videos [V1, V2]) is a hybrid technology, which combines a laser with a transparent water jet that precisely guides the laser beam by means of total internal reflection at the water/air interface (Figure 1, left), in a manner similar to conventional optical fibres. The coupling unit (Figure 1, right) is a complex precision device designed to produce a very stable, non-turbulent water jet, surrounded by assist gas (helium) to further improve the stability of the long water jet. In general, the jet working length is approximately 1,000 times the diameter of the nozzle, which means a working length of around 50 mm for a 50-μm-diameter nozzle.

The low-pressure (up to 800 bar) water jet continually cools the cutting zone and efficiently removes the debris. LMJ technology resolves the significant problems associated with dry lasers, such as heat-affected zones (HAZ, Figure 2), contamination, deposition, oxidation (Figure 3), micro-cracks, deformation, hence a lack of accuracy in particular for thicker materials.

Figure 3 illustrates the difference in cutting quality between conventional dry laser and LMJ processing on a stainless-steel plate. As can be clearly seen, there is almost no HAZ with LMJ and the cutting edge is sharp and free of burrs.

From the graph of the absorption coefficient in water (Figure 4), it can be seen that a large range of laser types (from ultraviolet to infrared) has an absorption coefficient below 0.2 cm^{-1}, which is regarded as the threshold of tolerable absorption, or the transparency 'window' as indicated. Among them, the green laser (532 nm) is very close to the optimum as it has the lowest absorption coefficient.

A recent LMJ application is the drilling of holes in aerospace turbine metal blades provided with a ceramic

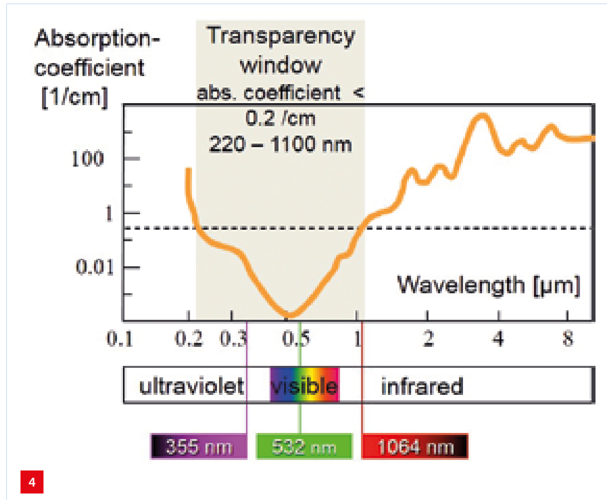
Table 1
Comparison of LMJ with other precision-cutting technologies (data dependent on various factors and therefore only indicative) [2, 3].

	LMJ	Laser*	Wire-EDM	(Abrasive) water jet	Milling/ cutting
Materials	Non-reflective materials		Conductive materials	Not ideal for brittle or extreme hard materials	
Thickness (up to)	20 mm	A few mm	50 cm	A few cm	
Cutting speed (up to)	A few mm/s	A few cm/s for thin materials	A few mm/ min	A few mm/s	
Part accuracy (±, down to)	A few µm	25 µm	A few µm	25 µm	A few µm
R_a (down to)	0.1 µm	0.3 µm	0.05 µm	1 µm	0.3 µm
Kerf width (down to)	0.03 mm	0.08 mm (V-shape)	0.03 mm	0.5 mm	1 mm
Edge quality	Excellent	Thickness-dependent	Excellent	Good	Good
Heat-affected zone	Almost none	Yes	Some	None	None
Set-up	Fast	Fast	Slow (start holes needed)	Fast	Moderate

** Excluding ultra-short-pulse laser.*

3

Below a stainless-steel shaver blade, three comparisons of cutting quality between conventional laser (middle row) and LMJ (bottom row) processing. (Image credit: Synova)



4

Water absorption spectrum from UV to IR wavelength. (Image credit: Synova)

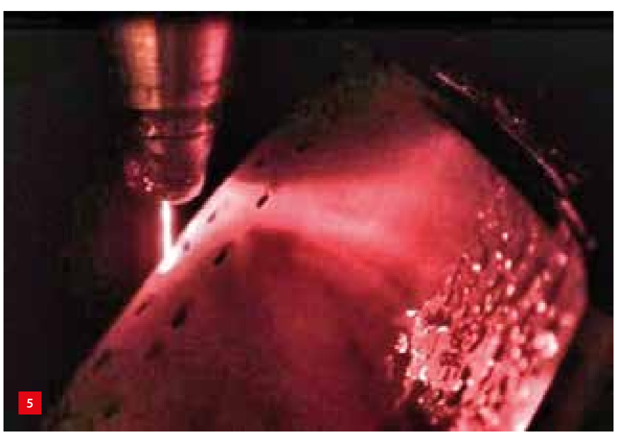
thermal barrier coating. The removal of the ceramic coating and the through-drilling of the metal blade are executed in one set-up (Figure 5), which is not possible with a traditional laser due to its short working length.

Table 1 gives a comparison of LMJ with other precision-cutting technologies. As can be seen, LMJ features easy set-up, high precision, small kerf and good edge quality. Compared with conventional dry laser processing, it can process thicker material with much less HAZ. Wire-EDM (electrical discharge machining) on the other hand, shows characteristics similar to that of LMJ but has a slower set-up and a lower process speed. However, depending on the product geometry and product quantity, wire-EDM could be more economical, as will be discussed later.

Laser MicroJet system

Different LMJ systems are supplied by Synova for different end applications, with some more details in [4]. Each system consists of four key parts [5]:

1. Laser source, which generates nanosecond laser pulses.
2. Optical head, which couples the laser into the water jet.
3. Integrated water system, which filters, deionises, degases, pressurises and controls the quality (resistivity and particle content) of the water supply.
4. Axes system, which varies from two up to five axes.



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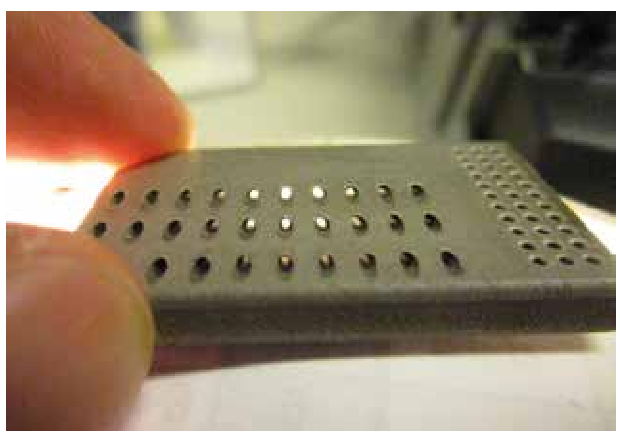
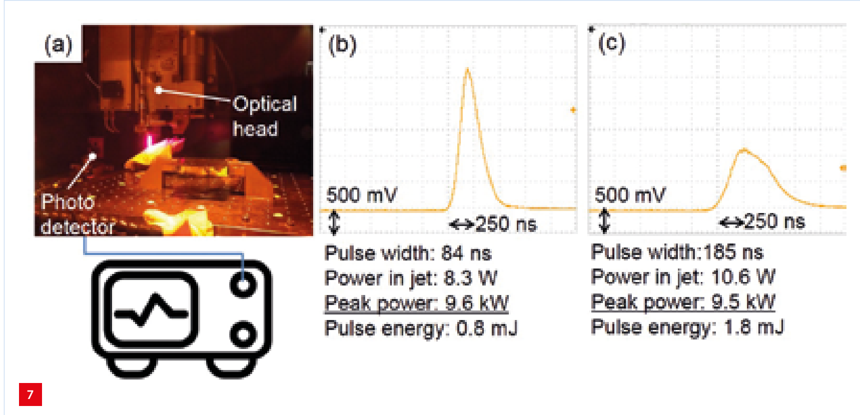


LMJ drilling holes in high-pressure turbine blades. (Image credit: GE Power)

Synova's MCS 300 LMJ system at Ter Hoek.



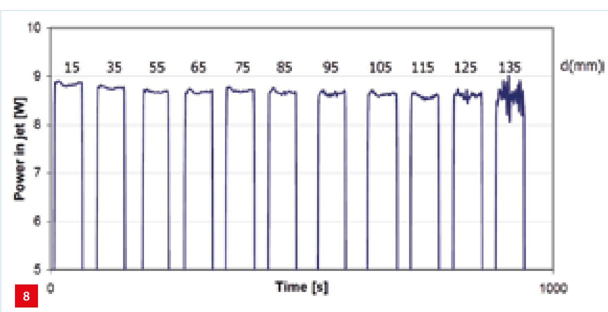
Laser characterisation.
(a) Set-up to measure the laser pulses.
(b) Measurement of a relatively short laser pulse.
(b) Measurement of a longer laser pulse.

The LMJ system at Ter Hoek is an MCS 300 series (3-axis) machine, which is Synova's LMJ technology integrated on a Makino machine platform (Figure 6). The position accuracy is ±1 μm in both the X- and Y-axis. The 3-axis machine enables high-precision metal and hard-material machining such as cutting, drilling and grooving. Together with Erowa-based workpiece clamping systems, which are widely used at Ter Hoek, it is possible to combine LMJ with EDM [V3] and precision electrochemical machining (PECM) [V4] technologies also available at Ter Hoek, without losing the workpiece reference.

Different nozzles with a diameter from 30 to 80 μm can be used, which results in a machined kerf width from 32 to 100 μm, respectively (the exact value is material- and process-parameter-dependent and even can be smaller than the nozzle diameter), and a working length of about 1,000 times the nozzle diameter. The associated jet pressure is between 50 and 500 bar, exerting negligible forces (< 0.1 N) on the workpiece.

Laser characterisation

The system is working with a pulsed, frequency-doubled Nd:YAg laser with a maximum output power of 50 W (single cavity) at 532 nm (green laser). Besides the laser power, the frequency (6-60 kHz) and pulse width (70-500 ns at FWHM) of the pulsed laser can also be tuned to the application. To characterise the laser after coupling with the water jet, the waveform of the pulsed laser was acquired via a photo detector (DET10A, 200-110 nm, ThorLabs) and displayed on an oscilloscope (TDS 2012C, Tektronix) with the set-up shown in Figure 7a. A laser power probe (Fit, Laserpoint) was placed underneath the jet to measure the laser power.



Measured laser power for a given jet length from 15 up to 135 mm, with an 80-μm-diameter nozzle (laser settings: 5 kHz, 10 W). (Image credit: Synova)

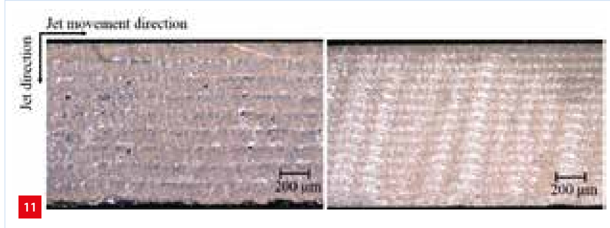
Generally, a certain level of peak power is needed to be able to ablate the material and longer pulses will lead to a higher process speed. However, providing sufficient peak power, short pulses will minimise the heat damage. An example is shown in Figure 7b (shorter pulses) and Figure 7c (longer pulses), where the two pulses have different pulse width and energy, but the same peak power.

Regarding the laser power evolution along the jet working length, tests have been done at Synova; the results are shown in Figure 8. It can be clearly seen that the laser power is rather stable at increased jet length, which confirms the theory of total internal reflection of the laser beam at the water/air interface, until at 125 mm the laser power starts to fluctuate, indicating that perturbations (jet instability) are becoming more dominant. As a consequence, the laser beam maintains a constant diameter up to this working length, which results in highly parallel kerfs.

Characterisation of kerf surface

Depending on the workpiece thickness, laser power and process speed, the workpiece can either be cut in a single-/ mono- or a multi-pass strategy. In a multi-pass strategy, the

Comparison of the kerf surface of a 2-mm-thick stainless-steel sample machined with the mono-pass (left) and multi-pass (right) strategy.



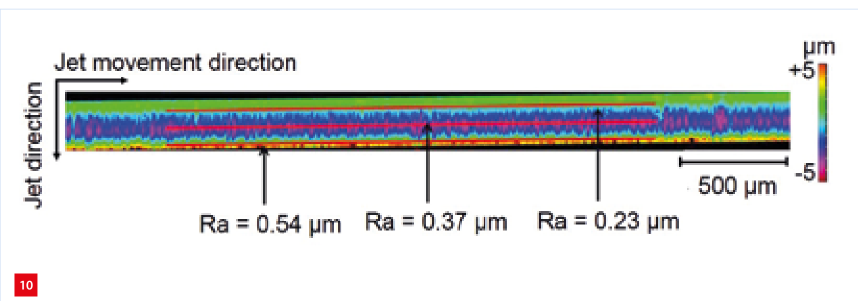
Comparison of the kerf surface of a 1.4-mm-thick silicon sample machined with the multi-pass strategy; left and right with different laser power and process speed values (see the text).

material is cut through after several reiterations of the same tool path with each pass cutting a section of the total thickness, similar to a milling process.

Figure 9 shows an example of the same workpiece (2-mm-thick stainless-steel sample) machined following the two different strategies, with the same laser parameters, except for a different process speed. Both photos were taken by a digital microscope (Keyence VHX5000), also for Figure 11. With a mono-pass strategy, the laser needs time to cut through the material at each position along the jet movement direction.

The processed surface can be characterised in three different sections along the jet direction, as shown in the left figure:

- the top section where the laser enters the material, showing a relatively smooth surface;
- the middle section, where the laser is fully contained in the material and high-efficiency cutting is guaranteed; on the other hand, redeposition of molten material occurs in this section probably due to insufficient local cooling by the water jet, which in turn increases the surface roughness;
- the bottom section where the laser cuts deep into the material; the water jet becomes less stable and may deviate from the ablation front, which causes jet oscillation and generation of vertical striation (similar to abrasive water jet machining) – as a result, the surface becomes even rougher and less material is removed in this section, which yields a concave barrel shape, as can be seen more clearly in Figure 10.



Topography measurement of the kerf surface of a 0.2-mm-thick brass sample machined in mono-pass, with the profile roughness R_a indicated at three different locations [6].

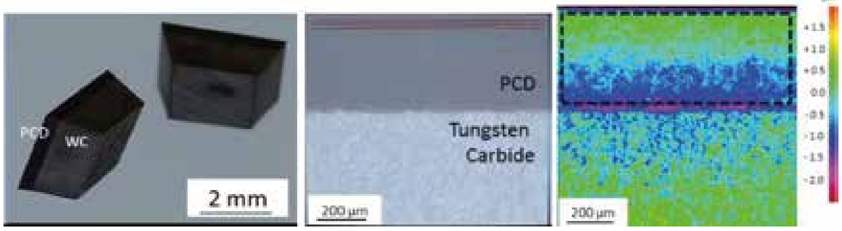
Please note that the surface topography after mono-pass as seen in Figure 9, left, is more common for ductile materials than for hard materials, and with further process-parameter (laser power and process speed) optimisation for surface quality, both middle and bottom sections can be smoother.

Similar observations can be derived from the topography measurement of a 0.3-mm-thick brass sample processed with the single-pass strategy, as shown in Figure 10, which was taken by a 3D optical microscope (Alicona Infinite-FocusSL), also for Figure 12, middle and right. The surface processed with the multi-pass strategy (Figure 9, right), on the other hand, clearly shows the different tracks after each pass. Despite the different surface sections as discussed for Figure 9, left, overall the mono-pass strategy results in a smoother surface than multi-pass due to the absence of the tracks as shown in Figure 9, right. However, the surface roughness produced by multi-pass is more uniform as each layer is cut under more or less the same conditions.

Unlike ductile metals, brittle materials such as semi-conductors and ceramics, are more prone to material damage such as chipping. Figure 11 shows the kerf surface from the same silicon sample, cut with a multi-pass strategy, but now with different process parameters: the left one with higher laser power and lower process speed, and the opposite for the right one. As a result, fewer but bigger tracks are seen in the left one, more but smaller tracks in the right one. Chipping is clearly visible at the back/exit side of the material in Figure 11, left.

To reduce the chipping, generally the process speed has to be increased to reduce the depth of cut per pass. Higher laser power on the other hand, will increase the heat input, and redepositioning of the debris on the cut walls is also seen in Figure 11, left, which will deteriorate the quality of the kerf surface. In order to obtain a clean kerf surface with less chipping, relatively short laser pulses similar to the ones in Figure 7b have to be chosen together with an appropriate process speed.

Besides cutting a single material, Figure 12 shows the kerf surface of a polycrystalline diamond (PCD) tool with tungsten carbide (WC) substrate, cut by a 5-axis LMJ



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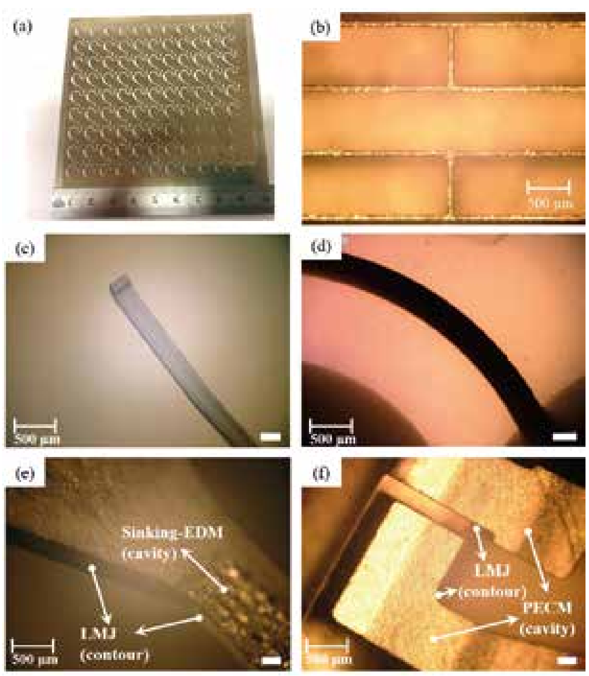
PCD tool with WC substrate cut by LMJ [5].

system, with the kerf surface shown in the middle and the topography measurement on the right, with the marked region indicating the PCD layer. There is a dark blue region near the bottom of the PCD layer, which is probably caused by chipping; further beneath there is a magenta region at the interface, which indicates some loss of cobalt as the binding material, probably due to the instability of the jet when crossing the interface.

Despite the issue at the interface, the sample has been cut through in one set-up; the surface roughness (S_a, measuring field 1 x 0.35 mm^2, vertical resolution of 50 nm and lateral resolution of 2 µm) of the PCD layer and the WC layer is 0.20 ± 0.02 µm, and 0.40 µm, respectively. The same sample has also been cut with wire-EDM; the surface roughness (S_a) measured on the PCD layer is 0.29 ± 0.02 µm, and 0.31 ± 0.01 µm on the WC layer, which is comparable to LMJ. The process speed of LMJ however is six times that of wire-EDM [5].



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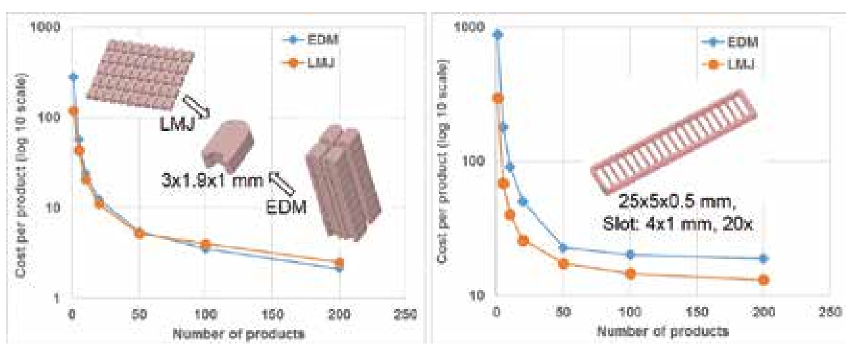
Products made by LMJ at Ter Hoek.
(a) Stainless-steel rest material after functional parts (11x9 pieces) have been cut off.
(b) Stainless-steel grid with 60 µm wall thickness.
(c) Stainless-steel gripper for medical application.
(d) Alumina ceramic piece with 6 mm thickness.
(e) Tungsten piece made with LMJ and die-sinking EDM.
(f) Titanium piece made with LMJ and PECM.

Applications at Ter Hoek

The application of LMJ technology at Ter Hoek is twofold: the application of LMJ itself including process development and validation, and finally series production; and the integration of LMJ with EDM and PECM technologies.

Various materials have been tested, including metals, ceramics/hard materials, gemstones, semiconductors and composites. The application areas include the semiconductor, electronics, automotive, aerospace, medical and watchmaking industries, as well as tool manufacturing and micromachining in general. Regarding the applications at Ter Hoek, LMJ is found to be an ideal technology in the following cases:

- Cutting small but complex functional parts from thin sheet metal (from 0.02 up to 2-3 mm) with feature sizes down to 50 µm and precision within a few µm. Examples are shown in Figure 13a and 13b.
- Precision drilling of small holes in thin sheet metal up to a certain aspect ratio.
- Creating flexible mechanisms, such as springs, in thin sheet metal. An example is shown in Figure 13c.
- Precision cutting of other materials aforementioned with a thickness up to a cm, particularly for insulating materials which cannot be processed with EDM. An example is shown in Figure 13d.
- Integration with die-sinking EDM and PECM technology for cutting precision contours, ideally suited for prototypes and small and medium-sized batch production; and with wire-EDM for the precision manufacturing of small start holes. Examples are shown in Figure 13e and 13f.



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Two examples of the cost-per-product evolution for LMJ and EDM; the product on the right needs more start holes for wire-EDM to cut each slot.

Though the working length of LMJ is rather high, it is found to be more efficient when processing thinner metal sheets, because the effective process speed (the process speed divided by the number of passes when applicable) drops dramatically with the increase of the material thickness. On the other hand, LMJ is rather flexible and ideal for making prototypes.

Additionally, a calculation module has been made in-house to compare the cost for making the same product between LMJ and EDM. EDM consists of hole-drilling EDM and wire-EDM steps, with the former step making the start holes for threading the wire for the latter step. Two examples are shown in Figure 14, where the right one needs more start holes for wire-EDM to cut the slots. In both examples, it is clear that the cost per product for EDM is initially higher than for LMJ due to the higher set-up cost including start hole drilling.

Beyond a certain product quantity (tipping point between 50 and 100 pieces), EDM is winning in the left example because multiple plates can be stacked to be machined at once as illustrated in the figure, as a result of which the running cost is reduced. LMJ, on the contrary, has a lower set-up cost but a higher running cost as products are not made in stacks as with wire-EDM. However, when lots of start holes are needed for wire-EDM, as in the right example, the tipping point has virtually vanished. To conclude, depending on the product geometry, LMJ can be more economical than EDM for both small and large product quantities.

Conclusion

LMJ is a hybrid technology combining laser and water jet technology, enabling certain advantages as compared to conventional dry laser technology, including longer working length, precise and parallel cut, better local cooling and hence a smaller heat-affected zone, and last but not the least, less particle deposition and contamination.

Ter Hoek has started to explore the process of LMJ and provides its service to the high-tech industry since 2014, for both prototyping and serial production. LMJ is found to be more competitive than wire-EDM technology when producing small but complex parts in thin sheet metals. Besides the application of LMJ alone, focus is also put on integrating LMJ with EDM and PECM technologies also available at Ter Hoek. Furthermore, calculation modules have been made to have a quick comparison of the cost per product between LMJ and EDM, to offer a better price for the customer.

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[6] Bai, Y., et al., "Reducing the Roughness of the Kerf for Brass Sheet Cutting with the Laser MicroJet® by a Systematic Parameter Study", *Proceedings Lasers in Manufacturing Conference 2015*, contribution 154, 2015.

VIDEO

[V1] Synova Laser-MicroJet in 2 Minutes, *www.youtube.com/watch?v=Q_IRaONosxc*

[V2] Ter Hoek LMJ animation, *www.youtube.com/watch?v=FNSfRC6kYdU*

[V3] Ter Hoek EDM animation, *www.youtube.com/watch?v=TzkiCb-pLC4*

[V4] Ter Hoek - Precision Electro Chemical Machining (PECM), *www.youtube.com/watch?v=p_uW_Y6relY*

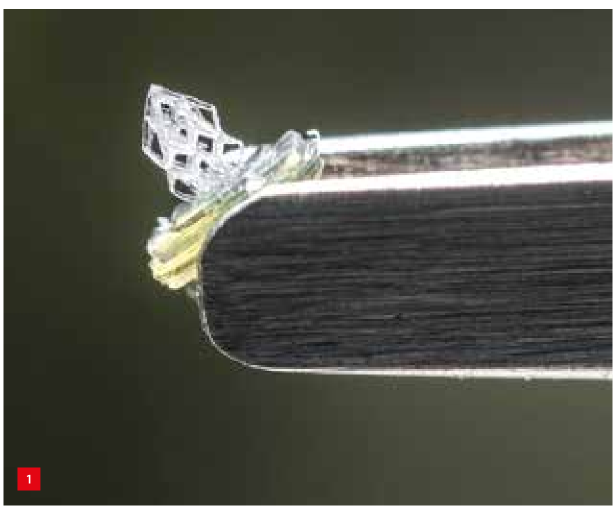
µ-AM

There are two current global trends in manufacturing: miniaturisation, demanding parts and components with highly precise (sub)-micron-level resolution; and the move towards digital manufacturing (Industrie 4.0). Additive manufacturing (AM) is a digital manufacturing technology catering for the move towards shorter product lifecycles, and allowing mass customisation. Nanofabrica has introduced a new technology at the intersection of AM and micromanufacturing, opening up the possibility for manufacturers to benefit from the inherent advantages of AM while achieving micron-level accuracy over a build envelope of 5 x 5 x 10 cm³.

JON DONNER

Nanofabrica, founded in 2016, has recently developed an AM platform that provides an end-to-end solution for manufacturers requiring (sub) micron levels of resolution and surface finish. To date, key AM platform developers struggle to get resolution under 50 µm, and the few companies that have strived to provide a micro-manufacturing AM solution are either extremely expensive in terms of machine costs and cost per part, or extremely slow, or can only print parts that are very restricted in size.

Killer applications have been identified in the area of optics, semiconductors, micro-electronics, MEMS, microfluidics, and life sciences, covering products such as casings for micro-electronics, microsprings, micro-actuators and microsensors, and numerous medical applications such as microvalves, microsyringes, and micro-implantable or surgical devices.



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A diamond-shaped lattice in ABS, a shape that can only possibly be manufactured by AM, and not by CNC machining or injection moulding. The structure has an ultra-high surface area and is, therefore, useful in heat dissipators. Part size 0.3 x 0.3 x 1 mm³, print time 45 minutes, and print layer 3 µm.

AUTHOR'S NOTE

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Microfluidics is a good example of how a true micro-AM technology can outcompete traditional manufacturing processes. Microfluidic channels are used to move incredibly small volumes of liquid, and many of them incorporate functioning components such as filters and pumps. Traditional micromanufacturing processes such as micromoulding hugely limit the freedom of design for such microfluidic channels, and it is almost impossible to manufacture functional substructures in them using such processes. The Nanofabrica AM technology overcomes these barriers without compromising precision or quality.

The technology

The new AM technology enables high precision at a cost required for industrial manufacturing. It is based on a technology that is well known in the AM world, namely a Digital Light Processor (DLP) engine, which is combined with adaptive optics that electronically controls various critical optical working point parameters such as focus, tilt, and astigmatism. The DLP unit is placed on an optomechanical apparatus which facilitates real-time corrections of other working parameters, mainly location and accuracy in the XY plane. For example, laser distance measurements are used to correct positioning errors. The apparatus also corrects for degrees of freedom such as wobbling to allow for better surface finish on parts.

The closed feedback loop is the core element that enables reaching very high accuracy while remaining cost-effective as a manufacturing solution. Where all other AM platform developers in this space achieve precision through great hardware, Nanofabrica tackles this issue with software, where solutions are easier, more robust, and less expensive. This is the first time adaptive optics have been applied to an AM technology.
Another unique aspect of the new AM platform is the ability to achieve micron resolution over centimeter-sized

parts. To enable this, a number of technologies have been combined.
Specifically, the innovative use of adaptive optics has been enhanced with technology and know-how used in the semiconductor industry (where the attainment of (sub) micron resolutions over many centimeters is routine). As a result, large 'macro'-parts with intricate microdetails can be built – at speed, following a multi-resolution strategy. The parts where fine details are required are printed relatively slowly, but in the areas where the details aren't so exacting, parts are printed at speeds 10 to 100 times higher. This makes the entire printing speed anything from 5 to 100 times faster than that of other micro-AM platforms.

The multi-resolution capability is possible through the use of hardware which enables a trade-off between speed and resolution, and software algorithms which prepare the part and the printing path by defining and sectioning it into low- and high-resolution areas, which are then fed into the printer path and machine parameters. In fact, there is a spectrum of resolutions that allow speed to be optimised while maintaining satisfactory results throughout the part. Another algorithm family is focused on customised file preparation, optimising print angle, build plate orientation, support structures, etc., all to ensure the most accurate, timely, and cost-effective part production.
In addition, through rigorous R&D, and using extensive material development expertise, Nanofabrica has managed to develop its own proprietary materials (based on the most commonly used industry polymers such as ABS and PP), which enable ultra-high resolution in parts built through modifications in, for example, viscosity, surface tension, and spectral-optical penetration depth.

The new micro-AM technology is ideally suited to manufacture micro-parts with ultra-high surface area; examples are shown in Figure 1 and 2.

Partnering on DfAM

Nanofabrica is aware — as the first mover in the micro-AM space for production — that it establishes a partnership relationship with its customers that extends from product inception through to mass manufacturing. The technology is today the only micron-resolution platform aimed at true manufacturing applications.

Additive manufacturing offers freedom in design allowing users to create geometries of previously unimaginable complexity, complex and controlled lattices, extremely small and complex holes, as well as customised products. The key element to unlocking the full potential of any AM technology is design, i.e. design for additive manufacturing (DfAM). While AM users are beginning to take advantage of DfAM for macro-AM platforms, there is little to no understanding of the DfAM issues when using AM for micro-applications.
Much of the current DfAM conversation focuses on topology optimisation, lightweighting of parts, and consolidation of assemblies. Important as these issues are in maximising the advantages of AM, there are some other critical issues with DfAM. Specifically, that the primary design consideration with AM comes with the support structures that are needed for many additive processes.

Any parts that feature overhangs necessarily require support structures to enable their production with AM. Therefore, when designing a part with overhangs that will be additively manufactured, design skills must also be applied to the nature and placement of the supports themselves. While most AM software generates support structures automatically, the ability to design minimal but functional supports to optimise the final part demands a new design skill set.

Optics

One area where the technology has found a perfect fit is in the manufacture of various micro-optical parts and components. The ability to produce complex, extremely flat, extremely small, and extremely lightweight optics today opens up a huge amount of potential for product innovation in many industrial sectors. In addition, for a variety of


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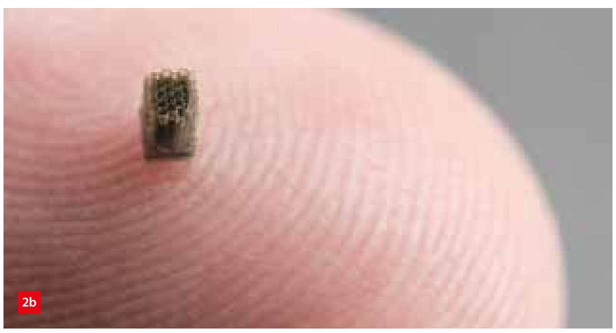
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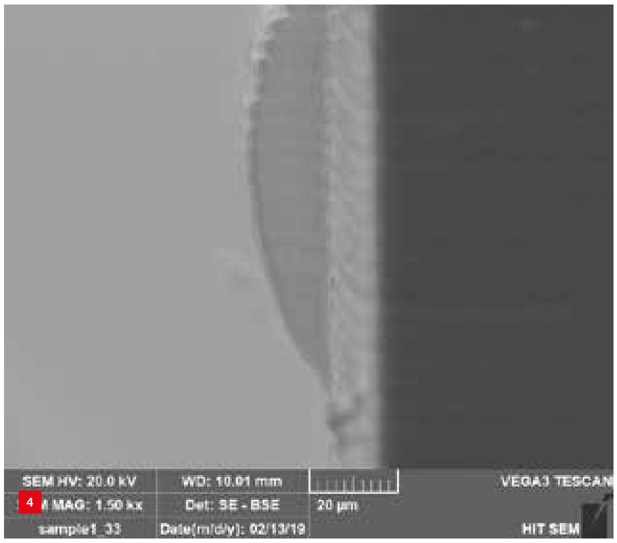
A honeycomb microstructure in PP, with wall thicknesses of ~20 μm over a height of a few mm. The part is made for a company that specialises in microbatteries. The ultra-high surface area is used to increase battery storage with minimal footprint. Part size 1.6 x 1.8 x 2.3 mm^3, print time 80 minutes, and print layer 2 μm.
(a) Under the microscope.
(b) In close-up.

A jig for alignment and coupling of optical fibres (3 x 3 x 6 mm^3) printed in ABS. The part has 100-μm holes where optical fibres are placed.

reasons including green manufacturing considerations and the design freedom that working in plastic allows, plastic has become an increasingly popular material for micro-optic applications.

Because of this, micro injection moulding has become a popular technology for micro-optics manufacturing in low-cost, high-volume production runs. Use of injection moulding for micro-optic manufacture, however, requires the optimisation of design, mastering, tooling, and production steps, meaning a close interaction between supplier and product developer is vital. The ability of the new micro-AM technology to overcome complexity issues and to eliminate the need for tooling is key, and it is therefore used for an array of applications such as the manufacture of jigs (Figure 3) and fixtures for optical alignment, optical connectors for optical fibres, fibre-optic ferrules and other small related elements, and optical elements such as lenses (Figure 4) and prisms. With continual development of surface finish, it is expected that imaging optics can be printed in the very near future.



Cylindrical microlens, 20 μ high and 100 μm wide, surface roughness in the order of 1 μm, material with 80% transparency for visible light.

FOCUS ON VE & DFX

In high-tech manufacturing, Value Engineering (VE) is relatively new and less embedded than, for instance, in the process, semiconductor, automotive and civil engineering industries. The need for VE and DfX (Design for Excellence) is, however, becoming ever more evident: extreme short product lifecycles, continuous cost price pressure, and a predominant focus on innovation and R&D, often at the expense of manufacturability. Moreover, many organisations understand the value of their products and services, but struggle to decompose such value to operational levels. Exactly this mismatch between value and costs is tackled by VE.

IVAN VAN DER KROON AND PATRICK STRATING

Introduction

Integral part of Value Engineering (VE) is Design for Excellence (DfX). DfX is a collective term, where the X may represent several properties, e.g. reliability, manufacturing and costs. The X points to the emphasis of the applicable design rules and efforts towards achieving this property.

Figure 1 is an example where some manufacturability aspects were not included from the start. It turned out that the original design required a machining approach that in turn led to contamination issues, long lead times and cost overruns. The design was changed based on this information and DfX input, in such a way that all three issues were resolved to fit within budget. The design remained practically form-fit-function, such that the impact on interfaces was insignificant. This is one of many examples showing manufacturability input on design is paramount for a successful design.

In practice, DfX can pertain to many issues and manufacturing aspects. VE puts such DfX efforts in a comprehensive value context, and hence stresses 'Design for Margin', i.e. designing a product that meets certain profit targets.

AUTHORS' NOTE

Ivan van der Kroon is system architect at NTS, with a track record in various high-tech fields, and six years of experience in Value Engineering, both as a project lead and a trainer. Patrick Strating is technology manager at NTS, with a track record in managing high-tech R&D and innovation projects. Currently, he chairs the Cost & Value Engineering workgroup at the Dutch Association for Cost Engineers (DACE).

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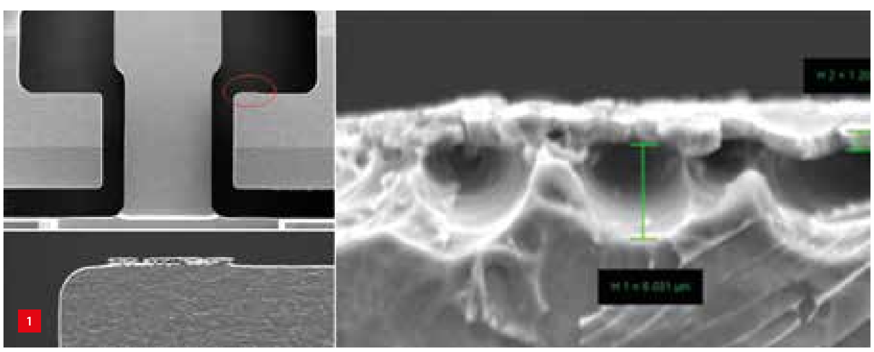

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Proto version of a flexure (top left) and two zoom levels (bottom left and right; the right image is 22 μm high). The cavities, a result of the initial machining approach, could not be prevented with the original design and pose contamination risks in the target environment.

Origins

Although some processes that have come up since the start of the 20th century are comparable to VE techniques, its emergence is usually ascribed to result from material and labour shortages during World War II [1]. Initially, it was developed at General Electric as a systematic functional approach for existing products, called Value Analysis: alternative design solutions needed to demonstrate cost reduction, products improvements or both. Its key distinction from other methods with comparable roots, e.g. Kaizen, is the emphasis on the required functions [1, 2, 3]. Problem solving within VE is structured and inventive and hence shows many similarities with the well-known TRIZ problem-solving method, originating in the Soviet Union in the 1940s [4].

In order to indicate that the method focused on the design process, the name Value Engineering was coined. In 1954, the methodology was applied by the US Navy and by 1996 VE procedures were mandatory for federal agencies. In Germany and Austria VE is also known as *Wertanalyse*. In the Netherlands, organisations such as DACE and NAP promote the application of VE.
A European Standard for Value Management was founded as EN12973. The standard covers several analysis methods and concepts. An example of the latter is value culture, i.e. the awareness in the entire organisation of value and its drivers. The standard targets no special sector, although one application area is public procurement compliance [5].

High-tech manufacturing

Implementation of VE tends to be difficult in high-tech industries because these industries are characterised by very stringent lifecycle demands and enormous pressure to bring the next technology iteration to the table, swallowing all attention and resources. In addition, the high-mix, low-volume business models show much variation and hamper easy cost-down business cases. Unsurprisingly, the common approach is to do the regular design first and the cost down later, which is one of the major pitfalls for VE.

VE as a method is multidimensional and multidisciplinary. The search for cost drivers should not be limited to design simplifications or procurement changes. All aspects should be considered: design, supply chain logistics, materials, assembly, part manufacturing technologies, regional production (offshoring), etc. It is important to use a structured process and framework to achieve confidence that all angles, expertises and stakeholders have been covered. It is equally important to involve stakeholders early on, as they probably will be needed to implement changes later on, or have to deal with consequences of design or manufacturing changes.

Table 1
Example of Function Analysis basics: three items make up the bill of material, each with different costs and support of the functions. Even though function 1 is cheaper, its value-effectiveness is poorer.

		Function 1	Function 2
Value		3	6
Cost			
Item 1	2	1	1
Item 2	3	2	1
Item 3	6	2	4
Total		5	6
Value/Cost		0.6	1

VE might be perceived as a blunt cost-down attempt and therefore often leads to resistance from a subset of stakeholders. But successful and prolonged long-term delivery benefits all parties, as long as a healthy margin is conserved for all stakeholders; this should be clearly articulated and understood between all parties to create a real win-win project. Another aspect of partnering is to treat suppliers as equals, match their disciplines to yours and provide an open information flow. The pitfall of not utilising stakeholder input is usually referred to as the not-invented-here syndrome.

Function Analysis

Analysis in VE starts with understanding the product's functionality. Each function of the product holds part of the product's value. A Function Analysis (FA) clarifies all functions of a product or system, and their value and costs. The value-effectiveness of a function is defined as value divided by its costs. The costs are estimated for all parts and projected on the function, see Table 1. Cost projection is not to be underestimated as a task, often facilitated by the cost engineer role. The valuation of functions is discussed in a later section. The function finding in FA is similar to the more modern Function Analysis System Technique (FAST) [6].

Subsequently, functions with low value-effectiveness are subject to scrutinisation. What alternatives are available? Can their performance or perceived value be changed? Is there cost without function? Also, high value-effectiveness functions deserve attention, but of a different kind: they run the risk of being copied by competition. Because FA has an inherent risk of becoming an endless search for the 'right' functions, a right dose of pragmatism and experience helps to deal with mutual dependencies and synergies of functions.

The goals of the functional approach are to a) force thinking in functions instead of product components, which is an ideation enabler; b) provide an understandable framework to easily convey cost overruns and added value to various stakeholders; and c) be able to deal with large solution spaces, and to subsequently assign manageable focus areas to zoom in on.

A common pitfall is related to the last aspect, as it often happens that the project scope is deliberately limited, with the reasoning that a smaller and less complex project has a larger success rate. However, limiting the solution space will lower the potential result of the project. A scoping tool is useful to deal with the apparent complexity by repeatably assessing and defining the most effective scope for the specific project. This starts with the history of the product, including, for example, previous efforts towards cost reduction. Obviously, rejected ideas in the new project should be archived for future reference.

System engineering is principal in high-tech new product development and can simply be extended by basic VE principles, for instance treating value as a technical measure and placing emphasis on functions. Vice versa, correct system engineering is one of the success factors for successful VE in high-tech manufacturing.

Ideation

Ideation, the ability to come up with alternative approaches to problems plays an important role in VE. Extensive literature is available on original thought, creativity and idea creation. In practice, and supported with own experience, it may be conjectured that new ideas are typically either projections of solutions in other areas or encountered unintentionally (coincidental). Consequently, settings can be created that yield significantly more ideas.

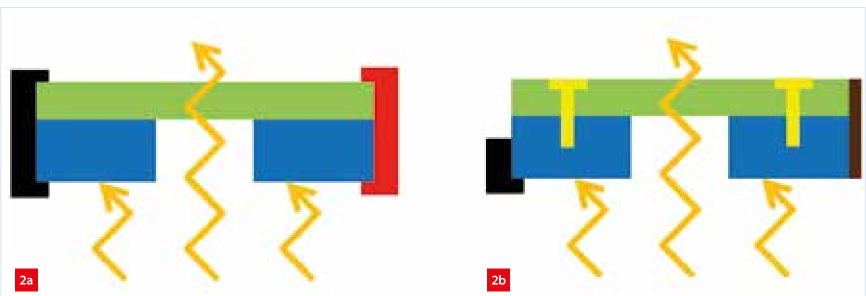
In our VE implementation, there are five distinct sources for ideation [4, 7, 8, 9]. Firstly, existing ideas at all stakeholders should be harvested, especially from the users and makers. This is a straightforward, but often poorly utilised source. A lot of DfX input originates from (internal) suppliers. It was already stated that the added value of suppliers is more than their delivered goods. Their technical expertise – it is their core business after all – and knowledge about cost drivers is critical. Especially in high-tech, suppliers are often very knowledgeable and engineers should acquire their design input, or consider outsourcing ideation to the corresponding suppliers.

As a side note, there is actually a cost risk to involving suppliers too late, as they may demand a steep price when the project cannot be stopped or adjusted anymore.

Secondly, external experts should be brought in to check for external solutions that might be applicable to the current case. The next method is to place problem owners together, for example in workshops or pressure-cooker sessions, and have them perform structured problem solving in an inventive setting. Soft skills and experience in facilitation and creating the correct setting and atmosphere will greatly increase the effectiveness of these processes.

Verification is a necessity in any development. It can also be employed to falsify ideas as soon as possible. This not only keeps the project lead time under control, but often leads to new or amended ideas. The last ideation source is using FA to track functions, alternative solutions, and their value-effectiveness during ideation. This proves key to finding a solution within the corresponding budgets and generates additional ideas in the process through inventive problem solving [4]. An example thereof is the redesign of a beam shape module, see Figure 2.

The required accuracy of the beam led to stringent tolerances, originally resulting in an expensive precision-grinded reference. This function was solved differently by evaluating all joining options. The selected solution was to first align the aperture to the compensator, and secure by bolts. Tolerance analysis showed that now a less precise and smaller reference was sufficient. The cover's main function became obsolete in the process, as the aperture and compensator are now placed as one assembly. The cover's aesthetic function is now realised by bolting a polished sheet metal part to the disks' assembly. Ultimately, a 70% cost reduction in hardware was obtained, while decreasing the set-up time and the risk of an incorrect combination of aperture and compensator.



A particle beam (orange) passes through a cylindrical beam shaper module (side view shown). The beam's cross-section and optical path length are altered by a metal aperture (blue) and a plastic compensator (green), respectively. Both are aligned to a reference (black).
(a) A cover (red) prevents one disk from falling out, while the other is collected, and for aesthetic reasons. Reference and cover are mounted in a frame (not shown).
(b) Alternatively, the disks are joined by bolts (yellow) and covered by a sheet metal part (brown, on the right), while using a smaller, less precise reference (on the left).

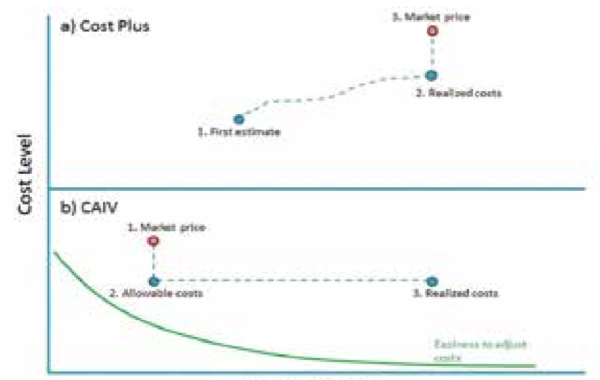
Target costing

During a product design, new functionalities often are being added without taking into account the ability or willingness of customers to pay for such added functionality. Or, a supplier quotes at an unexpected price level and needs more managing effort than accounted for. When such a margin problem is signalled, the traditional response is to omit basic functionality, i.e. client value. However, this is a waste of the resources that were already spent.

In the traditional approach, an initial cost price is estimated, often allowed to increase during the development process. The sales price is set by adding the desired margin on top of the final cost price, or worse, a smaller than planned margin is accepted right-out. This is known as cost-plus pricing, see Figure 3a.

A primary step is to recognise three principles. Firstly, contrary to the above situations, it is much easier to influence costs at the start of the design process, as this is where the main design is outlined.
Secondly, the design should converge on costs, i.e. the product should be designed to the cost level based on the market and margin targets.
Lastly, the costs are continuously monitored during development and deltas are acted upon immediately.
This approach is coined Target Costing or Cost-As-an-Independent-Variable (CAIV), see Figure 3b.

Costs often come with large tolerances in early stages for new designs, as it can be difficult to determine cost for a design concept. A skilled cost engineer associated with the product design project is therefore indispensable to provide cost estimations and assist technical experts in finding a cost-effective solution. Moreover, the cost engineer should monitor the product's costs, cost targets and cost trade-offs, playing a key role to manage cost targets, develop cost models and lower the cost uncertainty level according to the project's progress. Therefore, 'design to cost' is a popular paradigm.



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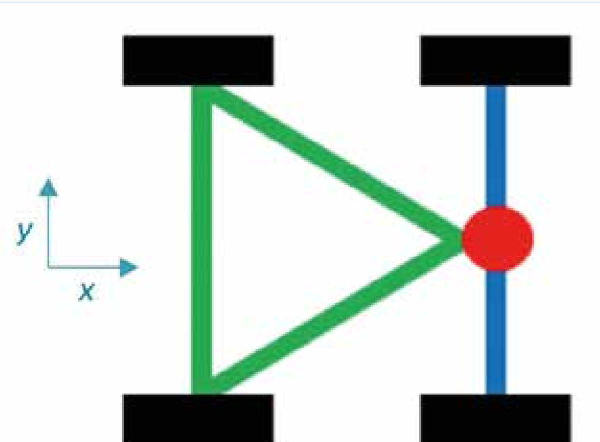
Product cost levels as a function of project time.
(a) Cost Plus approach.
(b) CAIV approach. The green line indicates the relative easiness to implement changes during the project.

Value

As reflected in the name of Value Engineering, the concept of value is key, but sometimes teams struggle to make value operational. The example of a bearing solution (Figure 4) shows how value can be perceived in different ways, but that ultimately it can be used as an objective technical measure.

DfM (design for manufacturing) experts analysed the design and found a 40% cost reduction in the pivot and the beam, by combining parts and changing the material and the machining strategy. However, further analysis and tests showed that the overconstraint did not lead to a performance issue; the resulting stresses and parasitic motion were within budget. Since the function 'remove overconstraint' did not contribute to the system level requirements, it was not value-effective, even after a sharp cost reduction by DfX.



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A slider (green) able to move in the x-direction is supported by air bearings. Stiffness requirements lead to four bearings in z (black) and two in y (not shown). To solve the static overconstraint (six bearings and one degree of freedom), a pivot mechanism (red) was added to allow Rx motion of two z-bearings with respect to the slider. In the original design, this added costs for the pivot leafsprings, a beam (blue) and cleanroom assembly.

This could have been prevented if the design team had allocated value to all system functions and subsequently acted earlier on their value-effectiveness. In practice, this often proves difficult to implement in a team or organisation. Conceptually, the solution usually lies in establishing a value definition and valuation method at the start of the project, supported by all stakeholders.

While this general direction is clear, value remains a difficult concept, perceived differently by different stakeholders, but it often relates to the amount the customer is willing to pay for a certain product. For example, contamination can reduce value for a specific customer but less so for another. Such properties often relate to the costs of higher-level systems and can sometimes be deduced from benchmarks or market analysis.

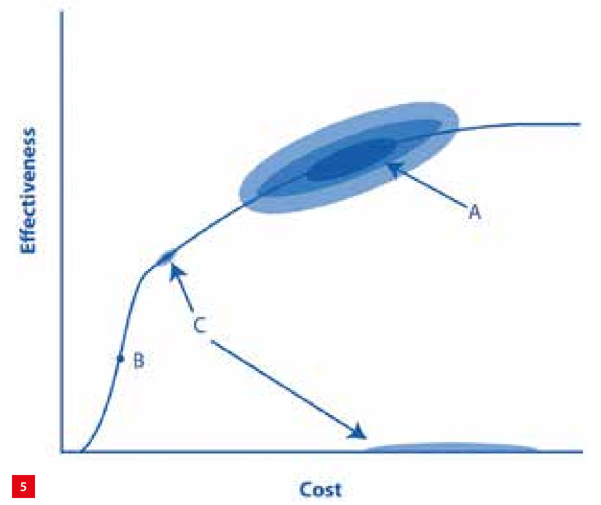
It is good practice to take total cost of ownership, availability and lead times into account. Value should be established after intensive deliberation with clients and departments such as sales, marketing, after-market and service. For complex products, it can be necessary to track multiple values if the market is segmented.

With value defined, the next step is simple: value equals the allowable costs of the product, see Figure 3b. The allowable costs are made up by margin, development and product costs. Over the lifecycle of a product, it is key to design-in the required cost downs, such that the margin targets are met. This also holds for product sequels/families/variants/platforms, as uprated products or spin-offs fill in the position of the current product. It should be noted, however, that value, like other technical measures, may vary over time. As such, cost roadmapping requires continuous attention.

A time-to-market target may put strain on the development process, and one should also keep in mind that there is both qualitative and quantitative value in the market launch of a new technology level. If a decision between time-to-market and certain development aspects is needed, a trade-off in terms of value is the way to go. If time-to-market is prioritised, one should plan ahead for the cost reductions required in later stages.

Financing

Properly set up and executed, VE works. Based on our experience, we are inclined to make the bold statement that cost reductions of 15-45% are possible in a large majority of re-engineering projects with performance conservation, when sufficient diligence in VE is put to the table [7, 8, 10]. For a new development (greenfield), the product is directly designed to allowable costs. As the latter avoids future potential costly redesign and re-sourcing, it is preferred



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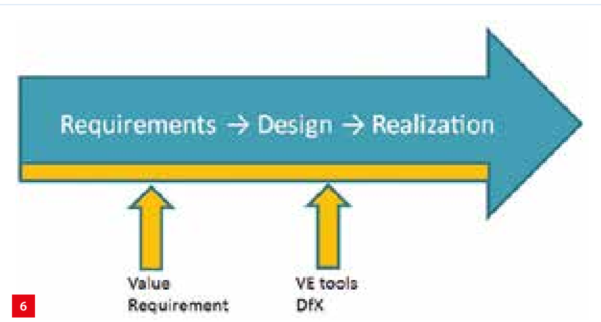
The (value) effectiveness of three different design concepts as a function of costs. The uncertainty in the estimates is indicated by the blue area around a concept. For example, the uncertainty for concept A is large, while very small for B. The uncertainty region is not necessarily connected, as shown by concept C. The current maximum achievable effectiveness is often plotted by fitting a trend line through the different concepts [11].

over VE of existing products, although the process is nearly identical.

Ideally, VE project costs are proportionally borne by the beneficiaries. Of course, the non-recurring expense (NRE), concerning engineering and prototyping, for example, includes the VE effort. To develop a business case, a very simple model is to map the NRE to a value increase or cost saving, multiplied by a risk factor. Another method is to plot the value-effectiveness versus the costs of multiple solutions and indicate the risks, see Figure 5. Concepts or ideas not meeting business case requirements and other constraints are then easily dropped.

Note that NRE itself ideally is subject to VE principles: a certain NRE target follows from the value definition, the project finds solutions to meet the NRE targets and escalates on overruns. Examples of NRE reduction are combination of product versions, computer-aided engineering, clustering or bucketing of ideas to minimise successive product configurations, and implementation speed-up. This way the project and its NRE are in control. Note also that a VE project does not necessarily involve many experts and a lead time of months. It can be scaled down to a limited investment too. Business constraints should always determine the most pragmatic approach, and when and why and at what scale to start a VE project.



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In a development project, stakeholder expectations are translated into requirements and a product is designed and realised according to these requirements. In a simplified representation, some type of value requirement needs to be added to the requirement set. VE tools, best practices and DfX are used during the design and realisation phases, often in multiple iterations, to make sure the intended value is actually created.

Embedding VE in a value culture

If applied constantly and repeatedly, all facets of VE and DfX should be consolidated within the organisation. We found that the VE approach and activities have a healthy fit with standard development processes, see Figure 6.

In practice, not all stakeholders may display commitment to value targets. Typical examples are lacking cost awareness within the own organisation, insufficient alignment between sales, engineering and finance, and suppliers who believe it is business as usual. Correct execution of VE has the important benefit of driving commitment towards a common value perception, aligning all stakeholders and having them understand the necessity of the value target for the economic viability and market success of the joint product. Establishing and maintaining such a value culture is a stepping stone for any future VE project.

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TAKING A CALCULATED STEP TOWARDS AM-PRODUCTION OF HIGH-END METAL PARTS

The transition from subtractive machining to additive manufacturing (AM) – particularly in metals – is challenging. In fact, it can only be achieved by having a complete change in mind-set to outside-the-box creativity, using DfAM (Design for AM) for highest added value. Any practical approach should start from market demand, acquiring in-depth fundamental knowledge of how AM works: the advantages, pitfalls, equipment and prerequisites. On that solid base of expertise, the machine-centric road as presented here – leaving aside the proven way of upgrading knowledge and experience by starting with outsourcing AM jobs – could be taken to invest in AM and start exploiting its many advantages.

JAN WIJERS

Additive manufacturing (AM), or 3D printing, of metal parts is rapidly spreading for production purposes, helped by global frontrunners making their appearance in this multi-billion dollar field of highly innovative, layerwise e-manufacturing technologies. Effectively, AM starts by directly downloading a 3D design, followed by fusing deposited metal powder into complex, near-net-shape parts, monolithic to the core (see, e.g., *www.3dhubs.com/what-is-3d-printing*).

1

Highly functional precision component arising out of fine metal powder. (Source: LPW Technology)

AUTHOR'S NOTE

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Complementary production technologies

Having been around for over two decades now, AM definitely has specific benefits (and some drawbacks). This is not to say, however, that conventional metal removal is obsolete. Generally qualified as subtractive, these machining processes are still unsurpassed in machining speed, materials, surface finish and geometrical quality, at micro- as well as macro-level. Tools like moulds and dies – although themselves time-consuming to manufacture – are still by far the most effective means of producing identical parts in large quantities at a consistently high quality and an acceptable price.

Rapid Prototyping & Manufacturing (RP&M, as AM used to be called) in plastics has become the primarye alternative for producing single pieces or a small batch of high-complexity parts with enhanced (customer-specific) functionality. Undoubtedly, advanced AM has huge potential and is evolving towards – rather high-priced – toolless parts production, without the traditional, expensive form-generating tools. Nevertheless, most near-net-shaped applications are still destined for prototyping or product development, which is aimed at shortening the time-to-market. Beginning with polymer resin, AM has evolved into systems that use metal powder for 'growing' metallic parts (Figure 1). The first ceramic printers hit the market quite recently, along with experiments in carbon fibre and pasty concrete.

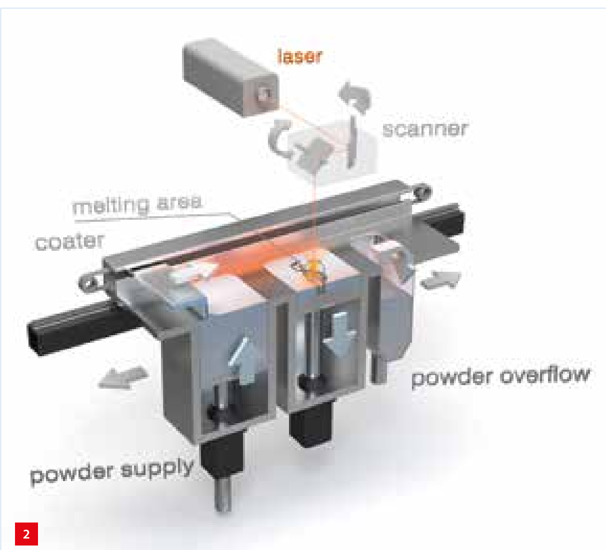
There is still quite a lot of manual, although increasingly automated, post-processing required for comparable quality levels. First of all, as final tolerances and roughness are not yet at an acceptable level directly out of the printer, 'chipping' (conventional machining) has to be used to improve final quality. Secondly, the safe but cumbersome transfer of powder, the design and removal of support structures, the handling of the build plate, the removal of residual (non-fused) particles, the separation of product(s) and build plate, as well as the heat treatment and surface finishing, still have to be made more efficient.

So, AM-parts handling remains fairly delicate and complex, while the cost of surface enhancement is often prohibitive. It can be concluded, however, that rather than disturbing – let alone disrupting – each other, both manufacturing clusters (AM and subtractive) are actually far more complementary.

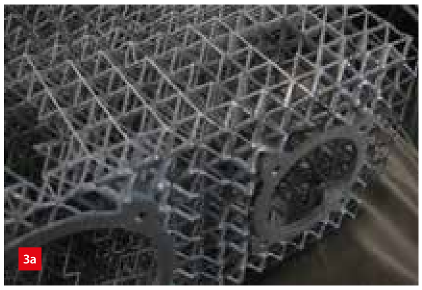
AM series production emerging

From personalised implants and hearing aid housings to lightweight aircraft and car parts, a broad array of successful business cases of complex products, which were previously hardly producible, have proven the unique potential of generating processes, with each alternative technique (Figure 2) likely to yield (slightly) different product properties.

The essential precondition for the transition to AM is a willingness to radically change the way of thinking to outside-the-box. A complete reversal in mind-set is necessary; adapting or recreating a product design is



Principle of one of the well-known AM processes. (Source: LaserCusing)



Examples of lightweight AM products.
(a) Intricate wire-frame structure for a space application. (Source: ESA)
(b) Smartly engineered cooling nozzle, manufactured to order. (Source: Innogrind)

neither effective nor efficient. It starts with designing from the inherent advantages of AM, while being prepared for a long learning trajectory. More and more, rules and specific STM, ANSI, BSI and ISO standards are lending a helping hand.

The real power of AM lies in its outstanding, matchless freedom in design (DfAM) and in manufacturability, independent of geometrical complexity, material, structure and – to a certain degree – functionality, performance and the form-generating procedure. Paramount is that in the design, overall functionality prevails, including internal functionality that cannot be realised conventionally. For example, typical of AM design is the drive for 'lightweight': large, low-mass surfaces and support structures (Figure 3a) and patterns incorporating printed internal supplying, cooling (Figure 3b) and venting channels, thin-walled cross-sections and spatially open configurations, combined with additional smooth hydro, pneumatic or aerodynamic features.

Contrary to conventionally produced components, where general CAM rules apply, every additive design should be individually analysed in technical and economic terms for the best result. AM's grow strategy leads to monolithic, more robust products with lower part count and without partition lines and assembly interfaces.

Metal printing future

Top-ranked companies are in the lead in developing and commercialising high-grade metal powders, reliable machine systems, software packages and high-quality applications. This includes, amongst others, AM-machine builders GE, Siemens, MTU, BMW, HP, EOS, Trumpf, 3D Systems, Renishaw, SLM and GF; while on the metal powder side there is Oerlikon and Uddeholm; in software Siemens, Dassault and Materialise; and as service providers for macro- and micro-component manufacturing there is Materialise, Shapeways and LayerWise. Current drivers are a variety of key application sectors such as aerospace, medical, semiconductor, electronics, automotive, high-tech and personalised luxury goods.

In niche markets, such as micro-AM, AM XL (very large build volume) and AM in more or less exotic materials such as ceramics, the choice is still rather limited regarding equipment as well as material. Actual micro metal printing cases are rare, but a number of companies do already produce and use microprinters tailored for the job (3D Micromat, 3D-MicroPrint) or are on the verge of (experimentally) implementing AM-microparts in their products.

All in all, an impressive line-up of metal-based digital processes are gaining traction in the industry at an increasingly faster pace, raising pressure on conventional metalworking. As innovation can strengthen one's competitive position, managers in a fair number of SMEs are considering the introduction of AM, along with the Industry 4.0-inspired digitalisation. Many are seriously pondering intricate strategical matters such as justification – modernising production, expanding the business or beating the competition – and choosing between a complete switch-over and the development of new markets for AM. Issues include the timing, the best method for implementation, and the integration of AM in the entire digital process chain.

True enough, AM is alive and kicking; on the other hand, practical help during this time- and energy-consuming transition is only being offered by a rather limited number of companies, institutes, knowledge centres (ACAM Aachen Center for Additive Manufacturing, Sirris, Mikrocentrum) and specialists (Flam3D, Additive Center, Additive Minds/ EOS).

Challenging switch-over

Some SMEs actively push the transition – preferably in a multidisciplinary project style with the employees involved in this radical change – finding that AM under production conditions sets a drastically different challenge. Such challenges include identifying suitable parts and determining whether these are ideal to print in series. An AM model for 'see, feel and fit' purposes, a prototype of unrivalled creative freedom, an urgent part-on-demand or critical spare part, a pre-series or a one-of-a-kind special… These all differ widely from real-life series products, especially in the high-end sector.

There is far more to it, to say the least, than simply selecting and acquiring any odd type of AM-apparatus. Such an investment doesn't guarantee a successful and seamless integration into the existing workshop or plant; far more structured effort has to be put into it for that purpose. Certain additional restrictions should be kept in mind upfront. For example, most machines feature a relatively small size regarding the maximum build volume. Part orientation during manufacturing defines the delamination risk under load. In most situations, a separate work facility will be required with dedicated provisions for operator safety, such as a loading station and filtering and ventilation in both the process chamber and the overall AM facility, even when a state-of-the-art professional AM system is adequately sealed off and conditioned.

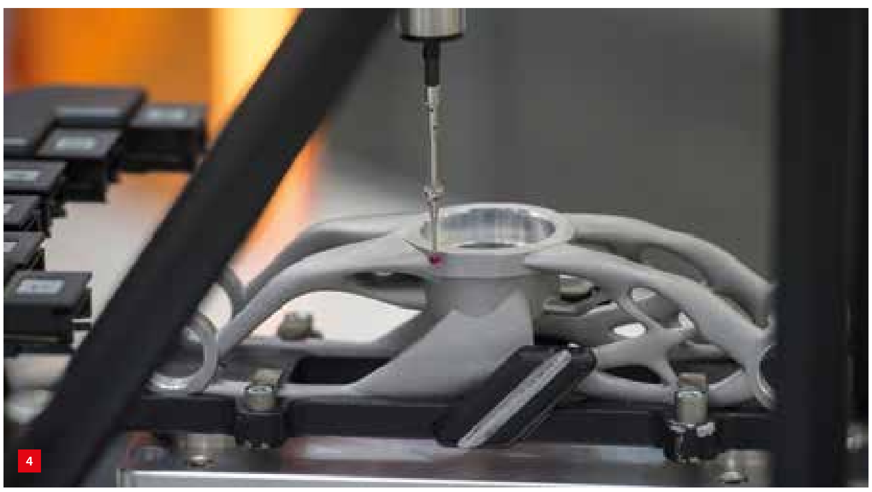
It has become evident that for AM technologies on their way to maturity, advanced closed-loop monitoring of the process constitutes the key to success in industrial practice. The number of steps in the digital, layerwise production of metal parts is considerably reduced, compared with conventional fabrication; for example, no clamping of workpieces, no tool changes, no assembly, etc. Nevertheless, a huge set of parameters is still directly involved, over the entire AM sequence, which complicates the monitoring.

Most AM machines operate almost autonomously, directly drawing on the part CAD file. Nevertheless, the availability of an advanced, company-wide connected, cyber-secure software platform should be taken into account as a crucial backbone for the entire production chain – especially in the front office, but also for downstream (post)processing. It is an absolute necessity for seamlessly handling the conversion and rapid modification iterations of the quickly expanding datasets – in 3D solid-model style – through all the inter-linked stages of design, simulation, actual AM, machining, inspection (Figure 4) and finishing.

Other essential aspects of the transition towards AM (see also the annex: AM technology checklist) are supplementary training, occupational safety, cyber-security measures and service of the inherently complicated AM equipment.

Production aspects

A growing list of in-process-controlled AM processes – above all powder bed fusion (DMLS/SLM/EBAM),



Inspecting the quality of an AM component. (Source: EMO'18)

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Cross-section of a monopart showing intricate flow features that are impossible to machine and hard to inspect. (Source: EOS)

directed energy deposition (LBM) and binder jetting (BJ) – is generating series of multifunctional high-tech parts of, both internally and externally complicated, geometries that comply with stringent industrial specifications for geometry, quality and consistency. Metallurgical problems can arise, as the earliest that specific mechanical properties will emerge, is during the actual metal fusion – i.e., in slightly less than 100 per cent dense layers – inside a very restricted melt pool, characterised by extreme cooling rates.

Heat treatment helps to improve the metallic structure of adjacent layers by lowering internal stresses and tightening dimensional tolerances. Certain AM processes are restricted in choice of metal, varying from (high-strength) steel and aluminium alloys to titanium, magnesium, CoCr and copper. The latter poses problems because of its high reflectivity and heat conductivity, and was only recently announced to be 3D-printable.

More often than not customers will make certification mandatory, with aerospace, the high-tech industry and medical technology in the forefront. Validation of the process, machine tool, material and applications is a time-consuming procedure. Test samples, destructive testing and costly X-ray / CT scans are all necessary in registering the absolute data. Few controlling and measuring technologies are available to inspect internally (Figure 5) as well as externally. Hence, most of the so-called ‘proof’ is invisible.

In addition to the high price of the powder as the starting material, transferring and handling the powder in the right way with respect to operator safety is far more intricate and difficult than with the standard solid blank, rod, strip or sheet metal. On the other hand, AM can reduce costs, for example due to AM’s unique ability to ‘grow’ multiple (micro) parts on the build table during a single production run, either by nesting parts (2D) or by stacking them on top of each other (3D), including supports (Figure 6). This is – aside from the introduction of multiple lasers, which raises system investment – the ultimate way to reduce build time and cost per part.

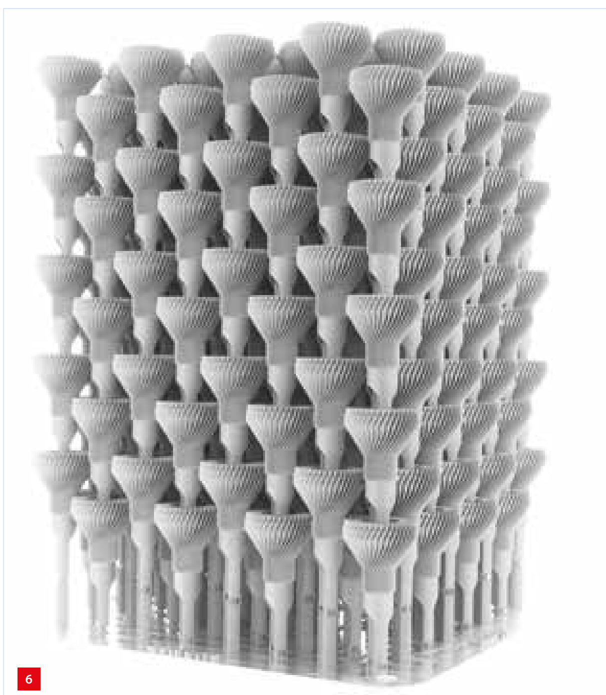
Added value

Crucial for a successful market introduction is the added value AM can generate regarding the inner and outer configuration of products (design, haptics, wear-resistance), their functionality and performance, and the price. In certain branches, attaining the lowest cost is the decisive factor, whereas in other branches speed, load characteristics, quality or surface integrity are the predominant considerations. In the medical industry, for example, the availability of customised implants, intricate instruments or devices is the key factor, rather than price. In Formula 1 racing and the like, the shortest real-time delivery and an unprecedented aerodynamic design freedom are the driving aspects; price is irrelevant. Saving time by switching to monolithic components and thus avoiding assembly activities is generally a welcome side-effect.

In nine out of ten high-end cases, a specifically AM-designed monolithic part cannot be fabricated in a traditional way. For example, contour-conforming, widening and constricting flow channels or duct systems – almost up to the outer skin – are virtually impossible to realise without AM, as are weight-saving yet sturdy honeycomb cross-sections. The reverse – producing a conventional design in additive style – only brings minor or even no advantages.

First pragmatic step: outsourcing

In the tool and die industry, as well as in precision- and micromachining, it is usual to tackle challenges in a pragmatic way, either by doing everything yourself or by outsourcing selected jobs. So, why not in AM as well, by



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Towering stack of LED micro-heatsinks. (Source: Renishaw) outsourcing AM jobs to a trusted service provider or joining a shared facility such as that offered by K3D (*www.k3d.nl*), for example? In that strategic way, first of all less time has to be spent in-house, while specific knowledge and experience in design, engineering, production and finish procedures can be obtained along the way in the outsourcing trajectory.

Furthermore, one can avoid a possibly risky investment in a company-owned AM-machine, the prices and footprint of which are far above those of conventional industrial equipment of identical working volume. In the meantime, typical aspects of both the process and the machine can be investigated, such as mechanical – static and dynamic – and thermal properties, weight and/or material reduction, special design features related to hydraulic or air flow properties, flatness and surface roughness, and specific cooling needs.

Plastic as a stepping stone to metal

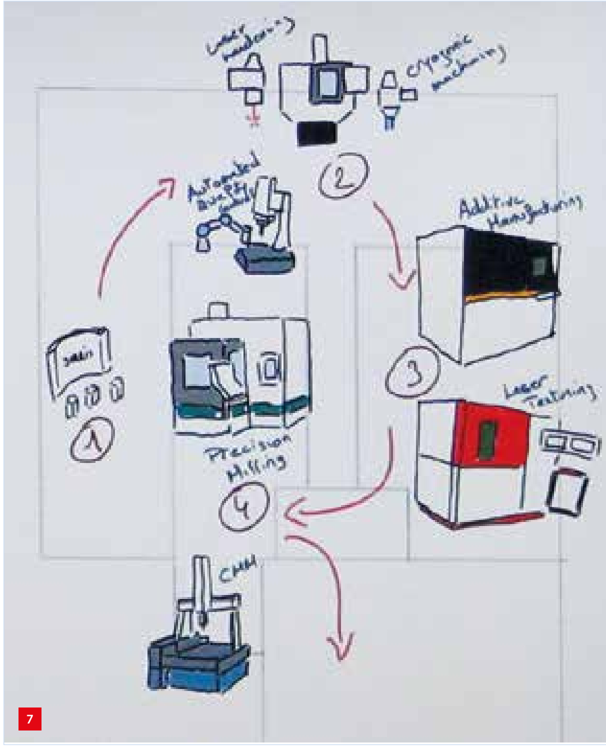
The next pragmatic step could be buying or leasing equipment that produces plastic prototypes, models or more sophisticated parts. In general, the greater part of potential challenges and learning moments in metal AM – except for the far higher operational temperatures and related aspects – will resemble experiences with polymers.

Dedicated on-the-job training for working in the AM chain in the initial plastic testing period – and later on with a metal printer – will undoubtedly be of direct help for a few additional practical purposes, regarding the infrastructure and other needs inherent to any AM machine. For general applications of everyday parts – such as fixation and auxiliary tools in the assembly stage as well as jigs and templates – and for testing the switch-over from heavier and more costly metal parts, an affordable 3D printer for high-performance plastic suits well in most cases.

Integrated factory

As soon as AM equipment comes into the picture, it is quite rational to seek the proper balance by investing in a machine that fits technically, economically and strategically within the existing machinery infrastructure. In that way, new possibilities can be tested in practice with a mix of subtractive and additive processes, to find the proper combination; for example, to start – as a way of re(verse) engineering – by removing the wear from conventionally machined products through adding wear-resistant layers to restore the original geometry.

At that moment, decisions have to be made regarding a proper clamping system that is stable, able to be changed quickly and above all a precise interface on all machine tools inside the new production chain. Already well-known producers, such as System 3R, of standard zero-point tables,



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Early sketch of the AM Integrated Factory vision of Sirris.

workpiece- and toolholders, as well as automation modules, provide proper and proven solutions without loss of accuracy that fit in current-generation AM machines.
In Belgium in 2018, Sirris presented the AM Integrated Factory project as a demonstrator, to motivate SMEs to make a gradual transition to AM (Figure 7). To the available high-level metalworking machinery were added a Concept Laser M2 laser printer, a high-power direct diode laser and a Lasea femtoseconde laser for hardening and microtexturing, respectively, and a mobile Kuka cobot automation set.

Hybrid platform

In actual metalworking practice such as sawing, milling and wire-EDM (preferably in a single clamping set-up) established intermediary or post-processing steps can be made with high precision and productivity to help realise high-quality parts, using references on faces and in fits. Therefore, in many cases a kind of hybrid choice is quickly taken at the expense of one of the many single-machine platforms.

Closest to everyday practice in the workshop, a hybrid CNC milling centre incorporates an optional AM-head for LMD – direct laser or electric arc solid metal deposition either by filament or powder (rather fast and rough, needing more 'chipping', capable of realising magnum parts) – or LMF powder-bed technology (laser metal fusion, offering the best micro-part accuracy at lower build speed; but requiring a high investment in powder, see Figure 8). It should be observed that the additional process makes the machines less economic; while one process is running the other is idle.

An example of a hybrid platform, the Lumex Avance-25 technology centre, integrating a fibre laser for state-of-the-art metal sintering (AM) and a machining centre for high-accuracy, high-speed milling. (Source: Matsuura)

Line or integrated platform

Starting an AM factory (Daimler/EOS, Renishaw, Siemens, 3D Systems, GE, Oerlikon/Citim, and so on) can be achieved industrially via the modular coupling of standard AM-machines (Figure 9), with the automation either integrated or as a robotics extension in WAAM style (Wire-Arc AM). However, this is still in its infancy.

Relatively few SMEs have dared to take a head start like Dutch firm Kaak and its sister company K3D (Figure 10). They directly invested – future-proofing their business – in one of the very first fully integrated AM platforms, from Additive Industries, basing their investment on an extensive feasibility study and the corresponding business case. In the newest, scalable high-volume-production version of Additive Industries' MetaFab1, the CAD-file, so to speak, enters with the selected metal powder up front, whereas the near-net-shape products, separated from the build plate, exit at the end.

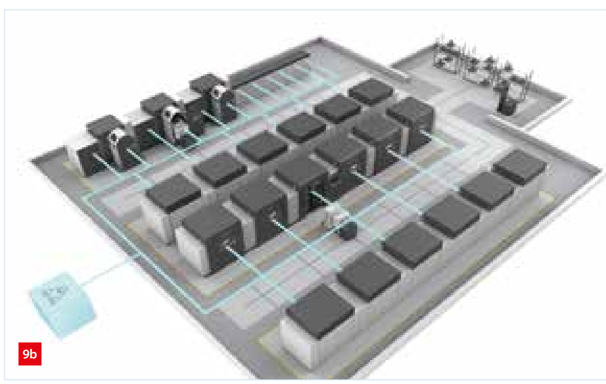
Conventionally machined (left) and AM-produced vacuum-forming mould for a transparent (blister) cover. The AM product performs better in terms of weight, wear resistance, functionality and cooling power during forming operation. (Source: K3D)

This one-of-a-kind additive production system can be specifically configured for a company or product or as an AM platform, both in hardware and software terms. Inside the sealed machine enclosure, series of modular units such as up to four full-field multifibre lasers are active, overlapping in their working range and remelting printed metal both horizontally and vertically during the multi-spot grow cycle. Minimising the mutual interference is already being investigated, as are multiple build chambers, with automatic powder bed supply and material management under inert conditions (including reuse/recycling), and heat treatment.

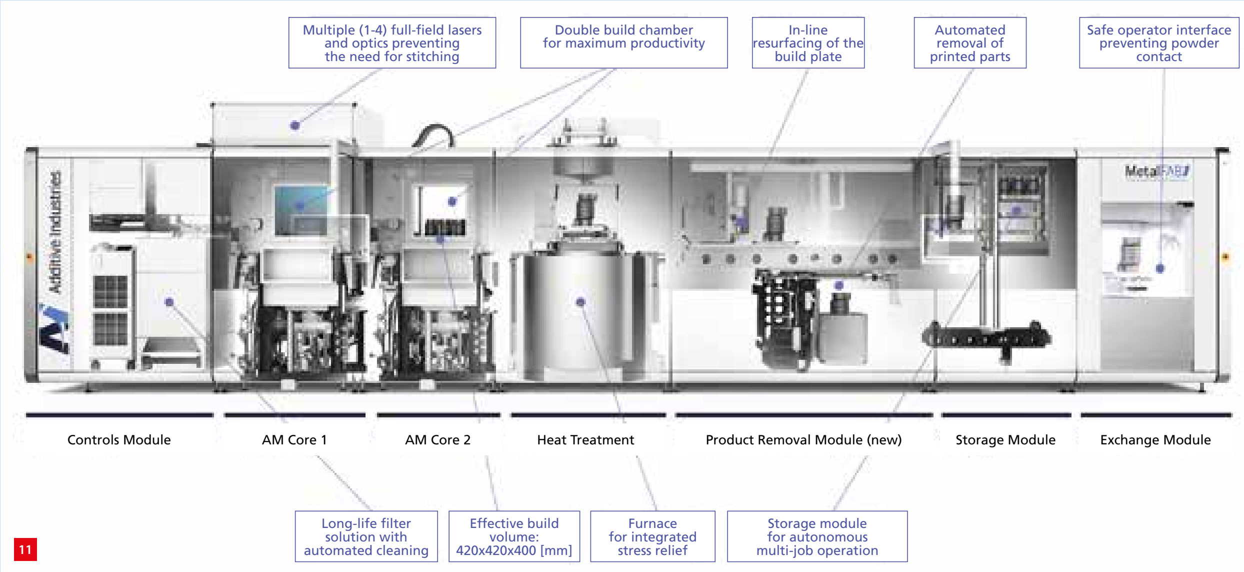
The latest version (Figure 11) even contains a set-up for separating the product(s) and a unit for surface milling (resurfacing) the top side of the build table. Automatic stocking and exchanging the build plates involved for the next jobs, as well as additional logistic robot activities, proceed autonomously and safely along a linear guide at the back side. In order to offer customers adequate possibilities for in-house process development and application optimisation, a dedicated version is available.

This spring it was announced that the first MetalFab1 had been sold in China, which is quite an achievement in the additive world.

The AM game is on, beyond prototyping.



Schematic layouts of automated AM facilities.
(a) Renishaw.
(b) 3D Systems.



View inside the newest generation MetalFab1. (Source: Additive Industries)

Annex: AM technology checklist

Survey of items (not exhaustive) that have to be considered thoroughly in the technology/machine selection phase.

Specifics of selected AM process

- Productivity / Reproducibility / Repeatability / Flexibility / Reliability
- Size versus cost and complexity / Consistent production quality with identical parts / Intrinsic advantages

AM machine

- Dimensions: Overall (X.Y.Z) / Work chamber (X.Y.Z) / Build table (X.Y.Z) / Total weight
- Installed electrical power / Compressed air / Water
- Maximum part envelope (X.Y.Z) / Max. part weight / Max. workload
- Support structures needed (automatic generation)
- Inert atmosphere: vacuum/Argon
- Laser: Type: YAG, fibre or diode / Spot size / Number: 1-4 / Scanner or XY-stage / Build speed / Scan speed
- Number of 2D-stacked or 3D-nested parts
- Technology database (process and machine settings)
- Range available metals/alloys
- Proprietary or open software
- Powder dimensions (Ø) / Attainable detail size/resolution
- Surface roughness R_a
- Achievable minimum wall thickness
- Recycling (manual/automatic)
- Feasibility/Acceptance tests (preliminary/final) including measuring report

ICT assets

- Software:
  - 3D Solid CAD, CAM, CAE / AM- and machine-specific software / Integrated simulation
  - Operating system / File formats (STEP, IGES, STL, ….) / Calibration
  - Data and process management / Network
  - Updates / Guarantee
- Hardware:
  - Interfaces / High-capacity data transfer and memory
  - Compatible process control / HMI type / Tablet and mobile phone remote control
  - Diagnostics / Service (updates included)

AM facility

- Dimensions
- Environmental conditions / ATEX conformity / O_2/moisture-controlled stocking cabinet
- Personal and spatial safety measures / Safety means
- Laser type / Laser safety class
- Ergonomic conditions
- Auxiliary means / Conditioning and filtering system (dimensions, capacity)
- Operating time / Operation costs / Logistics
- Gas supply / Argon, CO_2, He, gas mixture

Operational aspects/costs

- Investment budget / Total cost of ownership / Return on investment
- Initial AM-machine
- Metal powder (machine load, in-stock)
- Automation / Process and cyber security / Quality assurance / Training and schooling

MAINTAINING HIGH STANDARDS, TAKING NEW DIRECTIONS

The high-tech industry is desperate for well-qualified employees, including instrument makers, thus it is good news that the Leidse instrumentmakers School has grown considerably during the past years. Dick Harms, who recently retired as director of the LiS, gave the school a stronger public profile and was inspirational concerning the extension of the school premises. His successor, Godelieve Bun, will continue on this chosen path of growth, focusing on further increasing the intake of students, renewing the curriculum and professionalising the school organisation. Support from high-tech companies and DSPE will remain needed.

The Leidse instrumentmakers School (LiS) is one of the oldest Dutch vocational educational institutions. The school was founded in 1901 by the Leiden professor and Nobel Prize-winner Heike Kamerlingh Onnes because he needed professionals who could develop and make tools for his research into the liquefaction of helium and the phenomenon of superconductivity at ultra-low temperatures. Over the years, the LiS (Figure 1) has retained its status as an independent professional school, dedicated to the training of (research) instrument makers, despite the trend towards scaling-up that has led to the establishment of large, multi-discipline regional training centres.

Modernisation

In 2008, Dick Harms, a former service manager at Toshiba Medical Systems Europe, a former marine officer, and a keen amateur radio operator, was appointed director of the LiS. His job was to strengthen the public profile of the LiS and foster the growth of the school in terms of student numbers, in order to meet the growing demand from industry for good instrument makers, while retaining the quality inherent in small-scale education. Harms succeeded in securing the LiS' independent position, although the discussion on the status of small professional schools in the Netherlands will probably never end.

1

The Leidse instrumentmakers School with the recent extension in the front.

For instance, the LiS still has to defend its four-year curriculum ("Isn't three years enough?") and the high examination/qualification level ("Aren't your alumni a bit overqualified?"). To both questions, the answer is a definite "No". Until 1995, the school had a five-year curriculum, with the fifth year dedicated to making complex instruments, such as lasers. Nowadays, four years are really necessary – consequently, there are more lessons in the class schedule than required by the government – to give the students sufficient training in the realisation, including the design, of research instruments. Given the industrial need for highly educated instrument makers, the school takes pride in qualifying its students at a high level of theoretical knowledge and practical skills.

Growth

During Harms' directorship, with the support of the board (consisting of several volunteers from Leiden University), the LiS expanded and modernised its facilities so it could double in size to a maximum capacity of 400 students. Since 2008, the number of students has grown from 155 to over 300; the school has 40+ staff, including some 25 teachers and 10 educational support personnel. The LiS was able to expand thanks to additional funding from the Ministry of Education,

LiS teacher Frans Folst (left) showing King Willem-Alexander (middle) the art of making glass instruments during the opening ceremony for the new wing of the LiS premises.

The incoming and retiring director of the LiS, Godelieve Bun and Dick Harms, respectively.

the city of Leiden and Leiden University, as well as from private parties and companies. At the beginning of December 2016, His Majesty King Willem-Alexander of the Netherlands officially opened the new wing of the school (Figure 2).

Characteristics

At the occasion, Harms made an attempt to characterise the LiS and its alumni: "Our graduates are able to find work all over the Netherlands, and sometimes even abroad. They play an important role in research and development due to their high level of knowledge, skills and creativity... There are perhaps a number of characteristics that are very important for the quality of education in our school, such as our connection to scientific culture, the well-equipped practice environment and the development-oriented culture between students and teachers, shaped especially by the enthusiastic teaching staff. More than half of our teaching time is spent in practical learning; therefore the school is full of expensive equipment and machinery (Figure 3). Furthermore, the LiS trains students in multidisciplinary communication."

Overview of the equipment and machinery in the recent LiS extension. (Photo: Hielco Kuipers)

Further growth and professionalisation

Having achieved his main objectives, Harms decided to retire. His successor, Godelieve Bun, a former innovation and business development manager in the food industry and a former team leader in the precision engineering department of HU University of Applied Sciences Utrecht, will continue to pursue the growth strategy (Figure 4). This will require the further expansion and professionalisation of the school staff, to accommodate the growing number of students and keep up with the increasing regulatory burden. One of Bun's intentions is to intensify the collaboration with fellow professional schools – at management as well as operational level – for developing and exchanging best practices in school administration.

Elective modules and specialisations

Following the introduction of elective modules to secondary vocational education (replacing the so-called 'free space') and the latest update of the qualification file for the research instrument maker education (see the text box), the LiS curriculum (see Table 1 and Figures 5 and 6) has been renewed. Some elective modules are already in place, while others are still under construction. These modules enable students to customise their programme with respect to their career perspective. Each year the students can take up a module, which covers one day a week during a full semester. For all options, see Table 1.

For example, the 'Instrumentation for Space' module aims to train students to specialise in the design and construction of instrumentation for satellites, rockets and astronomical observatories. The special programme was set up with support from the Regional Investment Fund, local government, (research) institutes (like NLR, NOVA, SRON and TNO) and companies (including Airbus, AJB/Madern, ISIS, Lens R&D, Microtechniek, SSI and WestEnd). By choosing the 'Instrumentation for Space' elective module

Qualification file: Research instrument maker

The Vocational Education and Industry Association (*Samenwerkingsorganisatie Beroepsonderwijs Bedrijfsleven*, SBB) is in charge of the qualification file that defines the requirements which a student has to meet in order to qualify for the research instrument maker diploma. The following professional description has been derived from the file: Research instrument makers work with both conventional and CNC multi-axis machining centres. They make complex, compound and single products, applying different processing techniques to a variety of materials. Their tasks are of a multidisciplinary nature and they work autonomously, systematically, creatively and with focus. They have the capacity for innovation, are skilful and have good spatial insight. They often work in teams with academically trained researchers and are able to communicate professionally with them in both Dutch and English, and are able to analyse the challenges and problems presented to him. They are then able to convert the presented problem into an actual construction and to test its functionality. They can be deployed flexibly and pay attention to environmental and sustainability issues.

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Table 1
The LiS curriculum for the research instrument maker education.

Theory	
Specific education	*General education*
Professional theory	Mathematics
Design theory	Physics/Chemistry
Electricity theory	Technical management
Materials theory	Dutch
Drawing/Computer drawing	English
CAM	Calculus
Informatics and Metrology	Career orientation
Assembly and Maintenance	Citizenship education
Elective modules	**Workshop training**
Instrumentation for Space	Metal
Optical Manufacturing	Optics
Optical Engineering	Glass
Drone Technology	CNC
Entrepreneurship	
Methodical design	
Innovation	
English at HBO* level	
Mathematics as HBO* preparation	
Design projects	
The Unit (group project, semester 2)	
Physics demonstration set-up project (group project, semester 6)	
Design of research instrumentation (group project, semester 7)	
Final assignment (individual project, semester 8)	

(HBO is the Dutch abbreviation for higher vocational education)*

and doing a space-related project and/or internship, a student can develop a space specialisation.

Already in 2014, a precision medical technology/life sciences & health specialisation was introduced at the LiS with the aid of a Centre for Innovative Craftsmanship (*Centrum voor Innovatief Vakmanschap*, CIV) subsidy. Now this medical specialisation has been absorbed into the regular programme, through numerous contacts in this field with high-tech companies, universities, research institutions and academic medical centres. In the same vein, an optics specialisation is now under development.

The CIV subsidy was also instrumental in the start-up of the LiS Academy (see below) and LiS Engineering, which acquires contract work from companies. During an internal internship at LiS Engineering, students can manufacture (and design) instruments and components.

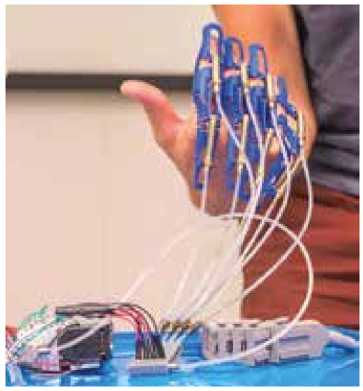
Increasing the student intake

High on the new director's priority list is a further increase of the student intake. To that end, she will intensify the nationwide promotion of the school. Currently, a modest 20 per cent of the influx comes from outside the greater Leiden region, so there is potential for growth. Intensifying collaboration with regional training centres, especially in Eindhoven, Twente and the northern Netherlands, may contribute to this.

A promising model is one where students follow the first two years of a more general precision engineering/tool maker education at a school near them, and complete their education with two years in Leiden (and at companies in their own region for their practical assignments) dedicated to research instrument making. A first attempt at this kind of collaboration was made by Dick Harms, and Godelieve Bun will further explore opportunities, which should ultimately contribute to the overarching goal: increasing the influx of qualified personnel into the Dutch high-tech industry.

A special focus will be given to recruiting female candidates, as the current share of female students at the LiS is a mere eight per cent. Bun aims to increase this share to 15 per cent. In this respect, a life sciences & health specialisation (see below) might help.

In the end it's not the influx but the outflow of graduates that counts. To achieve a high graduation rate, the LiS used to select the most promising candidates from among applicants, but for a few years now this has not been permitted under the Dutch vocational educational system. So, now the LiS invests in its intake procedure for candidates, to test their motivation and fit for the highly


Examples of practical exam and project work.

challenging education at the LiS. The idea is that this will help them to make a well-founded decision on whether or not to register. In addition, the LiS strives to provide extensive coaching and guidance for students during their career at the LiS, to minimise unnecessary drop-out.

Towards university level

Graduates from the LiS have good job perspectives, yet many of them opt for extending their 'educational career' at a university of applied sciences, to deepen their knowledge and design skills or broaden their horizons. To promote this option, the LiS helped Inholland University of Applied Sciences – with input from industry and the scientific community – to start a Precision Engineering programme in Delft, as a specialisation in its Aeronautical Engineering programme, which kicked off in the 2017-2018 school year. The LiS provides part of the workshop trainings, manufacturability lectures and training in processing techniques.

Life-long learning

Over the past several years, government policy has aimed to encourage life-long learning at the secondary vocational education level to promote the labour mobility of professionals who traditionally used to stay in their jobs for a very long time, while well-trained craftsmen will also be valued by other employers. The LiS Academy already provides refresher and further training courses on the design and manufacturing of precision technology systems. In addition to one-day practical courses in turning and milling and hot glass processing, the LiS Academy offers a five-day Manufacturability course (see the following pages).

The aim is to further expand the range of services offered by the LiS Academy, for instance by introducing courses based on the elective modules or regular parts of the LiS curriculum. In addition, the LiS Academy will seek to collaborate with other professional organisations (both education providers as well as customers) to improve and increase its impact.

Support from industry

No doubt, the commitment to life-long learning will give a boost to the LiS Academy and further intensify relations with the industry. The LiS has for decades received firm support from the business community. Many companies submit challenging (individual and group) project proposals for LiS students and some have even gone as far as donating machines for the LiS workshop. These include a CNC ultra-precision hard-turning machine from Hembrug Machine Tools in Haarlem and a CNC wire-EDM machine from

Impressions from the workshop training. (Photos: Hielco Kuipers)

Ter Hoek Vonkerosie Rijssen, both donated in 2016 for the LiS extension.

In 2017, the LiS officially became the first Haas-Technical education center (HTEC) in the Netherlands. The LiS workshop is equipped with two Haas Super Mini Mills, a Haas VF-1 machining centre and a Haas ST-10Y lathe. This equipment is used by the LiS for the advanced and high-tech education in CNC turning and milling. Haas Automation can take customers and prospects to the LiS for demos. In addition, Haas supports some LiS students with scholarships. This collaboration has introduced the LiS to the international HTEC-education network.

Support from DSPE

DSPE has also been a keen supporter of the LiS. No wonder, given the fact that LiS alumni were among the founders of DSPE's predecessor. This close relationship is illustrated by the fact that the LiS director has a position on the DSPE board. In particular, as both Dick Harms and Godelieve Bun stress, DSPE can plead the case for the qualification file and other educational matters whenever needed. In the interest of its members and the entire Dutch precision community, DSPE can act as an advocate of the LiS.

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Manufacturability course

The Leidse instrumentmakers School often works with bachelor, master and Ph.D. students from universities (of applied sciences) who come to the LiS with designs that look great. When they ask to make their product or instrument, however, the LiS may have to disappoint them and send them back to the digital drawing table, simply because their design is too difficult or too expensive to manufacture or even impossible to assemble.

For engineers who have little experience in the field of manufacturing, it can be difficult to choose the best manufacturing technique for their product. It requires an understanding of machining techniques and how they influence design boundaries: for example, the materials that can be used, shapes and tolerances that can be achieved, and the cost of the process. Furthermore, change is happening so rapidly that techniques that five years ago were just emerging and still very inaccurate might nowadays do the job.
Manufacturing of (precision) components is a very dynamic field, where significant improvements are made year on year. Engineers, especially those at the beginning of their career with little experience with manufacturability, can profit from dedicated information, demonstrations and guidance. With this in mind, the LiS has developed a five-day course on manufacturability.

Target group

This course is aimed at professionals with an interest in the manufacturability of (precision) components. It targets engineers with little machining experience, who would like to get basic experience in the manufacturing of (precision) components via lectures, demonstrations, practical experiences and company visits.

Theory & application

Concise courses will be given by experts from the different fields of metal manufacturing, for example milling, turning, 3D printing, sheet metalworking, spark erosion, surface treatments, laser cutting, etc., who will explain the different techniques and their (non-)applicability. At the end of the course, participants will have a theoretical working knowledge of the various techniques, including their design freedom (Figure 7) and applicability for different types of products.

Excursions & practice

Along with the theoretical aspects, the courses also offer plenty of time to discuss and observe the practical aspects. To illustrate the theory outlined in the courses, visits will be made to manufacturing plants to see the different

Gearbox realisation. (Credit: Hittech)
(a) Designed with the standard manufacturing techniques in mind.
(b) Design freedom offered by 3D printing.

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Explanation of the laser-cutting process at Suplacon.

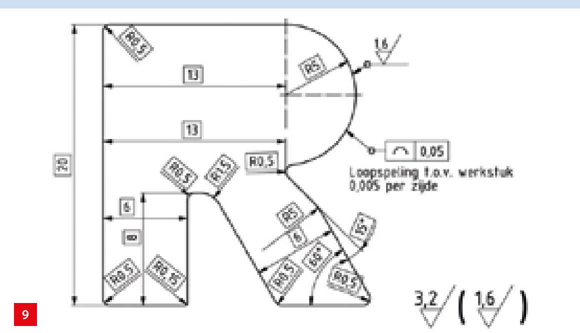
techniques in practice. Companies and institutes that will be visited include Ter Hoek Vonkerosie Rijssen (for spark erosion and the Laser MicroJet® technology, see the article on page 20 ff), Suplacon (for sheet metalworking and laser cutting, see Figure 8), NLR (for 3D printing), Mitutoyo (for measuring and tolerances) and of course the LiS (for CNC milling and turning).

The core philosophy of the LiS is learning by doing. Participants will therefore be requested, as part of the course, to undertake some assignments (Figure 9), which will help to show the connection between theory and practice. The results of these exercises and the implications of the different designs will be discussed with experts during the course. There is even the possibility for participants to discuss the general manufacturability of their own design with experts during the expert panel sessions.

Programme

During the five-day course, company visits and expert lectures are combined where possible, in order to bring the theory immediately into practice. Table 2 presents the typical programme. For the first half of the week, participants will stay in the east of the Netherlands, while in the second half of the week, the LiS will be the home base. Transportation between the various locations will be arranged.

At the end of the programme, participants will have sufficient knowledge to make well-founded decisions



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Part of the practical assignment focused on the preparation of manufacturing drawings for the spark erosion lectures and visit to Ter Hoek Vonkerosie Rijssen. The drawing is in Dutch and the text on the right reads "Running clearance with respect to the workpiece 0.005 on each side". (Credit: Ter Hoek)

Table 2
LiS Manufacturability course typical programme.

	Monday	Tuesday	Wednesday	Thursday	Friday
Morning	Introduction	3D printing (NLR)	Measuring and roughness (Mitutoyo)	Turning and milling (LiS)	Value Engineering (LiS)
Afternoon	Spark erosion (Ter Hoek)	Sheet Metal (Suplacon)	Surface treatments (LiS)	Discussion with experts (LiS)	Practical exercise (LiS)

about the manufacturing techniques for their products. They will have a good working knowledge of the implications of the different manufacturing techniques for the final accuracy (including the placement of the reference surfaces), the surface roughness and the cost of the product. They will be better able to talk with manufacturers, by having a more thorough understanding of the potential difficulties for manufacturers and knowing how to avoid them.

Miscellaneous

As well as potentially making new contacts with manufacturing facilities, this course also will bring together professionals from different companies and institutes. In the past it was observed that this enlarged network provides participants with new insights into their own design and manufacturing process.
Successful completion of the course earns the participant five points in the European Certified Precision Engineering Course Program (see page 78).
The course has been made possible thanks to the input from the following partners: Dutch Space, Hittech, Mitutoyo, Nederlands Herseninstituut, NLR, Suplacon, Ter Hoek Vonkerosie Rijssen and TNO, with the support from DSPE, Brainport Industries, DPT and FME.

Judging from the feedback of former participants, the course is greatly appreciated:

- "The course itself, most subjects, the interaction between the speakers/experts and the students, and the atmosphere were positive."
- "The discussion with the experts made me rethink the design of my product."
- "Now I understand the meaning of the different surface roughness parameters."

The next edition of the course will take place from Monday 4th to Friday 8th November 2019.

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(contribution by Frank Molster, public-private partnership manager at the LiS)

CASTING INNOVATION

Metal casting processes are a very efficient and economical way of producing functional products. However, they require casting process knowledge and expensive simulation software to prevent casting defects. New innovative products like the 'Castability checker' and a 'Foundry course for mechanical engineers' help to address the pitfalls in the development and supply chain.

ROY KASTELEIN AND ROB VAN TOL

Benefits

Compared to other production processes like metal 3D printing (additive manufacturing), forging, welding and machining, casting offers a very interesting portfolio of benefits especially for the precision industry; see Table 1. From this table, one would expect the precision industry to show great interest in castings, but of course there are also a few annoying drawbacks. In many cases castings are being used successfully in the final product; in some cases, castings create headaches at the management and quality assurance level. Why?

First reason: functional castings like frames, brackets, housings, etc. (Figure 1) are nearly always in the critical time path of a design & realisation project, because:

- they are the last parts in the assembly that are released, often connecting all other parts;
- the lead times for the fabrication of casting tools are usually long (except for rapid prototyping);
- finally, the first parts needed to build up the assembly are... the castings.

Therefore, any unexpected delay due to quality issues usually receives immediate management attention.

Second reason: casting process knowledge taught at universities and in CAD courses is relatively poor, so construction engineers are often not very familiar with casting designs. This is also an important aspect in the communication with the supplier about improving the design for castability.

In this article, these common pitfalls in a casting development trajectory are explained and practical solutions are presented that have been developed to support engineers in the precision industry to prevent casting problems in their designs.

AUTHORS' NOTE

Roy Kastelein and Rob van Tol started their foundry education at Delft University of Technology (NL) in the 1990s and pioneered with thermal simulations. Reunited at the WTCM Foundry Centre in Ghent (Belgium), they continued the development of casting simulation models with the aid of foundry experiments. For many years they have run their own consulting company, but since 2016 many activities have been centralised via the network of Lautus Castings.

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Table 1
Typical design characteristics of popular fabrication methods for mechanical parts.

Production process	Rapid prototyping	Serial production	Design freedom	Cost-effectiveness
Casting	Yes	Yes	Very high	Very good (local remelting)
Forging	No	Yes	High	Dependent on quantity
3D printing	Yes	Not profitable	Very high	Good for small complex products
Welding constructions	Yes	Yes	Moderate	Good for low-complexity products
Full machining	Yes	Not profitable	High	High scrap rate (external remelter)

Casting problems

Generally, designers divide casting problems into two categories: porosities and distortions. The root cause for these problems is in the design or in the casting process (or in a combination of both). In the Lautus Castings foundry course for casting specialists, 13 categories of defects are distinguished, most of them related to the production process (Table 2).

Table 2
Casting defects catalogue according to Lautus Castings.

Casting defect	Process step
1. Gas 2. Microstructure	Melt preparation and composition
3. Mould delay 4. Mould crack 5. Erosion, rat tails, flashes, etc.	(Sand) moulding line
6. Pre-filling, slack inclusions, oxide films 7. Air bubbles 8. Cold-shut	Gating design
9. Core gases 10. Shrinkage 11. Hot tearing	Solidification
12. Cold tearing 13. Distortion	Cooling down

Typical precision parts made by casting.

Here, the focus is on the most common defect as shown in Table 2, i.e. shrinkage porosity (no. 10), which is very design-dependent; see Figure 2. The robustness of the design to prevent shrinkage is called the 'castability' of the casting design.

Communication problems

An often-underestimated aspect in the development projects involving castings is the quality of communication between the CAD engineer and the casting specialist of the supplier. It is supposed to be 'co-engineering', which is a complex technical and commercial process often leading to misunderstandings.

Figure 3 shows the main steps in a traditional, so-called simultaneous engineering project of a cast product. The most important choices a construction engineer needs to make concern:

- production process;
- material selection;
- design concept;
- FEM (finite-element model) strength analysis;
- design modification loops to improve and meet specifications.

Then the CAD file(s), often with 2D drawings, are handed over to the purchasing department, which selects the supplier / foundry.

It seems a logic chain of actions, but the design is only simulated for functionality and not checked on castability. The castability check is a solidification simulation of the CAD model only, which shows the 'hotspots' indicating the highest porosity risks of the design. If these 'shrinkage porosity' areas are on the same location as the 'highest-stress zones', there is a problem to solve.

Typical shrinkage defect in a casting.

Interdisciplinary co-engineering

A far better development scenario is presented in Figure 4, where FEM functionality simulations are carried out in parallel to 'castability' simulations of the design (but not yet of the process). It offers much more purchase flexibility in the supplier selection and less production risks due to a better product design. The impact of such a 'castability check' by the designer is huge. All potential suppliers receive relatively easily castable designs and will quote accordingly. Quotes will be lower than in the case of designs that are 'complex to cast' and there are no (hidden) 'design change requests'. In other words, the design process is faster (fewer redesign loops) and the production process will become more robust and cheaper.

Bottlenecks

A casting simulation is usually not executed in the design stage (by the CAD engineer) because of the following bottlenecks:

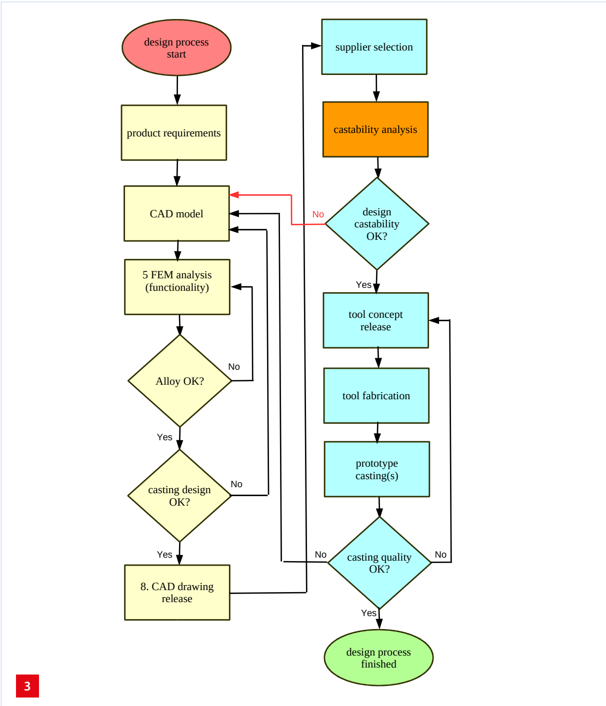
1. Casting simulation software is complex, expensive and in general requires a casting specialist to execute and analyse.
2. Managers are afraid that internal casting simulations might take over product responsibility, which of course must remain on the supplier's side.

Therefore:

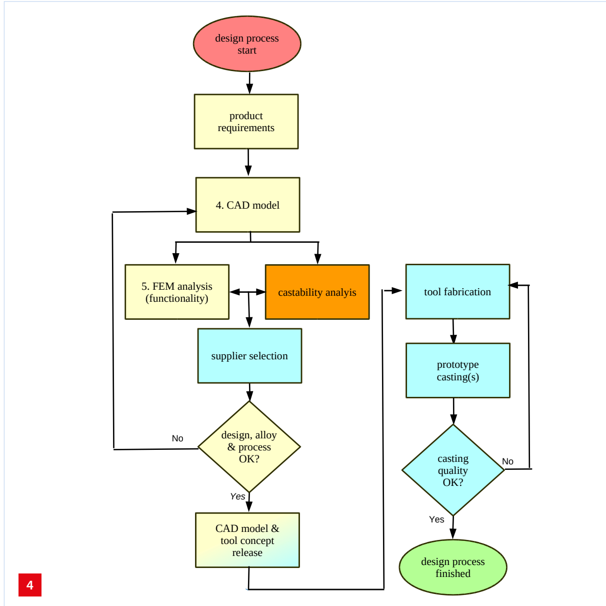
3. The foundry is expected to provide the castability data, but in general it is delivered only after the order has been signed.
4. The purchasing department mainly looks for the cheapest supplier, which is often the foundry without casting simulation software and a specially trained engineer. Such suppliers act on 'experience', not on 'data and knowledge'.

Lautus Castability Checker

To overcome these four practical bottlenecks, Lautus Castings – in collaboration with its network of experts – developed an easy-to-use 'castability checker' for CAD engineers, the Lautus Castability Checker (LCC). All features that are not needed in the design stage of the project, such as mould filling, are omitted. The software fully automatically generates a report with images showing the exact location of the hotspots in the design. Clear images show the locations with the highest porosity risks, which the supplier is expected to solve in his tooling and process. The hotspots can be compared with the highest-stress locations of the FEM functionality analysis to judge the robustness of the design.



Traditional simultaneous engineering flowchart, showing the engineering phase (yellow) and the supplier phase (blue).



Interdisciplinary co-engineering as suggested by Lautus Castings.

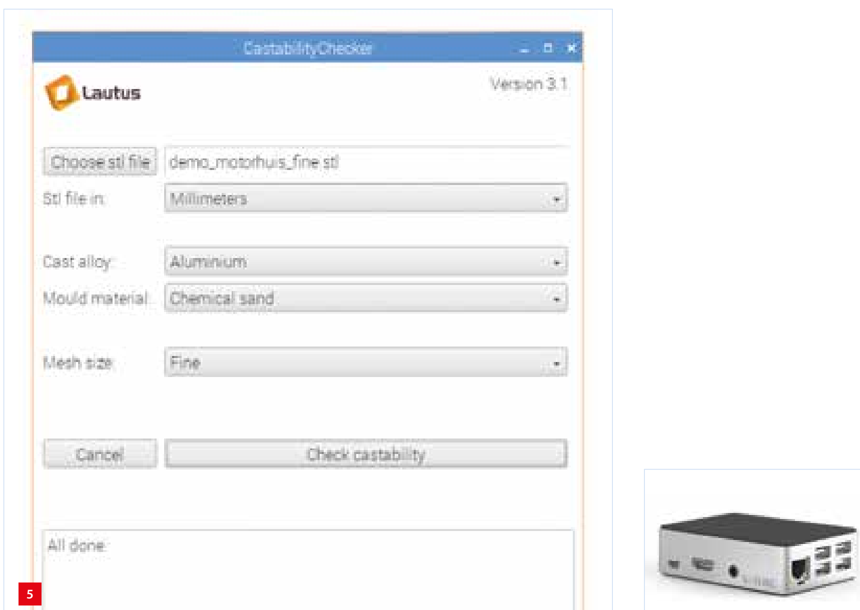
The LCC is full-FEM solidification software that runs on a Raspberry Pi (for ease of hardware support) and is operated by an interface with only six buttons to click (Figure 5). It requires an STL-file of the model and the type of alloy (aluminium, cast iron, bronze or steel) and mould material (sand, metal die or ceramic shell). The mesh of the model is fully automatically generated including the moulding box around it.
The software is based on open-source code, with additional code development, and used to solve the 3-dimensional heat transfer in the situation illustrated by Figure 6. In this case only solidification is observed and therefore the second term (convection) is zero.

All the material properties of the alloy, the mould material and the heat transfer coefficients that represent the boundaries are predefined in the software. The entire dataset is experimentally calibrated for an 'average foundry situation'. Temperatures are calculated automatically and pretty accurately in hundreds of thousands of elements during the solidification process.

However, in the first stage of a project the focus is on shrinkage (risk) locations in the design, which are not so straightforward to calculate. In that respect, it is important how the shrinkage is defined and represented by the software. There are two options:

- Hotspot model: the volumetric shrinkage of an alloy is projected onto the hottest or last solidifying zones.
- Feedflow model: during solidification the local shrinkage is compensated by a 'feedflow' from the highest point in the liquid phase according to the principle of communicating vessels. In this model, the defect will be indicated in another location or higher than the hotspot, as compared to the hotspot model.

Therefore, the most realistic shrinkage prediction is given by the feedflow model, but this requires that the complete gating system (which directs the filling of the mould cavity) is included in the simulation, which is not at hand in the design stage. The design engineer, however, wants to compare 'porosity risks' with the highest stresses in his or her design. Therefore, it was decided to implement the hotspot model to



The LCC tool consists of the LCC software (screenshot) pre-installed on a Raspberry Pi mini-computer (right). The software connects the mesh generator, the simulation algorithms and the automatic post-processor – all three are launched with one click of the 'Check castability' button.

Algorithm

The LCC software numerically solves the heat transport equation:

$$\frac{\partial \rho C_p T}{\partial t} + \nabla(\rho C_p T \vec{v}) = \nabla.(\lambda \nabla T) + \partial \frac{f_s}{\partial t} \rho L$$

Terms:
1. Change of the energy density with time
2. Convective heat transfer in the liquid metal
3. Conduction in the alloy and the sand mould or die
4. Heat release during solidification of the casting alloy

With:
ρ = alloy or mould density in kg/m³
C_p = heat capacity in J/kgK
T = temperature in K
t = time in s
v = metal flow speed in m/s
λ = thermal conductivity in W/mK
f_s = solid fraction of a certain volume (e.g. a mesh cell)
L = latent heat release in J/kg

indicate the 'centre(s) of shrinkage' in the CAD model. Conclusion: the LCC is not claimed to be the most accurate realistic casting simulation software available. But it is a fast and practical castability checker of CAD models, stripped of all input buttons that require casting knowledge and expertise. A report with clear images is automatically generated at the end of the simulation ready to share with suppliers.

Foundry course

For good communication, casting process knowledge is inevitable at both the client and the supplier side. That is the fifth bottleneck in the casting development and supply chain. To overcome this bottleneck a dedicated basic three-day foundry course was developed for CAD engineers and technical purchasers of castings. The course is in Dutch with a practical focus on the quality of a casting. It covers the complete plan-do-check-act cycle in a casting project and includes a hands-on workshop with the LCC solidification software.

Summary

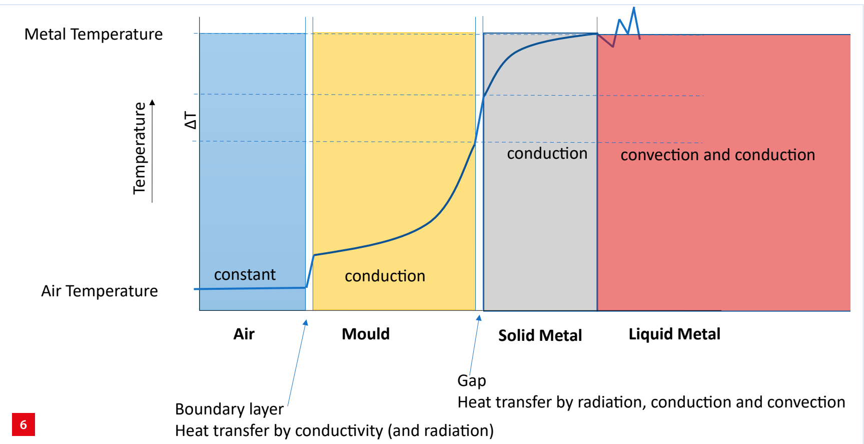
This article explains the tools that have been developed to fill the gaps in casting knowledge and castability data, in order to simultaneously:
- improve product quality;
- reduce lead times in the development chain;
- improve process robustness;
- reduce cost price.

Some tools, such as solidification simulations, are available today, but they are:
- (too) expensive;
- too complex to use;
- not ideal from the product responsibility point of view;
- only available via the supplier after the purchase order has been given.

The foundry engineers of Lautus Castings – and their network of experts – created a few practical solutions for the manufacturing industry, such as:
- a three-day basic foundry course for designers and purchasers of castings (Figure 7);
- a simple casting simulation tool for CAD engineers to check the 'castability' of a design;
- a call-centre for help on casting issues.

To conclude

The LCC has proven itself as a practical simulation tool as well as an excellent communication tool; see the case on the next page. By using the LCC, the serial process flow of traditional simultaneous engineering can be modified into a parallel interdisciplinary co-engineering process flow, with less redesign loops after release of the drawing. In practice, first-time-right prototype production and testing has been achieved using this method in different environments.



6

Schematic 1D representation of the heat transfer in the casting and the mould and across the boundaries.

7

The overall plan-do-check-act cycle underlying the Lautus basic foundry course for design engineers and technical purchasers of castings.

Motor housing case

To illustrate the practical use of the Lautus Castability Checker (LCC), we consider below the case of casting a motor housing (Figure 8a). The STL model of the raw casting with the triangular surface mesh (Figure 8b) can be exported from any CAD software. The LCC reads, checks and repairs bugs in the STL file and a surrounding box is created automatically to represent the mould. Figure 8c shows the volume mesh (mainly hexagonal) of the casting the software created. The (invisible) cells of the mould are also used in the simulation.

The motor housing.
(a) The final product.
(b) Triangular surface mesh of the CAD model.
(c) Volume mesh created for the FEM solidification simulation (mould cells have been made invisible).

The CAD engineer does not usually know the exact composition of the alloy. A general material database is used for groups of alloys and mould materials. A good approximation suffices, as material properties do not really influence the location of the hotspot. The inaccuracy in the size of the porosity is acceptable because the gating system is missing anyway. Only insight in the solidification behaviour of the part is required; the goal is not to create a realistic casting simulation as such. The foundry engineer is responsible for tool design, not the CAD engineer.

FEM solidification simulation results.
(a) Temperature.
(b) Liquid zones.
(c) Shrinkage in the hotspots.

The numerical simulation takes 15-60 minutes, depending on the mesh resolution chosen. The post-processor automatically generates a report with temperature charts (Figure 9a), the remaining liquid zones during solidification (Figure 9b) and the shrinkage (hotspot) prediction (Figure 9c). The report clearly shows the castability of the design, ready to share with the supplier. Conclusion: the foundry needs at least three risers to solve all the shrinkage issues. Any proposal with less than three risers is unrealistic and guaranteed to cause problems.

Although the castability check is now basically finished, the LCC can also be used to check the feeders suggested by the supplier.

Hotspots are predicted on each side of the motor housing (Figure 10a), as well as in the riser. The riser is big enough; the problem originates from the design because the feeding path has been cut off. By modifying the design with a slightly thicker section locally, the problem can be solved proactively (Figure 10b). The excess of material can be machined off if necessary.

Note that the castability check with the hotspot shrinkage model must be used carefully when risers are included. The top riser, for example, seems too small, but in reality it will be fine, as shown by the (more advanced) feedflow shrinkage model in Figure 10c. Please be aware that both models (hotspot and feedflow) use the same temperature simulation results. The hotspot method demonstrates the castability of the design, independent of the casting position, whereas the feedflow shrinkage is gravity-dependent. Hence, the feedflow model is more useful for the casting specialist in the design of the production tool.

PS: This part might be cast more easily in a vertical position, but that does not really change the story.

Predictions and modifications based on the simulation results.
(a) Castability check including the risers.
(b) Modification of the bottom flanges for preventing (hotspot) shrinkage in the casting.
(c) Shrinkage predicted by the feedflow model; the top riser will not create porosity problems in reality.

POST-AM

The diversity of printing technologies and materials used for additive manufacturing is growing steadily. Nevertheless, cleaning and surface finishing of printed metal parts still represents a challenge in many cases. New and further developed processes permit reliable, reproducible, automated post-processing.

DORIS SCHULZ

Additive metal processing is currently undergoing rapid development. In the meantime, processes which make use of binder-based systems such as metal injection moulding (MIM) are available in addition to the most widely used methods of laser melting (selective laser melting/direct metal laser sintering, SLM/DMLS) and electron-beam melting. These printing technologies make it possible to produce parts using, amongst other materials, traditional MIM powders and to sinter them subsequently, or to melt down MIM-bound metal rods.

Variety of tasks

Although the surface quality of the component depends on the utilised printing technology, design and material, post-processing is nevertheless indispensable in most cases. This involves a great variety of tasks. They range from removing the build plates, support structures and residual powder, as well as processing the usually rough surface – for example by means of smoothing, polishing and rounding – right on up to cleaning the workpieces in order to assure the required cleanliness for downstream processes (e.g. coating, bonding or welding). These manufacturing steps are still frequently executed manually, which is costly and time-consuming, and leads to inadequate reproducibility of the final result. However, various automated and automatable post-processing methods are available (Figure 1).

AUTHOR'S NOTE

Doris Schulz is a journalist. Her agency, based in Korntal, Germany, specialises in PR solutions for technical products and services. This article was commissioned by DeburringEXPO.

www.schulzpressetext.de

1 Various automated and automatable post-processing methods are available for treating the surfaces of additively manufactured parts, by means of which required surface finishing quality can be reproducibly assured; the final result is shown at the bottom. (Image source: Rösler)

Removing powder and support

The first step required for processes based on powder beds is to separate the workpieces from the build plate after coarse removal of the powder, for which vibration systems with targeted oscillation excitation and automatic swivelling of the component are available. Erosion or sawing can be used for separation and, depending on the utilised process, contamination with cooling lubricant accumulates and burrs occur, which also have to be removed.

Various solutions are available for removing sintered-on powder particles and support structures quickly and reliably. For example, a plug & play machine permits fully automated removal of sintered-on particles and support structures in a single work step. The procedure is based on a chemical/electrochemical process by means of which the workpieces are smoothed without any loss of edge sharpness. Advanced TEM (thermal energy machining) represents a further development for the removal of support structures from parts manufactured by means of DMLS technology. This technique even makes it possible to remove supports from inaccessible areas such as channels and undercuts in just a few seconds.

On the one hand, wet chemical cleaning processes with ultrasound or cyclical nucleation, as well as aqueous media or solvents which are matched to the material, can be used where residual powder which adheres to the part needs to be removed (Figure 2).
On the other hand, this task can also be executed by means of a newly developed blasting technique, based on a waterjet process which is used in combination with a minimally abrasive blasting medium. Correct matching of the parameters including type and size of the blasting medium, water pressure and treatment duration, as well as motion of the parts to be cleaned, make it possible to assure that the powder is fully removed even from complex geometries and undercuts, without leaving any blasting medium behind or changing any contours.
Amongst other processes, CO_2 snow blasting is used as a dry alternative for removing residual power. Powder particles can also be removed from delicate contours, undercuts and complex shapes with the help of this easy-to-automate process.

Surface finishing

Whether smoothing, polishing, rounding or the production of defined edges is involved, in the case of external, readily accessible surfaces this is made possible by means of milling, erosion, lapping, barrel finishing or laser polishing,


2

Residual powder can be removed, for example, by means of wet chemical cleaning processes combined with ultrasound. (Image source: Fraunhofer IGCV / Bernd Müller)

as is also the case with conventionally manufactured workpieces. However, these processes are quickly pushed to the limit in the case of internal contours and surfaces, as well as difficult-to-access areas of 3D-printed parts.

Barrel finishing
Existing technologies have been further developed and optimised in order to meet the requirements of additively manufactured parts. These include barrel finishing processes with process media which are individually matched to the specific task. They make it possible to achieve the desired degree of smoothing and the required finish with very short processing times – from high-gloss to satin-matt surfaces. In the case of components whose surfaces have to fulfil various requirements, suitably adapted system variants can be implemented so that only the required workpiece areas are immersed into the abrasive medium.

DeburringEXPO

Which processes ensure reliable and economically efficient post-processing of additively manufactured parts? Which new technologies are available to this end? Which criteria need to be taken into consideration for the selection of an ideally suited process? Answers to these and many other questions will be provided at the DeburringEXPO in the Karlsruhe Exhibition Centre (Germany) on 8-10 October 2019.

The exhibition portfolio includes equipment, systems and tools for belt grinding, brushing, abrasive flow machining, vibratory grinding, blasting with solid and liquid media, abrasive water-jet blasting, magnetic-abrasive deburring, ultrasonic deburring, chemical bath deburring, electrochemical machining (ECM), electron-beam machining, thermal energy machining (TEM), mechanical deburring, buffing, polish honing, electrolytic polishing, plasma polishing, laser polishing, immersion and brush polishing, solutions for industrial parts cleaning, as well as measuring, test and analysis systems for quality control, and technical literature.

WWW.DEBURRING-EXPO.COM

ECM
Coolpulse ECM (electrochemical machining) is also laid out for processing additively manufactured metal parts. Like conventional ECM, it's based on the principles of anodic dissolution of metal. However, a special, pH-neutral, environmentally friendly electrolyte is used in this case. Micro- and macrostructures on inside and outside surfaces can be improved through processing with this treatment, and defined surface characteristics can be reproducibly produced. Beyond this, support structure remnants and surface defects can also be removed.

Electrochemical processes which have been specially adapted for finishing the surfaces of 3D-printed parts, as well as processes such as electropolishing, are also available as further processing alternatives. This processing option makes it possible to smooth and polish surfaces in delicate 'valleys' in the workpiece, which nevertheless retain their sharp edges. Processing times of just a few hours are typical for electrochemical processes.

AFM
Flow grinding, also known as abrasive flow machining (AFM), is also used for finishing the surfaces of 3D-printed metal parts (Figure 3). The part is clamped for processing in a fixture at the AFM machine. The processing medium – a carrier material with defined viscosity and embedded abrasive particles whose type, size and concentration are adapted to the respective task – is caused to flow through or over the component area(s) to be processed in alternating directions at a defined pressure level by means of hydraulically powered pistons. Process parameters are continuously monitored in order to assure reproducible results.

Design for post-processing

The number of automated post-processing procedures, as well as the options they offer, are growing continuously. However, it's advisable to take available post-processing solutions into consideration already while the respective part is being designed, with which the required surface characteristics can be achieved.


3

The contours of this mixer component were smoothed and polished using an AFM process; the final result is shown on the left. (Image source: Extrude Hone)

A TOROIDAL CAVITY WITH 1-MICRON PRECISION

Eindhoven University of Technology (TU/e) has successfully produced a device for the generation of 100-femtosecond electron pulses, to be used in the study of thermal processes by observing the changes in diffraction patterns. For precision engineers, the most interesting component in this device is a radio-frequency cavity. This elliptically formed torus has been manufactured with a tolerance of ±1 µm.

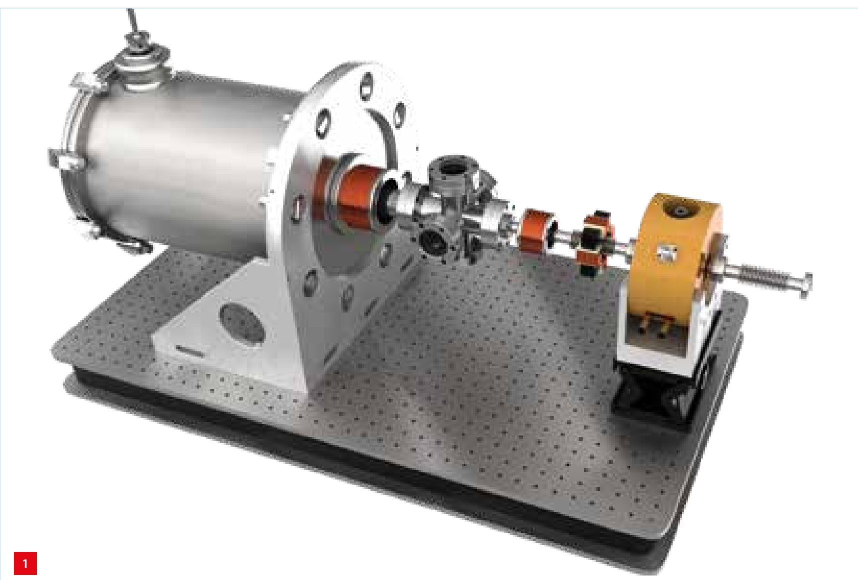
FRANS ZUURVEEN

The electron-optical device allows the recording of super-fast changing diffraction patterns. Figure 1 shows the serial chain of components: first a compact 100-kV electron source, next a beam line with focusing coils, and at the end a radio-frequency cavity, which is the subject of this article. The Coulomb expansion of the electron beam requires these focusing coils because the negative electron charge causes divergence. The cavity has been added to increase the compactness of every single electron pulse because the electrical fields at the centre of the cavity decelerate the first electrons and accelerate the last ones.

The 100-femtosecond devices are marketed by a TU/e spin-off company called Doctor X Works. Third parties are interested in these high-tech products because other suppliers have so far been unable to manufacture a cavity that is tuned exactly to a frequency of 3 GHz, thanks to its high (micrometer) precision. Competing cavities need to be fine-tuned using an added piezo-electric mechanism.

AUTHOR'S NOTE

Frans Zuurveen, former editor of Philips Technical Review, is a freelance writer who lives in Vlissingen (NL).



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The femtosecond set-up for studying atomic motion and matter. From left to right: 100-kV electron gun emission chamber; vacuum beam line for transmitting electrons with half the speed of light; focusing coils; microwave cavity; exit for femtosecond electron pulses to hit a target.

The toroidal cavity

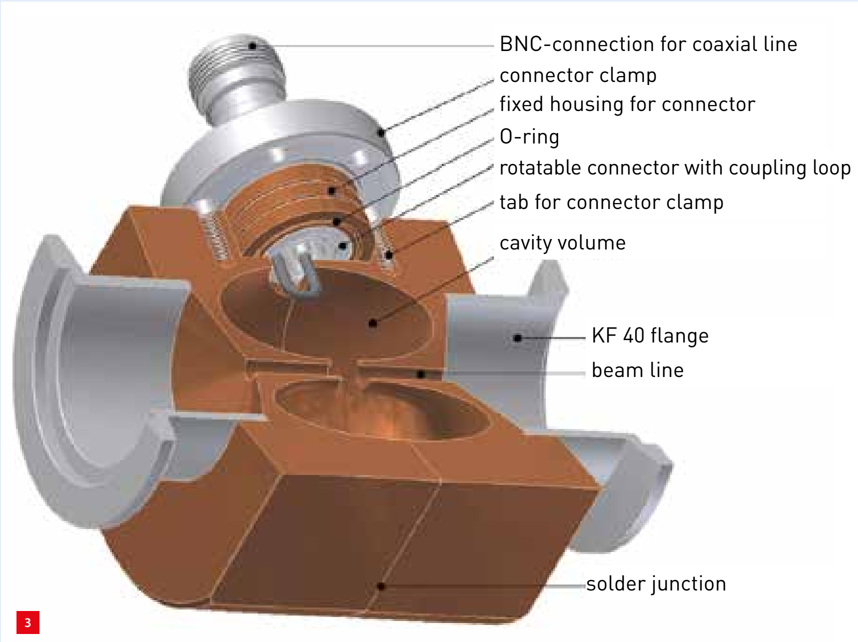
In principle, a cavity can be made additively or subtractively. But additive manufacturing technology is far from being accurate enough, making conventional machining technology mandatory. That's why the TU/e cavity has to be manufactured in two halves (Figure 2). These parts are made from 99.95% pure oxygen-free copper. Simon Plukker, precision mechanical engineer and instrument maker from the TU/e Equipment and Prototype Centre, says the problems with making this cavity can be subdivided into, firstly, the micromachining of these two different halves; and secondly, connecting them without disturbing the precision already achieved.

A radio-frequency cavity confines electromagnetic fields to their resonant frequencies. They reinforce to form oscillating standing waves in the cavity around the centre line, in this case with 3-GHz frequency and a wavelength of 100 mm in circumference. The oscillations are excited by an antenna (Figure 3), which is fed by 3-GHz alternating current.

Figure 4 shows the dimensions of the toroidal cavity, which are calculated in advance and have to be achieved with micron accuracy. The cavity cross-section consists of two quarter-formed ellipses with centres 1 and 2 at a distance of 3.0515 mm. At their 'deepest' point, the two ellipses, designated as 1 and 2, have equal curvatures.

2

The two halves of the microwave cavity, made from 99.95% pure oxygen-free copper.



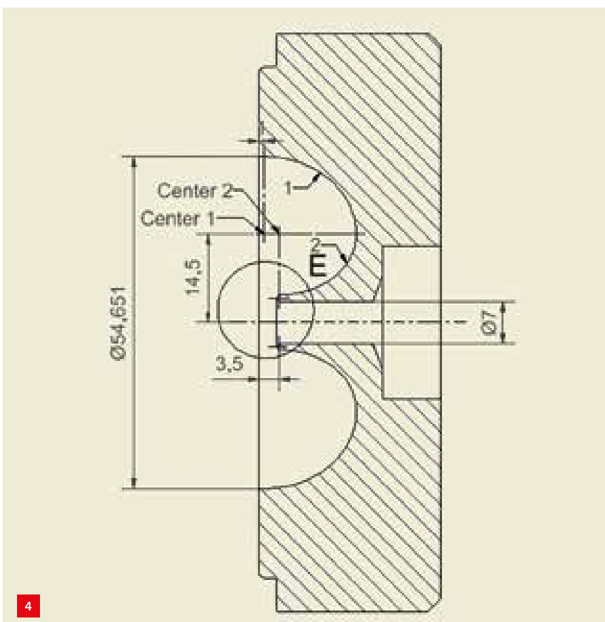
Schematic drawing showing a cross-section of the microwave cavity with the loop-like antenna at the centre of the toroidal form.

Machining one of the two cavity halves. The copper insert, which temporarily fills the antenna slot, is clearly visible on the upper side.

Cutting with extreme accuracy

To machine these delicate products requires special lathes. TU/e originally used the Colath, an experimental computer-assisted lathe with hydrostatic guides developed by Philips Research Laboratories in the 1960s. Simon Plukker was recently able to apply a Hembrug Mikroturn hydraulic turning centre.

Before the turning operation, the two halves are 'roughly' milled on a Hermle milling machine. They are then pre-processed on the Hembrug Mikroturn. After this, the parts undergo a heat treatment operation at 250 °C, aimed at removing internal stresses. The copper parts are then ready for reaching their final precision.



Part of the TU/e drawing of the microwave cavity.

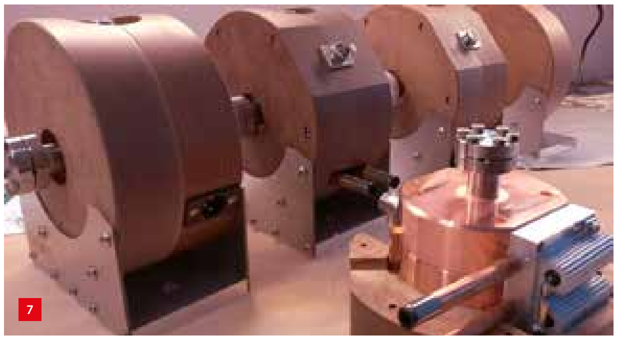
A specially formed diamond tool is used on the Hembrug Mikroturn. The aim is to machine both elliptical curves, pre-programmed in the Mikroturn software, in one cutting operation. To that end, the diamond tool cutting area is circularly formed across an arc of 185°. Starting at one side, all of the points on the cutting area do their accurate work consecutively, ending at the other side of the tool cutting area. Needless to say, all other machining operations, including the making of holes and recesses, are finished before the final cutting of the ellipses starts.

An additional complication when making these ellipses is caused by the interrupted cut required for the slot for the antenna in the cavity. Such interruptions would cause vibrations, resulting in inaccuracies. To prevent that from happening, a copper insert temporarily fills the slot. This insert is removed later in the production procedure (Figure 5). The diamond cutting operations are being performed at gradually decreasing cutting depth, the last one only 20 µm. The final roughness amounts 0.25 µm peak-to-valley. Figure 6 shows the testing of the TU/e products at the Zeiss Experience Center in Breda (NL).

Mounting and soldering

Connecting the two halves and fixing them together by soldering is the last – vital – operation. The forming and finishing of the planes to be connected is smooth, even to such a degree that the planes stick together as end gauge planes are supposed to do. Although a soldering action

6 Testing the TU/e cavity products at the Zeiss Experience Center.



7 Four completed cavities covered with an insulation layer of resin-bonded fabric. At the lower right, an uncovered cavity with equipment for thermostatic heating at an operational temperature of 43 °C.

is unavoidable, losing precision due to uncertainty about the thickness of the soldering agent has to be avoided.

Before starting the soldering operation, the two cavity halves have to be positioned with accurately coinciding centre lines. To that end, both halves are given a positioning rim of 84 mm in diameter. These two rims are manufactured with an accurate sliding fit, having been dimensioned by Simon Plukker during the turning process. The narrowly tolerated rim play guarantees a perfect common centre line. Heating the 'female' part makes mounting easier.
For a 'clean' soldering process, one of the two parts has a groove to accommodate a ring of soldering metal. After heating, superfluous soldering metal stays in the groove, thus preventing unwanted geometrical effects. Figure 7 shows a small series of produced cavities, each with an insulating mantle of resin-bonded fabric.

To conclude

After this cutting, mounting and soldering, the ultimate form deviation is not permitted to exceed the demanded value of ±1 µm. To verify this challenging property is not easy however. The best way of testing it is to carry out a practical action, e.g. test whether the cavity really does resonate at 3 GHz. When testing this in prototypes, the complete assembly showed an extremely sharp resonance peak, proving the effectiveness of all precision-mechanical operations.

INFORMATION
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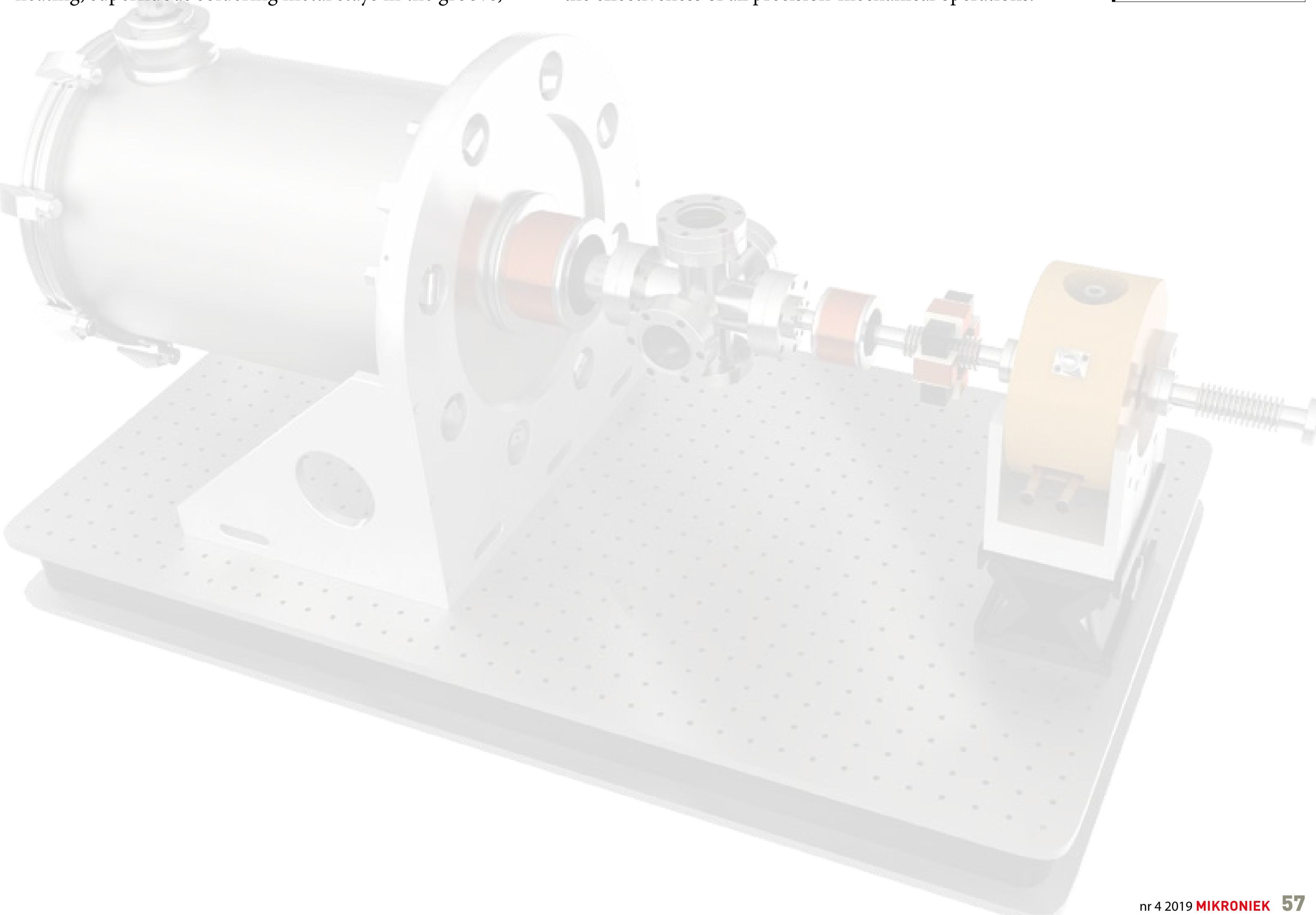


INDUSTRIALISING INNOVATION

In addition to critical technology, high-tech machines often contain standard functionality that is non-core yet still has to satisfy challenging requirements. OEMs are increasingly opting to outsource the design and production of these non-core modules to a system supplier, usually with strict cost and lead-time targets. A typical example is the loader and unloader modules that MTA – following its proprietary V² industrialisation model for simultaneous product and production development – realised for a die-bonding platform from Nexperia's Equipment & Automation Technologies department (E&A).

Partners

Nexperia
Nexperia is a global leader in semiconductor components manufacturing, with 11,000 employees across Asia, Europe and the US. Originally part of Philips and then a business unit of NXP Semiconductors, Nexperia became an independent company in 2017. At its headquarters in Nijmegen (NL), Equipment & Automation Technologies (E&A, formerly the Industrial Technology & Engineering Center) develops and realises solutions for semiconductor assembly, testing, inspection and automation for Nexperia's back-end semiconductor factories.
E&A collaborates with knowledge and manufacturing partners to innovate in the fields of design & control, imaging, data intelligence, process technology and industrialisation.

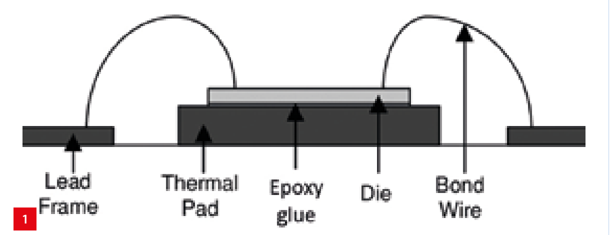
MTA
Based in Helmond (NL), MTA (100 employees) is an innovative and flexible high-tech company that develops and manufactures mechatronic modules and systems. Its clients are world-class OEMs in the high-tech industry. As a full-service system supplier specialising in industrialisation and smart customisation, MTA manages the complete lifecycle of a system, starting with development and engineering all the way through to series production and finally end-of-life management. At each of these lifecycle stages, MTA continually strives to achieve an optimum balance between quality, lead time and cost – building on its global supply chain partners, supported by MTA's own production facilities in the Netherlands, Eastern Europe and India.

WWW.NEXPERIA.COM
WWW.M-T-A.NL

For Nexperia's semicon back-end production activities, E&A has introduced a new high-speed die-bonding and die-sorting platform, the ADAT3-XF. The main goal during the development of the ADAT3-XF was to design the most flexible bonder in the world for the best total cost of ownership for the customer. Flexibility is becoming more and more important for Nexperia's customers, and a system that can be easily changed over to another process for only 25 per cent of the traditional changeover cost is a big advantage.

To enable that flexibility, a lot of attention was paid to the modularity of the system and its internal interfacing. Another advantage of focusing on flexibility is that it facilitates the development of specific modules within the system. A good example here are the strip loader and unloader modules that were developed by MTA.

The ADAT3-XF can be extended with these strip loader and unloader modules to constitute a complete die-bonding platform. In a die-bonding machine (Figure 1), a leadframe (strip) is loaded into the machine, an epoxy glue dot is placed on each die pad and on this glue dot the die is placed. After die bonding, a wire-bonding machine adds the wire bonds and then the connections are encapsulated in a mold compound into the end product. Figure 2 shows an example of an end product that has been produced in this way, namely Nexperia's high-runner SOT23.

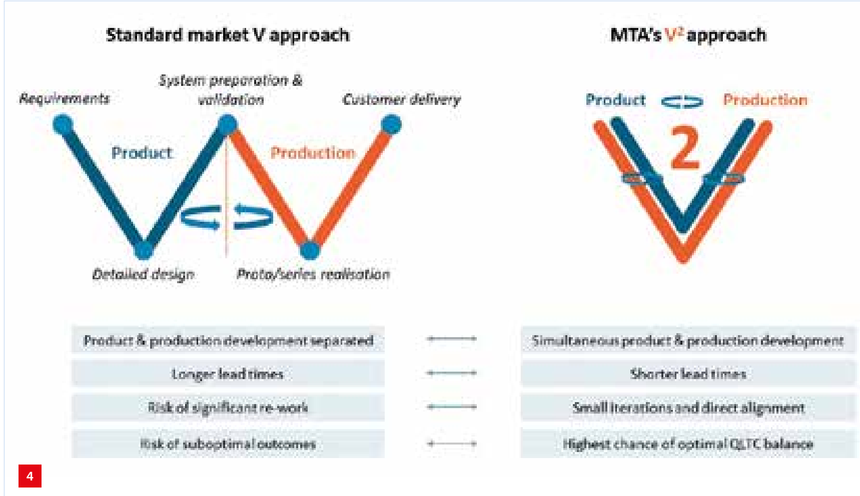


1 *Schematic of the die-bonding process.*

EDITORIAL NOTE

Input was provided by Patrick Houben, senior principal engineer at Nexperia/E&A, and John Willems, sales director at MTA.

Nexperia's high-runner end product SOT23.



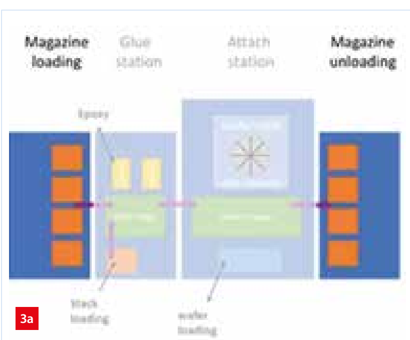
MTA's V² industrialisation model is a unique approach for simultaneous product and production development.

Figure 3 shows the schematic and a first realisation of the ADAT3-XF die bonder. The machine comprises a magazine/ cassette loader (the strip loader) that feeds leadframes/strips stacked above each other in a cassette into a strip-glue station. Then the ADAT3-XF performs the die-bonding step using a little robot for transferring the dies, cut from a wafer, to the strips. Finally, an unloader module collects the processed strips in cassettes.

Industrialisation

Focusing on the development of its core strip-glue and die-bonding modules, E&A decided to outsource development and manufacturing of the peripheral loader and unloader modules, under challenging cost and lead-time targets. MTA was selected as the system supplier because of its new proposition for the fast and cost-effective industrialisation of mechatronic modules, following the V² model (Figure 4). This model provides a unique approach for simultaneous product and production development, to reduce lead time, cost and risk.

Nexperia/E&A defined clear requirements and interfaces, but gave MTA the freedom to come up with design alternatives. MTA started with a preliminary investigation to determine whether cost and lead-time targets were feasible and to check whether MTA's industrialisation philosophy matched E&A's expectations. One aspect concerned the use of simple and inexpensive standard parts wherever possible. Practical examples of this include the use of sheet metal assemblies that are lightweight and easy to construct as a replacement for complex assemblies of machined parts, and the application of linear sliding guides instead of more expensive linear ball-bearing guides. E&A was happy to accept these substitutions.



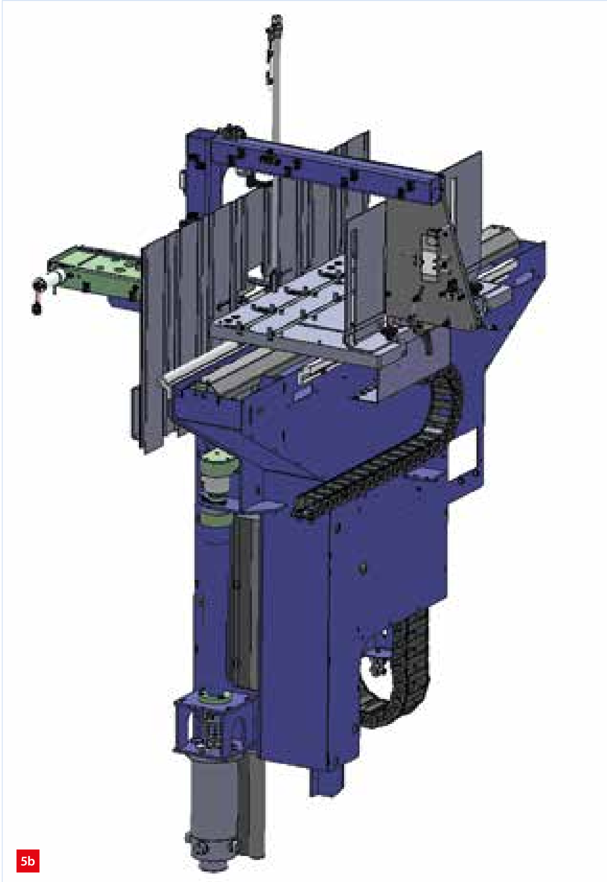
The complete strip-to-strip machine, showing the magazine/cassette loader and unloader on the left and right side, respectively, and the strip-glue and die-bonding stations in the middle.
(a) Schematic.
(b) First realisation.

Design choices

After the positive outcome of this exploration phase, MTA started engineering by making a few technical choices based not only on requirements and functionality, but also on manufacturability and cost. This type of 'concurrent' engineering helps to reach a right-first-time design, eliminating time- and cost-intensive design iterations and rework.

One of the technical choices concerned the fixing of the cassettes in the right position for loading or unloading; see Figure 5. The first design comprised a beam driven by two rotating arms that fixes all cassettes simultaneously (an original design requirement). This construction had a safety issue and was too expensive. After analysing the intended functionality and challenging the original specification, MTA designed a simpler alternative with a single pneumatic cylinder attached to a stationary beam that fixes only one cassette at a time, i.e. the one that is being loaded/unloaded. This option is simpler and takes up less space.

Another design choice concerned the transfer table, which has to position the cassettes accurately in such a way that all strips can be subsequently transferred through hatches that separate the loading and unloading module from the glue-dispense and the die-bond station of the ADAT3-XF, respectively.



The unloader module.
(a) A prototype containing three cassettes, with their positions all fixed simultaneously.
(b) The final design showing a simpler alternative for fixing only the cassette that is being filled with strips, using a pneumatic cylinder attached to a fixed beam. The green on the left indicates the belt that transports the strips out of the ADAT3-XF platform to the unloader.

Ultimately, the number of degrees of freedom (DoFs) for this table was set at two. The table translates sideways, in the y-direction, to bring the correct cassette in position, and vertically, in the z-direction, to feed the correct strip through the hatch using either a simple pusher or puller. Defining three DoFs was judged to be overdimensioned, adding unnecessary complexity. The cheapest option, namely only the z-direction translation, was discarded because accommodating multiple cassettes above each other would make the height of the loader/unloader (its 'vertical footprint') excessive.

One of the main design challenges was to develop a cost-effective 'stage solution' for the yz-movement of the cassettes, since the number of required axes is doubled with this concept. Because the required driver boards were already available in the machine cabinet, the added cost consisted only of the drivetrain hardware (motor, gear, guiding, etc). The concept design was tuned to the specifications, to prevent overdimensioning the function.

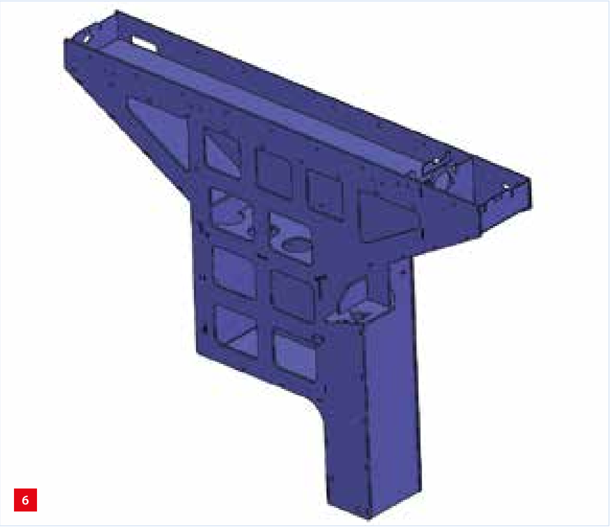
Since micron-precision positioning at high speed/acceleration profiles was not required, a low-cost trapezium spindle with linear profile guides (sliding carriage) was chosen, in a deterministic configuration of course for smooth guiding over long distances. Due to the self-breaking capability of this spindle type, no brake on the motor is required, while the inertial match was dimensioned such that no gearbox is required either and the spindle can be driven directly. In this way, a cost-effective solution is achieved that meets the specified requirements.

During tests it appeared that indeed no more performance can be expected than required from this function; an increased duty cycle leads to the spindle heating-up due to friction behaviour, resulting in an unstable motion situation. This proved that in fact no overkill is present in the design, which therefore has the right price/performance balance.

Manufacturing of the table required high-precision machining, as it is the critical part for determining the accurate and reliable transfer of strips. The base frame below the table was constructed completely from sheet metal, as referred to above; see Figure 6. The design was based on low-accuracy parts for the supporting structure (frame). The required accuracy is realised by a reference surface in the frame, which is aligned during assembly. Attached to the reference surface, a limited number of highly accurate (machined) parts guarantee the accuracy that is required for the functionality.

These examples illustrate how industrialisation-inspired design choices have been made. In all project stages, multidisciplinary reviews were performed, in which assembly engineers participated to safeguard ease of assembly.

An additional focus for a cost-conscious design was the limitation of the number of sensors and a critical selection procedure for the sensors that are indispensable. For example, the homing of the table movements is based



Design of the base frame of the transfer table of the loader/unloader module. It is completely made out of sheet metal.

on motor-current monitoring and an end stop that initiates a current peak. This saves a homing sensor by using parts that have already been integrated in the machine design. Other sensors have been selected in close cooperation with preferred suppliers of MTA and Nexperia. These suppliers were challenged to offer solutions that are reliable but definitely not overspecified.

Conclusion

As one of the first results of its V² model-based approach of industrialisation, which was introduced in 2017, MTA designed and realised loader and unloader modules within E&A's tight lead-time and cost targets. Prototypes and a first industrial version were built using parts from suppliers that had already been selected for series production. Figure 7 shows the complete die-bonding platform.

Both partners speak of a fruitful collaboration. Patrick Houben from Nexperia/E&A said, "MTA developed the modules from scratch, starting with simple block models representing functionality, to determine which functions to include in which module, drawing upon their expertise in manufacturability and simplicity. This helped to make well-balanced concept choices. They also acted very proactively: while we were still having to make some specific design choices, they were able to proceed with their engineering, anticipating the various alternatives."

MTA's John Willems said, "We deployed our own system architect on the industrialisation level, who knew to ask the right questions and could assess the requirements of E&A's system architect. They gave us the scope to challenge the requirements if necessary. As a result, we didn't have many issues regarding the interfaces between E&A's and MTA's modules. We managed to solve any issues within the scope of our modules, relieving E&A of time-consuming design rework. This first collaboration with Nexperia/E&A was a successful pilot. We now hope to receive their green light for following projects."

Overview of the complete die-bonding platform (with a prototype unloader module).

A HYBRID MACHINE

When manufacturing large quantities of shaft-shaped products, such as drive systems and hydraulic pumps, the most frequently used process involves soft pre-treatment, hardening and cylindrical grinding, possibly followed up by honing. The grinding quality is also prescribed as standard in the aircraft industry, for example. But what if you produce small to medium-sized series with a wide variety of workpieces, not all of whose surfaces require grinding and which can be processed faster with hard turning; or have workpieces with highly interrupted surfaces?

For manufacturers of these types of workpiece, this means a process involving several machines with the necessary set-up and changeover times. It also entails the risk of clamping errors. By combining both processes in a single machine, workpieces can be made in one clamping and machining step, resulting in significant gains in efficiency.
Hembrug Machine Tools has taken this on board with the development of the MikroTurnGrind 1000 (Figure 1) and now provides a solution for the top-quality, complete machining of high-precision workpieces.

EDITORIAL NOTE

This article was contributed by Hembrug Machine Tools, located in Haarlem (NL), which specialises in the development and construction of hard-turning machines.

www.hembrug.com

Grinding

The purpose of grinding as a finishing step is to obtain a surface structure that cannot be achieved through hard turning. The production of shafts places high demands on the surface structure of bearing and sealing surfaces. An example is a spiral-free surface structure, which is not possible with hard turning. For workpieces with highly interrupted surfaces, the turning can be used as a quick method of hard pre-turning. Finish-grinding is then used in the same chucking in order to accurately grind to the required size and surface quality. Because only minimal effort is involved after the hard pre-turning, the grinding disc wears down slowly and only a minimal amount of dressing is required.

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The hybrid MikroTurnGrind 1000 turning/grinding machine in hard-turning mode.

Hybrid process

The basis for a successful, highly accurate hybrid process is laid with the right machine and knowledge of the hybrid process. In order to absorb the high process forces released when turning hardened steel (up to 70 HRC), the machine must have a very high static and dynamic stiffness and must be thermally stable. Additionally, the machine must, logically, be geometrically precise.
The precision regards the concentricity accuracy of a main spindle, the repetition and positioning accuracy of the axes, and the resolution of the measuring system and the CNC control. These properties, combined with the right process knowledge of hard turning and fine grinding and the interaction between these two processes, ensure a productive and stable process with high form, size and surface finish accuracies. And a long tool life, too.

MikroTurnGrind 1000

Using the hydrostatic spindle and bearing components from the existing Mikroturn series technology, Hembrug has developed a fully-fledged hybrid turning/grinding machine, the MikroTurnGrind 1000. Here, fully-fledged means a machine that achieves exemplary accuracy in both hard and fine grinding (Figure 2).

It has a B-axis that offers optional space for a revolver with eight fixed VDI 30 tool holders, an external grinding spindle with a 300-mm diameter grinding disc and an internal grinding spindle. One of the grinding spindles can also be replaced by a milling spindle. The precise and extremely stiff B-axis is equipped with a double Hirth coupling and can be adjusted in 90 positions over 270°. Switching from turning to grinding can be done at the press of a button, without having to convert a unit. Dressing is

Close-ups of the grinding process with two different grinding discs.

done at a fixed point on the fixed or loose head and the cooling lubricant unit is filled according to the customer's needs. The machine can be equipped with an NC-controlled loose head and one or two steady rests to support long axes.

To ensure high accuracy, the machine comes as standard with a 4,000-rpm hydrostatic main spindle with a concentricity of < 0.1 µm, hydrostatic X- and Z-axes with a repeating accuracy of ±0.1 µm and a positioning accuracy of < 1 µm. The wear-free, hydrostatic bearing also ensures that the machine will continue to deliver the same level of accuracy after 20 or 30 years. Thermal stability is achieved by cooling relevant machine components and maintaining the oil temperature at 20 ± 0.1 °C. The maximum machining capacity is Ø 380 mm (flying) or Ø 200 mm x 1,000 mm between centres.

Grinding machines are also available with an integrated turning option. In this case, we talk about a grinding/turning machine, where the grinding process is the dominant technique. With the MikroTurnGrind 1000, the hard-turning process is dominant and the grinding tool is used for the finishing process. A combination machine for these techniques is nothing new, but with form and size accuracies of ≤ 2 µm and (spiral-free) surface accuracies of 0.1 µm (R_a) it is in competition with the best grinding machines, so Hembrug claims.

Case study: a main spindle

By way of example, Hembrug presents the production of one of its own main spindles, for which the machine is successfully used. These spindles were previously fully ground from a hardened state with a total machining time of 8 hours. These spindles are now produced in less than half the time. First of all, the relevant diameters are quickly hard pre-turned in the hardened state, partly because high swarf (chip) volumes are possible compared to grinding. The spindles are accurately ground to the required size with a minimum of grinding effort.

Hard turning also enables the machining of threads, grooves and grinding rollouts for an even more accurate overall result. Results achieved to date on (confidential) applications such as drive shafts: roundness 0.2 µm (flying), cylindrical shape < 1 µm and roughness 0.1 µm (R_a).

Conclusion

A hybrid machine, such as the MikroTurnGrind 1000, combines the advantages of hard turning and fine grinding. This allows manufacturers to use the most suitable technology for each surface to be machined.
Hard turning offers advantages, particularly for complex shapes and a combination of internal and external machining; higher machining volumes are possible; and the process is easier to set up and modify. In turn, grinding offers advantages on interrupted surfaces in combination with materials that are difficult to machine, such as inconel. In addition, fine grinding results in spiral-free surfaces.
A hybrid process therefore offers great flexibility, accuracy and economic advantages, especially for manufacturers of small to medium-sized series with a wide variety of products.

A CRITICAL PRODUCTION STEP

High component diversity, a range of dissimilar and often very sensitive glass types, widely differing product dimensions plus high throughput targets call for the use of very complex ultrasonic cleaning equipment at Carl Zeiss Jena (Germany). A close cooperation between the Zeiss project team and the manufacturers of the cleaning and water treatment systems has led to a solution that now serves as a pilot installation for the entire group of companies.

DORIS SCHULZ

Zeiss is an internationally leading technology enterprise in the fields of optics and optoelectronics, headquartered in Oberkochen, Germany. The Jena site, where the company was founded in 1846, is the headquarters of the central service company for the production operations of the Zeiss Group. This activity includes the manufacture of optical items. Here, more than 1,000 different spherical and plane optical components for the group's diverse products are made of well over 100 different glass types.

Parts cleaning

One bottleneck in the manufacturing workflow, particularly in core production – i.e., the activity in which the geometry of each optical part is generated – is parts cleaning. "Depending on the optical component, multiple cleaning steps may be necessary, so a very high workload must be handled. In order to ensure this while continuing to meet Zeiss' environmental standards now as well as in the future, we replaced our 20-year-old cleaning system some time ago", reports Heinz Ackermann, who together with his colleague Benjamin Wagner is responsible for the realisation of a new ultrasonic cleaning and water reconditioning system.

The contract for this project was awarded to UCM-AG of Switzerland, a member of the SBS Ecoclean Group (formerly Dürr Ecoclean), which had previously supplied several ultrasonic cleaning systems in use at Carl Zeiss Jena. The responsibility for the water reconditioning system was placed in the hands of Enviro Falk.

High demands

The new ultrasonic cleaning system was intended to provide combination processes comprising both solvent and water-based steps, like its predecessor. Different cleanliness standards had to be met, depending on the production operation and the optical part to be treated. Both a "ready for inspection" and "ready for coating" cleaning quality was to be achievable. "Fulfilment of this requirement was demonstrated in the running process. This way, we have redundant back-up capability for our entire cleaning process in the production line", notes Benjamin Wagner.

A further challenge lay in the fact that the glass types from which optical components are made can be highly sensitive to acids. These glass grades react more or less strongly to the cleaning and rinsing media used in water-based cleaning. "We performed many trials, exposing the glasses to the surfactant media as well as to diverse water qualities, e.g., de-ionised, osmotic or mixed water. We then examined them under 200x magnification to see whether surface defects had formed and to what extent abrasion had occurred", adds Heinz Ackermann. These findings found their way into the design of the cleaning and water reconditioning system.

Flexible equipment

The fully enclosed cleaning system comprises twelve stations in total. In the first four tanks downstream of the loading station, solvent cleaning can be carried out. The next four tanks are for cleaning with aqueous solutions. This section is followed by an immersion rinsing bath, two immersion spray rinse tanks (each with a lifting function), as well as a fine-cleaning tank with lift-out capability in which various water qualities can be used.

All twelve tanks for the wet chemical treatment of optical components are equipped with ultrasound devices; in the case of the two last cleaning tanks and the first rinsing tank, these operate with two frequencies that overlap in part.

For drying, infrared dryers are used. The parts pass through them on powered conveyor belts before being transferred to the unloading station. In the zone of the last rinsing tank and the dryer, a cleanroom filter with laminar flow is installed. This prevents recontamination of the product with airborne particles.

AUTHOR'S NOTE

Doris Schulz is a journalist. Her agency, based in Korntal, Germany, specialises in PR solutions for technical products and services. This article was commissioned by Ecoclean.

www.schulzpressetext.de

1a

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At the immersion-type spray rinse tanks, the optical precision components are sprayed off as they exit the bath for an improved rinsing result.

1b

The system cleans more than 1,000 different spherical and plane optical components made from well over 100 different glass types. To handle the specified high throughput, the ultrasonic cleaning system comprises three automatic transfer devices, which convey and reposition the cleaning racks, each within a defined area. It was quite a challenge to program this functionality at the software level.
(a) Overview.
(b) Close-up of a transfer device.

To reach the high specified throughput of 10,000 to 18,000 cleaned parts in two shifts per day, the system is equipped with three automatic transfer devices (Figure 1). These handle the movement and transfer of cleaning racks from the charging station to the last rinsing tank, operating each within a defined zone.

Complex software

Depending on their purpose, the optical components vary in size from 1 to 320 mm. For cleaning they are placed in product carriers of matching geometry, up to three of which can be inserted into the cleaning rack one above the other.

To accommodate the given production step and a specific optical part, more than 20 part-specific cleaning programs are currently stored in the system's controller. These are activated either manually or by barcode scan. Each program defines the cleaning and rinsing tanks to be used, the dwell time of the part at each station, the ultrasound power and frequency, etc.

"Realizing these programs at the software level, with three automatic transfer units, was not an easy task for UCM", recalls Benjamin Wagner. "On the one hand, the sequence must be fast enough to achieve the specified throughput. Care had to be taken to avoid all time loss, even with programs comprising forward and reverse transfers or skipping of individual tanks. On the other hand, the target dwell times in the water-based cleaning and rising tanks need to be accurately observed, and we are talking a minimum of 15 seconds here in the case of glass types sensitive to acids."

Water quality

To ensure that the same water quality is available at all times in every rinsing tank (Figure 2), the customer's water reconditioning system was integrated with the control software of the cleaning system as well. "To this end, UCM and Enviro Falk cooperated perfectly. This certainly helped to ensure that we now have a cleaning system that delivers very good results with all optical components and is deemed a pilot solution within our group of companies", Heinz Ackermann concludes.

INFORMATION
WWW.ZEISS.DE
WWW.UCM-AG.COM
WWW.ECOCLEAN-GROUP.NET

PRINTING TRANSPARENCY

The number of materials that can be 3D-printed is steadily increasing. Glass, however, is a 'difficult' material due to the high temperature at which it becomes liquid and the high viscosity of the liquid glass. The design and realisation of a glass 3D printer by QSIL and Demcon was therefore a major challenge, especially with regard to thermal control. The first glass products have since been printed and the research is now focused on improving the process in terms of resolution, accuracy and reproducibility, as well as finding commercial applications.

EDITORIAL NOTE

Input was provided by Ilze Vehoff, process improvement engineer, and Nina Huck, managing director, both at QSIL Netherlands, based in Winschoten (NL), a leading producer of fused quartz products (and until 2016 the glass factory of Philips Lighting), and by Pieter Lerou. He is CTO at Demcon kryoz, developer of fully integrated micro-cryogenic cooling solutions, based in Enschede (NL), and senior mechatronic systems engineer at Demcon, a high-end technology supplier of products and systems.

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In 2014, QSIL Netherlands filed a base patent for 3D printing of glass and quartz with a technology similar to FDM (fused deposition modelling). Around 2015, MIT (Massachusetts Institute of Technology) and Harvard University in the USA collaborated on developing the glass printing process (see video [V1]), for example aimed at architectural applications. However, the G3DP (Glass 3D Printing) platform as part of MIT's Media Lab is no longer online. Micron 3DP (Israel) announced a breakthrough in glass 3D printing four years ago, but has not been heard much since. In short, developing a printer for glass, as a highly viscous liquid at a very high temperature, is a tough proposition.

Status

QSIL Netherlands started development in 2014 and that resulted in a promising but simple prototype 3D printer for glass, following which Demcon was commissioned to develop a temperature-controlled version. The result received many positive reactions at the international Glasstec 2018 trade fair in Düsseldorf (Germany). A business developer is now looking for interesting applications, in areas including construction, healthcare (biocompatible prostheses), lighting and the arts. Figure 1 shows some examples of products that have already been printed using the QSIL printer.

An autofeed has recently been installed on the printer for the controlled continuous supply of glass rods to the printer; QSIL is currently doing process research – together with students from different universities, among others – to optimise process parameters. Examples include the various temperatures around the printing process, the motion control for the deposition table, and the speed of the supply of glass rods to the printhead.

Design

Figure 2 schematically shows the design of the printer, which works according to the well-known FDM process, with a stationary printhead and a moving deposition table. That table can move under the head in the X-, Y-, and Z-direction to have the correct shapes printed (the rotation R shown in Figure 2a has not (yet) been realised). Solid glass rods are supplied to the printhead, around which there is an induction coil that heats the glass to 1,500 °C, making it liquid so that it can be deposited, either continuously or dropwise, first on the table and then on the product being printed on that table; Figure 3 provides an impression. This takes place under a protective nitrogen (N_2) atmosphere to prevent oxidation of components at the elevated temperatures in the oven. QSIL has patented this FDM process for glass.

At present, QSIL mainly works with soda-lime glass, the most prevalent glass type, but borosilicate glass is also printable. The materials used in the print chamber are not designed to withstand the even higher temperature required for printing quartz glass. The glass rods are fed from a

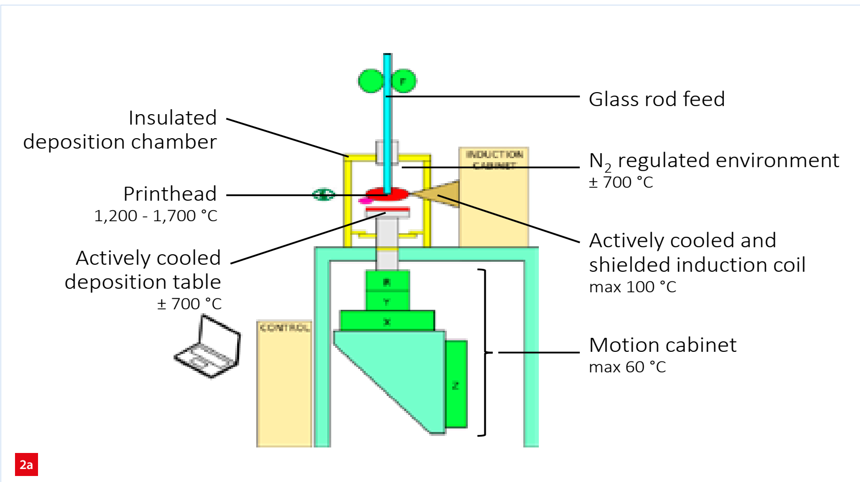
1

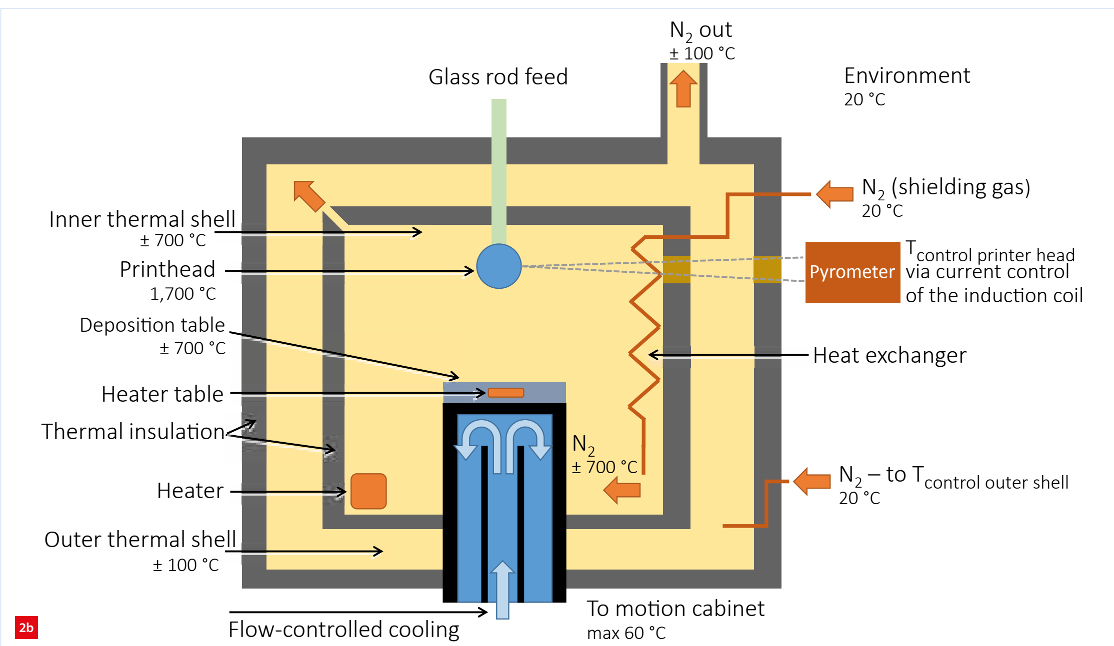
Examples of 3D-printed glass products.

cassette on top of the oven; this supply is still force-driven. Controlled dosing of the glass, depending on the pattern to be printed, still needs to be developed. This is partly necessary to prevent the accumulation of material at (sharp) corners and bends in a product, when the table has to slow down to take the turn and therefore, with uniform dosing, more material is deposited per unit of time.
Figure 4 shows the current print set-up at QSIL. It has a print volume of 10 cm x 10 cm x 10 cm and a print resolution of just under 1 mm, as determined by the diameter of the printhead. A smaller diameter, of 0.5 mm or even less, and therefore a higher resolution is certainly achievable, even if the drilling of a long narrow hole in the printhead is not easy. The starting material, thin glass rods, is not the limiting factor because, for example, glass fibres for data communication can measure less than 0.1 mm in diameter. Given the current print volume, actual printing takes in the order of a minute. Allowing the product to cool down in a controlled manner to relax the internal stresses requires more time.
The printhead and the deposition table are made from a refractory metal, because of its high melting point. The printhead has a lifetime of up to half a year; under the influence of the high temperatures it degrades and can then easily be replaced. In contrast to steel, for example, this refractory metal does not warp at high temperatures. Another advantage of the refractory metal is that the printed glass does not adhere to it, so that workpieces can easily be removed from the table.

The deposition table, together with the printhead, is located in an oven to adequately contain the process; the actuators are of course outside that oven, with a well-insulated feed-through for the table support. In order to ensure thermal control and safety, an outer shell has been fitted in the oven, which contains nitrogen at 100 °C. Thanks to thermal insulation, the outside of the oven is at 'room temperature'. The nitrogen environments in the inner and outer shell are both at overpressure, which means that heated gas can gradually be discharged to the outer shell, where it is mixed with nitrogen supplied from outside at room temperature, and then vented into the environment.

Impression of the process in QSIL's glass 3D printer.





Schematic design of the glass 3D printer by Demcon.
See text for further explanation.
(a) Overall system.
(b) Thermal characteristics of the core system, i.e. the oven (insulated deposition chamber) with printhead and deposition table.

4 Realisation of the glass 3D printer at QSIL, with the XYZ-stage below the oven and the autofeed unit on top.

Modelling

Given the complexity of the design and the high temperatures involved (as a result of which radiation plays an important role in addition to convection and conduction, due to the T^4 factor from Stefan-Boltzmann's radiation law), a model study was first carried out at system level. Subsequently, finite-element model (FEM) simulations were performed for detailed analysis, covering the 'hot spots' in the system; a FEM analysis of the entire system would be virtually impossible.

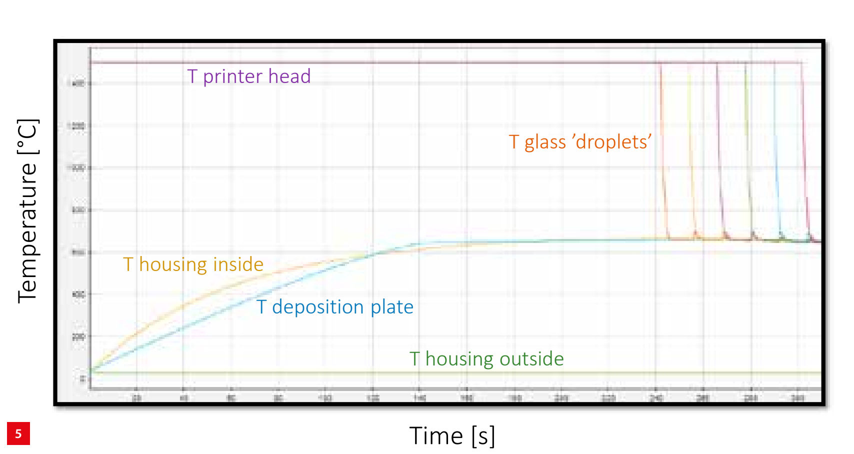
For such model studies, Demcon kryoz works with Simulink, the MathWorks graphical environment for simulation and model-based design for multi-domain dynamic and embedded systems. Demcon kryoz developed its own toolbox covering the thermal, fluidic and vacuum domains to provide all the required thermal properties of a wide range of materials, as well as the technical specifications of standard components such as fans and pumps. In this way, a so-called lumped-element model (LEM) has been made for optimising the thermal and flow parameters as well as the geometric dimensions of materials and components.

The simulations were used to investigate and optimise the thermal behaviour: how long does it take before the system is sufficiently heated up to start printing (relevant time constants); how long does it take for the system to cool down in case of emergency (thermal mass of the system); what is the best thermal control strategy for the oven; where should thermocouples and other sensors be placed; what is the best motion control strategy for the deposition table; are the materials resistant to high temperatures and large temperature changes, etc.?

Deposition plate thermal control

One of the design aspects that has been studied using the simulations is the temperature control of the plate of the deposition table. This must be just above the glass temperature (the temperature at which the glass becomes brittle on cooling, or soft on heating), so that it lies around 700 °C. At that temperature, the mechanical properties of the liquid glass are favourable, with sufficient strength and stickiness: internal stresses do not accumulate upon rapid solidification, but the product 'under construction' also will not collapse under its own weight when solidification proceeds too slowly. Based on simulations with various options, a combination of a heating element in the deposition plate table and liquid cooling via the table support with a tube-in-tube design was selected.

The combination of heating and cooling is associated with the radiation emitted by the printhead at 1,700 °C. In the initial phase of a print job, the table is located near the printhead and the radiation load is high, which means that the table must be cooled. While the object to be printed is gradually being built up, the table moves downwards and thus moves away from the printhead; as a result, the radiation load (which inversely scales with the squared



5 LEM-simulation (lumped-element model) of the glass 3D printer in discontinuous mode (firing glass 'droplets'), showing the evolution of the temperature of the various system parts: temperature (0-1,400 °C) vs time (0-300 s). Each glass droplet quickly cools down from printhead to deposition table temperature, with the table in turn displaying a little temperature spike upon droplet impact. At t = 0 s, the printhead was already at operational temperature, whereas the heating of the table was then switched on.

distance) decreases and additional heating is ultimately required to keep the table at the desired temperature.

Heat exchanger

An important factor in the thermal management of the oven is the nitrogen in the inner shell. This is preheated using spiral heaters and reaches the desired temperature in a heat exchanger. Using the simulations, its length and diameter were optimised. Over its entire length, tiny holes have been made in the heat exchanger through which the nitrogen flows into the oven; this ensures a homogeneous flow and minimal disruption of the temperature distribution in the oven.

Further research

Many aspects have already been included in modelling, but other, more advanced, aspects have not yet been considered, such as making the instantaneous thermal control of the oven and motion control of the deposition table dependent on the specifics of the part of the product that is to be printed at that very moment. Nevertheless, the physical realisation of the printer is already yielding good results and the control is working properly. For example, it is possible to keep the temperature of the deposition plate within 10 °C of its target.

Further process research is now focused on, among other things, the resolution and accuracy of the printing process, the transparency of the printed products (for optical applications) and the control of their surface properties, such as roughness. The need for better reproducibility, thinner layers and more complex forms drives this research. Ultimately, regardless of the material, freedom of form is the great promise of all AM processes.

VIDEO

[V1] Mediated Matter Group (MIT), "Glass", *vimeo.com/136764796*

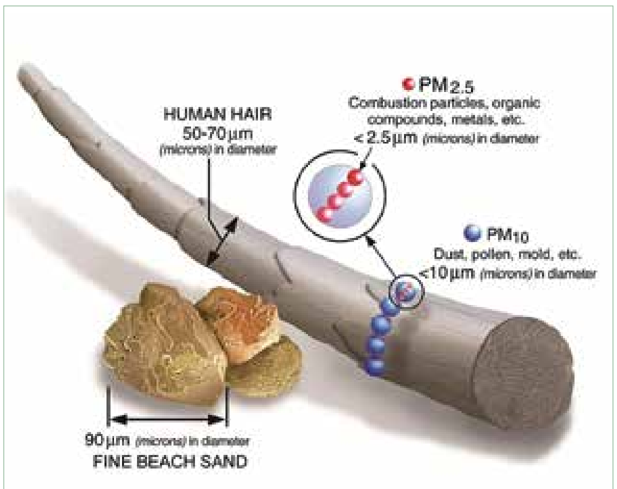
DSPE KNOWLEDGE DAY: ENGINEERING FOR PARTICLE CONTAMINATION CONTROL

Contamination control is crucial for modern-day precision engineering, but has not yet received much attention in a DSPE context. At the end of June, the DSPE Knowledge Day on Engineering for Particle Contamination Control was organised at Fontys University of Applied Sciences in Eindhoven (NL), in collaboration with VCCN (Association of Contamination Control Netherlands) and DSPE members VDL ETG, NTS and Thermo Fisher Scientific. Some 30 people, from companies including ASML, Océ, MI-Partners, JPE, Festo, SMC, Frencken, Mevi and Masévon, showed up for the premiere of a DSPE event on this topic.

John Timmermans, system architect at NTS, presented engineering design guidelines for particle contamination control. He discussed the variety of particles and their properties. One example, related to the particle deposition rate, is the relationship between particle diameter and drop time. Below 1 µm diameter particles remain airborne, above 10 µm they will fall within minutes leading to deposition on a surface. The impact of particles, depending on their size and nature, ranges from wear of bearings and faults in an integrated circuit (IC) to infections in a patient. Timmermans made a nice analogy to illustrate the impact of a particle: a 0.1-µm particle that drops on a 20-nm wide IC structure compares to a 10-m diameter rock hitting a car.

Design guidelines

Regarding measures to prevent or mitigate contamination, underspecification (with the risk of unforeseen damage) is as bad as overspecification (too much design effort and cleaning action). For instance, in lithography sub-µm particles have to be considered, whereas for printing contamination by sub-50-µm particles can be neglected (i.e. regarding the visible print quality, but perhaps smaller particles can obstruct printhead nozzles).



Typical diameters of particles.

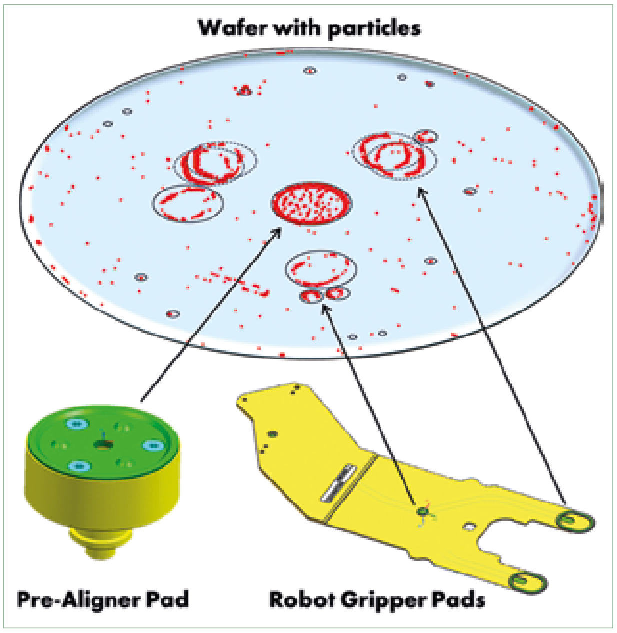
For the design for cleanliness of parts, Timmermans recommends keeping things simple: limit the number of parts in a module or system; design flat surfaces with low roughness; give edges and corners a rounded finish; provide for open structures that are accessible for cleaning; limit the number of holes, especially the blind and threaded ones; minimise the contact surface for vacuum parts; and minimise the amount of welds, especially at the vacuum side of a system.

For systems the design rules can be formulated even more concisely: minimise contamination sources, spreading and effect. For example, by respectively: limiting the number of moving parts; positioning critical surfaces upstream of contamination sources; and placing a pellicle in front of a reticle. As a practical case, Timmermans presented the design and operation of a printer system. Here, the use of an enclosure minimises the influence of people, one of the major contamination sources in normal-day operation. A fan with HEPA (High Efficiency Particulate Air) filters in the ceiling, combined with an outlet at floor level, provides a mini-environment with laminar downflow draining particles. Finally, the contamination effect can be minimised by periodic cleaning of the printer heads and testing of the nozzles.

Life of a particle

Kasper van den Broek, tribology expert at VDL ETG, talked about the development and implementation of particle contamination control. He took the perspective of a particle: how it is generated, how it moves and how it settles on a critical surface. For each of these three stages – source, transport and deposition – methods for analysis as well as testing are available, ranging from nano-scratch indentation tests for particle source testing to atmospheric flow Computational Fluid Dynamics for particle transport analysis and the use of so-called witness plates for particle deposition testing.

The design of a wafer handler – with over ten contamination-critical positions, four moving robots and various (either vacuum or atmospheric) environments –



Particle deposition analysis of the back side of a wafer, showing the relation to contacting parts of the wafer handler, such as the pre-aligner pad and the gripper pads. (Image: VDL ETG)

served as the case for illustrating all six (2x3) aspects of particle contamination control: analysis, respectively testing of source, transport and deposition.

Particle analysis
One of these aspects was highlighted by Alexander Bouman, manager of product management at Phenom-World, part of Thermo Fisher Scientific. He presented the automated particle analysis using a scanning electron microscope (SEM): in a SEM image, particles can be counted and their morphology can be determined, typically in the size range of 500 nm up to 2 mm. With the addition of an EDX (energy-dispersive X-ray) detector on the SEM, the chemistry of the particles can be unveiled as well.

As an application example Bouman discussed one of the challenges of additive manufacturing (AM), concerning the reuse of metal powder that remains after a printing job. Morphology and granulometry of the metal powder may be changed by the recycling, resulting for instance in satellite or agglomerate particles. This may in turn affect composition, homogeneity and resolution, and hence mechanical and thermal properties of a printed product. SEM analysis can help to determine powder quality and predict AM product quality.

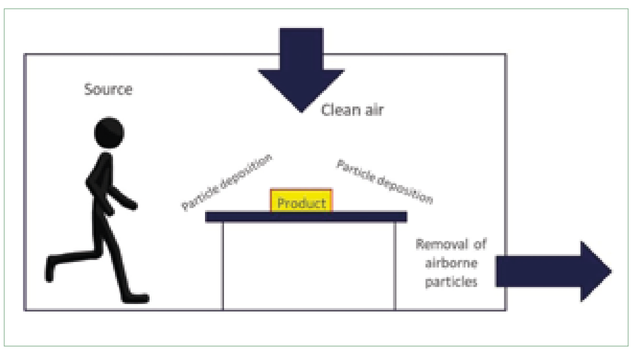
Manufacturing
The last speaker was Koos Agricola, contamination control expert at Océ and Brookhuis and VCCN board member. He discussed particle contamination control during manufacturing, when product surfaces can be


Virgin (left) and recycled ('contaminated') metal powder for additive manufacturing.

contaminated by deposition and transfer via contact with people, tools, work surfaces, incoming goods, packaging, etc. Agricola presented the ISO standards for air and surface cleanliness in a clean controlled environment and the relation with particle deposition rates.

To make his point, he used the case of an inkjet printhead to identify potential failure modes related to particle contamination during manufacturing of the printhead and to make the associated risk assessment in order to determine contamination control requirements. Practical measures can include limiting the exposure of critical parts; cleaning parts just before assembly; automating and executing critical assembly processes in dedicated mini environments; and cleaning all surfaces on every shift.

VCCN
Agricola's presentation concluded a lively DSPE Knowledge Day, but the topic of particle contamination control in manufacturing remains 'hot'. To help Dutch industry manage this issue, VCCN is running the 'Nano-Micro cleanliness' project group, which aims to write guidelines. Companies such as ASML, Thermo Fisher Scientific, Philips, Océ, NTS, AAE and VDL, as well as TNO, participate in this project group. On 7 November 2019, VCCN will organise a mini-symposium on this topic.



People are one of the major contamination sources.

WWW.NTS-GROUP.NL
WWW.THERMOFISHER.COM
WWW.VCCN.NL
WWW.VDLETG.COM

DSPE OPTICS WEEK BACK IN EINDHOVEN

The fourth DSPE Optics Week will take place from 30 September to 3 October 2019 in Eindhoven (NL). The four-day event includes a symposium, supplemented by a fair and demonstrations, and a three-day course. The symposium provides a fascinating overview of the developments and challenges in optomechatronic systems. The new course for optomechanical system design bundles the broad expertise of some of the Netherlands' most experienced system architects and designers.

In 2013, at the initiative of DSPE, the one-day DSPE Optics and Optomechatronics Symposium took place in Eindhoven. This was successfully continued in 2015 in the form of an Optics Week in Delft (NL), featuring an optics and an optomechatronics course in addition to the symposium. To extend the scope abroad, DSPE decided to organise the Optics Week 2017 in the German city of Aachen and to involve representatives of well-known German companies and institutes. In addition to the symposium and courses, there was a demonstration day at the Fraunhofer institutes IPT (production technology) and ILT (laser technology). The fourth edition of the Optics Week will now take place in Eindhoven again, at Fontys University of Applied Sciences.

Symposium

The week starts on Monday 30 September with the DSPE Optics and Optomechanics Symposium, supplemented by a fair and demonstrations. Jelm Franse, senior director Mechanical Development at ASML, acts as chairman of the day and Paul Urbach, professor of optics at TU Delft, will kick off the symposium with his views on challenges in optomechanics and optomechatronics.

Companies and research institutions from the Netherlands, Germany and China then provide a wide range of presentations, focusing on the design and thermo-optomechanical modelling of complex optomechatronic systems, such as lithography machines, 3D printers and electron microscopes. Speakers come from ASML, Delmic, Hittech Multin, VDL ETG, PTB, TNO, TU Delft, Raith and Shanghai Precision Measurement Semiconductor Technology.

Premiere of course on optomechanical system design

The second part of the Optics Week, from 1 to 3 October, concerns the Optomechanical System Design course. DSPE has taken the initiative for this new course to promote the importance of optomechanical system design. The course offers mechanical, mechatronic and optical engineers a broad overview of this omnipresent multidiscipline and contains numerous design examples that illustrate the tricks of the trade in optomechanical system design. The teachers are experienced system architects and designers: Lennino Cacace (AC Optomechanix and TU Delft), Pieter Kappelhof (Hittech Group), Gabby Aitink-Kroes (SRON) and Jan Nijenhuis (TNO).

The first day of training takes the step from optics to optomechanics and starts with the layout of optical systems and the influence of positioning errors on their performance. Topics such as tolerances, alignment and signal degradation are subsequently presented. In addition, the system engineering tools are provided that contribute to optimum cooperation between the optical and mechanical engineer. The second day is all about mechanics for optics. Subjects include the design of alignment mechanisms, the (thermal) stability of optical systems and the mounting of optical components with the aid of clamping or gluing. Potential 'showstoppers' are on the agenda for the last day of the course and will include the cable routing in optical instruments and the required surface treatments. A concluding mini-workshop is about optomechanics under cryogenic conditions, featuring the instrumentation for astronomy.

Partners

The Optics Week 2019 is being organised by DSPE in collaboration with RWTH Aachen University and the Fraunhofer Institutes IPT and ILT. Other partners are Brainport Industries, Holland Instrumentation, Optence, PhotonicsNL, Spectaris and Cluster NanoMikro-WerkstoffePhotonik.NRW. Participants in the symposium can subsequently deepen their knowledge of optics and photonics during the Photonics day that PhotonicsNL, the unique portal and trade association for photonics in the Netherlands, will be organising on 1 October at the High Tech Campus Eindhoven.

WWW.OPTICSWEEK.EU

BRIEF METAL ETCHING Q&A

Photochemical etching is a metal machining technology that has numerous advantages over traditional sheet metalworking processes, key among which is its applicability to a range of metals and alloys — even ones that are difficult to machine using traditional metal machining technologies.

Q. What are the unique characteristics of chemical etching?

A. Using photo-resist and etchants to chemically machine selected areas accurately, chemical (or photochemical) etching has the ability to manufacture burr- and stress-free precision metal parts with complex geometries, achieving accuracy to ±0.025 mm, while maintaining the flexibility to make last-minute design changes, and mass-produce prototypes quickly (Figure 1). In addition, chemical etching is often the most economical option for producing custom parts with complex designs and strict tolerances, as unlike other processes, cost does not increase with design complexity. Finally, the use of inexpensive and easily re-iterated digital phototools allows for low-cost trial & error of design configurations, again often not possible with other methods.

Q. Which metals are suitable for chemical etching?

A. Virtually any metal can be chemically etched, but as with most metal machining technologies, some are easier to process than others. Demand from industry often focuses on metals that have attractive attributes, and it is on these metals that Precision Micro's efforts are focused.

1 *Chemical etching in Precision Micro's facilities.*

Profile

Precision Micro has well over 50 years of experience, and is Europe's market-leading chemical etching expert. Its continual investment in research and development of chemical etchants and process parameters means that today even the most challenging metals can be processed in volume and to exacting standards in terms of tolerance and accuracy. All of this is underpinned with quality management systems, with the company accredited to ISO 9001, ISO 13485, IATF 16949, ISO 14001 and AS 9100.

WWW.PRECISIONMICRO.COM

Q. Can you etch titanium?

A. Titanium is lightweight, strong, has excellent fatigue performance, as well as offering high resistance in aggressive environments. These favourable properties, however, prove to be a problem when machining.

Titanium's high strength, low thermal conductivity, and chemical reactivity with traditional tool materials (at elevated temperatures) significantly reduces tool life when machining. Its relatively low Young's modulus leads to spring-back and chatter, causing poor surface quality on the finished product. In addition, during turning and drilling, long continuous chips are produced, which can lead to entanglement with the cutting tool, making automated machining challenging.

The use of chemical etching overcomes many of these issues, but even etching titanium is difficult, as the metal forms a protective oxidised coating when exposed to air, meaning it cannot be etched with standard etch chemistries. To overcome this, Precision Micro developed a proprietary process, investing in specialist equipment and process chemistry to produce etched parts comparable to the ones

EDITORIAL NOTE

This article was based on press releases from Precision Micro. The company is based in Birmingham, UK, and has pioneered photochemical etching for over 50 years.

produced in stainless steel. Now it is supplying, for example, a number of biocompatible medical devices to industry-leading OEMs such as cranial and dental implants which benefit from complex openings with depth-etched countersink features.

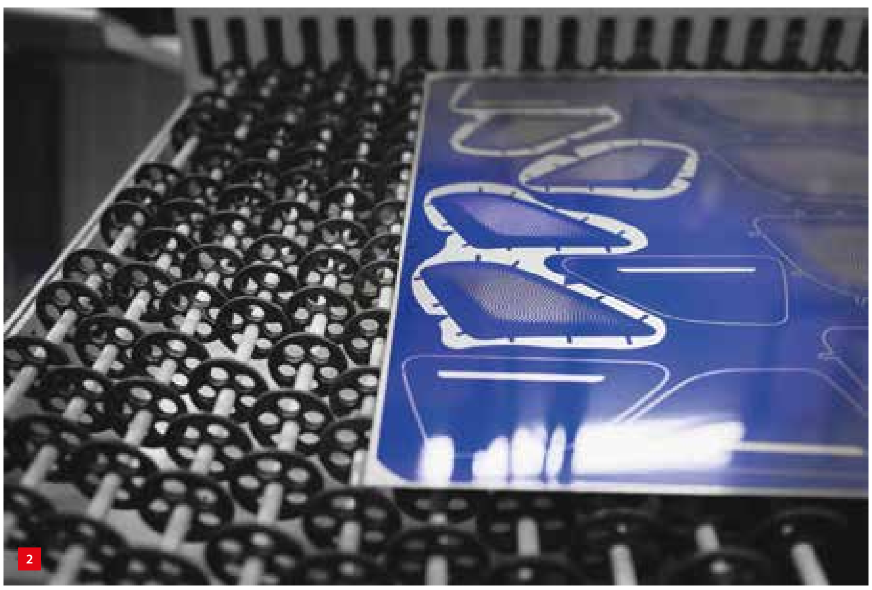
Q. Can you etch aluminium?

A. Aluminium exhibits many of the attributes of titanium — notably its high strength-to-weight ratio and natural corrosion resistance — but whereas titanium is stronger and more corrosion-resistant than aluminium, the latter has a better fatigue limit, which makes it ideally suited to aerospace applications where fatigue limits must be high.

When conventionally machining aluminium, there are a number of problems, the biggest being what is termed 'the built-up edge' — basically the welding of workpiece material to the tool edge, and the subsequent loss of effective geometry which causes increases in cutting forces and quality problems such as scratches in the surface and cloudy finish. For many suppliers, aluminium is also difficult to photo-etch effectively as the heat energy it releases during etching – in this case the process is exothermic – often results in a rough, granular edge.

As with titanium, a proprietary method has been developed for etching aluminium and its alloys, producing edge profiles comparable with those etched in a much easier-to-process metal, namely stainless steel.

As an AS 9100-accredited supplier, Precision Micro etches components for a wide range of aerospace applications, including lightweight helicopter air-intake grilles and heat-transfer plates used in aircraft dehumidifiers and engines, the latter often requiring multiple designs which can be set-up cost-effectively.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Stainless steel speaker grilles with complex hole arrays and surface engraving are supplied by Precision Micro to automotive OEMs in quantities of multiple millions each year. The tooling is too complicated for stamping and the mesh pattern is too complex for laser cutting.

Q. Can you etch steel and stainless steel?

A. Precision Micro photo-etches a wide range of austenitic (300) and ferritic martensitic (400) series steel grades from stock, as well as specialist grades including Sandvik Chromflex strip steels and nickel chrome, all of which amounts to the supply of more than 2,000,000 steel components each month.

Etching is suited to pretty much any stainless steel component between 0.01 and 1.5 mm in thickness (Figure 2). Precision Micro specialises in a number of applications, including:

- Meshes, filters and sieves: with metal removed simultaneously when etched, multiple aperture geometries can be incorporated without incurring high tool or processing costs, and where punch-perforated sheets are prone to distortion, photo-etched mesh is burr- and stress-free with zero material degradation; the process does not alter the surface finish of the material – no metal-to-metal contact or heat source is used which can mar the surface – offering a highly aesthetic finish.
- Flexure springs for ABS braking systems, medical biosensors, and fuel-injection systems: burr- and stress-free means springs function for longer, as the process does not alter the fatigue strength of the steel.
- Fluidic plates for liquid-to-liquid or liquid-to-gas heat exchangers and fuel cells; complex channels etched into plates which remain perfectly flat.

Q. Can you etch copper and copper alloys?

A. As a relatively soft metal that exhibits high thermal and electrical conductivity, copper etches quickly in standard etch chemistries, unlike contact machining processes which can stretch copper out of shape and alter its properties.

Copper and its alloys are highly durable, ductile, and malleable, meaning they are well suited to forming and plating post-etching. Precision Micro produces thousands of 3D electrical contacts, pins, terminals, EMI gaskets, shieldings, lead frames and connectors each month for automotive, electronics, aerospace, and medical applications.

Q. Can you etch nickel and nickel alloys?

A. Nickel's high resistance to heat and corrosion makes it a popular choice when developing a variety of parts and components, it being commonly used as a protective outer coating for softer metals. Precision Micro can apply its photo-etching to pure nickel and an array of nickel alloys. One recent application involved the processing of Inconel, a high-temperature nickel-based superalloy which as well as superior heat resistance also exhibits excellent resistance to corrosion, pressure, and oxidation.

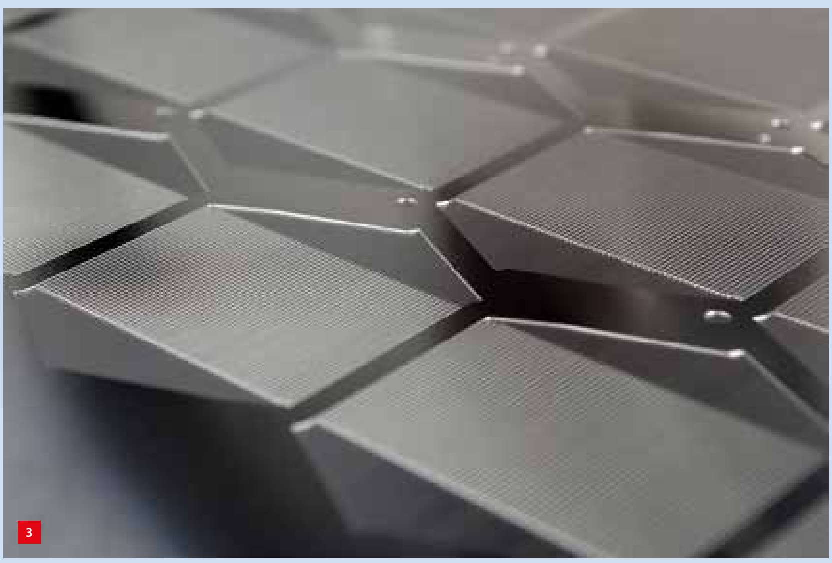
Bipolar fuel-cell plates

Fuel cells are one of the alternatives in the current transition towards low-carbon vehicles. Traditionally, bipolar fuel-cell plates have been CNC-machined from graphite, an extremely expensive and highly permeable material that is not ideally suited to mass-manufacturing applications. Therefore, numerous materials have been assessed as alternatives, and because of the demand for competitively priced, relatively easily-to-manufacture, durable materials, metals (especially stainless steel and titanium) have become increasingly popular. Stainless steel exhibits an array of characteristics that make it ideally suited for bipolar fuel-cell plates, including its inherent strength, chemical stability, low cost, and relative ease of mass production.

Fuel cells are produced by stacking precise and intricate plates machined with complex grooves or channels which enable liquid and gases to flow, and can be manufactured using either CNC-machining, hydroforming and stamping, but there are question marks over the scalability and capability of these processes. For example, stamping and hydroforming compromise planarity (flatness) and introduce stresses and burrs. Single-point machining processes and presswork tooling can also be slow and uneconomical, especially during R&D.

As an alternative, photochemical etching offers advantages when producing complex components such as bipolar fuel-cell plates (Figure 3), as outlined above. In addition, it removes metal simultaneously, meaning complex channels or flow fields can be etched to 0.025 mm on both sides of the plate. This versatility enables designers to vary the size and shape of channels and incorporate headers, collectors, and port features without additional cost, which is not possible with alternative technologies.

Precision Micro typically manufactures bipolar plates from 316- or 904-grade stainless steels in plate sizes to 1,500 x 600 mm^2, but plates can also be specified in exotic and hard-to-machine metals (such as titanium) for lightweight and corrosion resistance in high-temperature fuel-cell applications.



Bipolar fuel-cell plates produced using photochemical etching.

EUSPEN IN SPAIN

This year, euspen's International Conference & Exhibition was held in Bilbao, Spain, at the Euskalduna Conference Centre. The event continued to reflect the burgeoning interest in cutting-edge developments in micrometer- and nanometer-level engineering. The keynotes featured advances in precision engineering technologies when applied to the evolution of aeroengines; building and shaping regional innovation eco-systems in precision engineering and nanotech; and surface metrology in times of big data and AI.

CHRIS YOUNG

The European Society for Nanotechnology & Precision Engineering (euspen) exists to advance the arts, sciences, and technology of precision engineering, micro-engineering and nanotechnology, to promote its dissemination through education and training, and to facilitate its exploitation by science and industry.

As such, the society's annual event — this year held in Bilbao, Spain — surely fulfils this objective, bringing together as it does the cream of the precision engineering community at one venue to network and push the boundaries of micro- and nanoscale manufacturing. Between 3-7 June 2019, upwards of 400 delegates populated the Euskalduna Conference Centre in Bilbao, which was a venue that most attendees valued as it allowed the vital flow of attendees from the conference and poster session areas into the exhibition (Figure 1).

This year, the exhibition showcased about 40 key suppliers, including first-timers Accumold and Nanofabrica, and many repeat exhibitors, such as Aerotech, ALIO Industries, Precitech, Ametek, Heidenhain, Attocube, IOP Publishing, Huber, IBS Precision Engineering, Kinetic Ceramics, JPE, Mad City Labs, Nanotech, MI-Partners, PI, Olympus, Polytec, Queensgate Instruments, SmarAct, and SIOS.

AUTHOR'S NOTE

Chris Young, managing director & CEO of UK-based Micro PR & Marketing, is a media partner of euspen.

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1 This year's euspen Conference venue, the Euskalduna Conference Centre in Bilbao.

Themes

The conference themes included design and performance of measuring instruments and machine tools, mechatronics and control, metrology, advances in precision engineering and nanotechnologies, mechanical and non-mechanical manufacturing processes, replication and additive manufacturing, applications of precision engineering in biomedical sciences, handling, robotics and automation, Industry 4.0 for precision manufacturing, and precision design in large-scale applications.

Keynotes

The first conference keynote was presented by Prof. Norberto López de Lacalle (Figure 2) from the University of the Basque Country (UPV/EHU), who analysed the advances in precision engineering technologies when applied to the evolution of aeroengines. "Aeroengines and turbines are a high-added-value system, in which precision, quality and productivity are demanded in manufacturing processes, and difficult-to-cut materials, safety demands and other aspects are involved. Safety comes up first, and to achieve that precise machines, metrology in process, NDTs (non-destructive tests, ed. note), and quality aspects are ingredients in the recipe of success. The only way to accelerate the evolution of processes in this industrial niche is cooperation between tier-1 aeroengine makers, and machine tool and technology providers, along with universities."

Prof. Egbert-Jan Sol from TNO/Radboud University in the Netherlands (Figure 3) explained how success in precision engineering is all about people. "With a tradition of more than a century in *Machinenbau*, Europe is still leading in equipment and instrumentation. Large-scale measuring of nanoparticles for semiconductor EUV, mechatronics for

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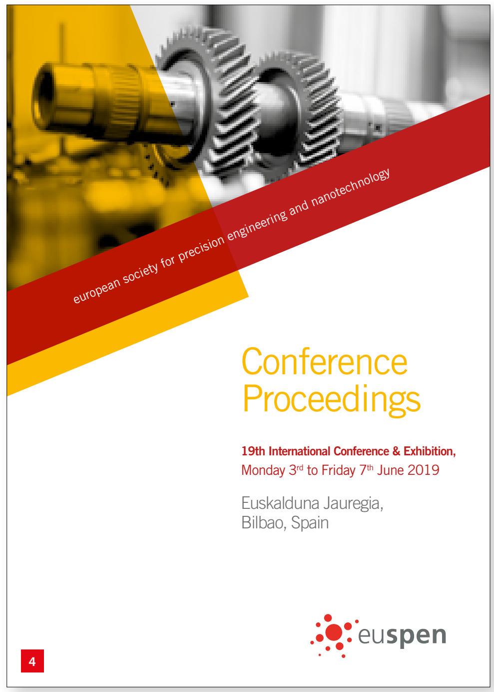
Keynote speaker prof. Norberto López de Lacalle: "The only way to accelerate the evolution of processes in the industrial niche of aeroengine and turbine manufacturing is cooperation between tier-1 aeroengine makers and machine tool and technology providers, along with universities."

the E-ELT telescope, and laser-based data communication with microsatellites are recent examples. Technology, in particular new, very powerful, digital tools, evolves rapidly. No one, not even large companies, can do everything by themselves. So, today's successes are also determined by regional innovation eco-systems. Building and shaping such eco-systems, also in precision engineering and nanotech, is a social skill and in the end it comes down to people and their ambitions."

Prof. Han Haitjema from KU Leuven (Belgium) presented a review of methods and literature on error separation and noise effects in surface metrology in times of big data and AI (artificial intelligence). This included error separation, gradient measurements and an averaging method for absolute flatness. He also discussed traceability issues of 'intelligent' data evaluation, especially when combined with AI.



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Proceedings of the 19th euspen Conference.

Awards

According to the conference organisers, 814 author submissions were made to the 2019 conference from 29 countries representing 223 organisations. Rich pickings from these submissions were shortlisted to the papers presented at the conference, or included in the poster sessions; these can be found in the proceedings (Figure 4).

This year, the best oral presentation award went to Mark Naves from the University of Twente for his paper, "Design of a large stroke flexure-based suspension for an iron core torque motor".

The poster presentation award winners were Philipp Gräser, Technische Universität Ilmenau, "Investigations of different compliant manipulator concepts for a high-precise rotational motion"; Lu Zheng, Newcastle University, "Wettability and liquid flow control in microfluidic channels by vibration assisted micro milling"; and Saint-Clair T. Toguem, Ecole Normale Paris-Saclay, "Customized Design of Artefacts for Additive Manufacturing."

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Keynote speaker prof. Egbert-Jan Sol: "Building and shaping regional innovation eco-systems is a social skill and in the end it comes down to people and their ambitions."

Learning

Attendees at the euspen annual event have numerous opportunities to learn beyond the conference and poster sessions. On site this year were four tutorial sessions and three workshops.

The tutorials covered micro/nano injection moulding; areal surface metrology – instrumentation and characterisation; passive damping in mechatronics by means of polymers; and design concepts for sub-micrometer positioning.

The workshops were devoted to industrial in-process manufacturing metrology as well as two EU dissemination projects, concerning multifunctional ultrafast micro-probes for on-the-machine measurements, and process fingerprint for zero-defect net-shape micromanufacturing.

Success

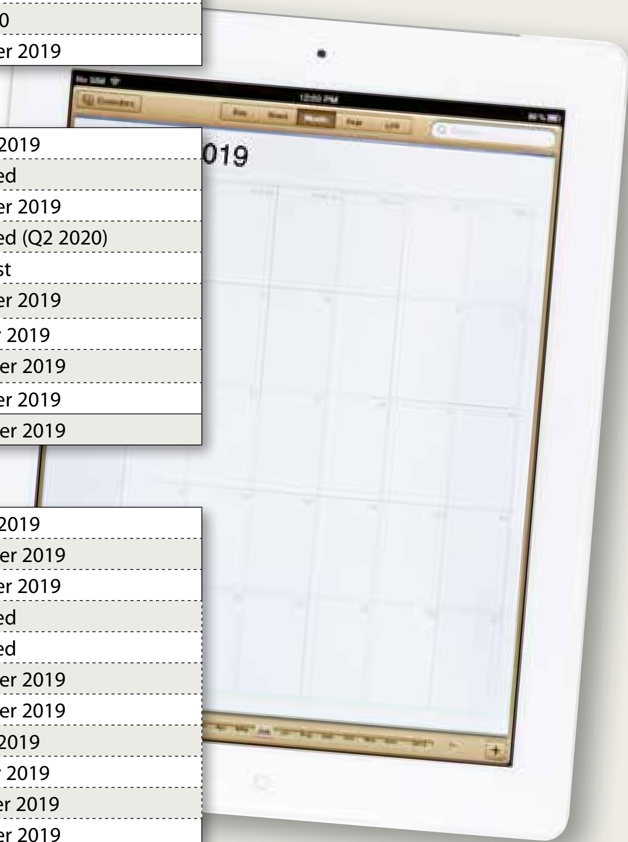
According to David Billington, executive director at euspen, the event was a big success. "In Bilbao, we saw perhaps the strongest range of exhibitors in our 19-year history, and feedback from the delegates was such that we feel confident to say that the level of excellence in the conference, tutorials, and workshops was the best yet. This reflects the continual dynamism and growth in the area of micro- and nano-technology. Industry is becoming more and more engaged with the possibilities that exist and can provide commercial advantage these days, and as academics, researchers, and active OEMs see this progress, we as a society feed the demand for quality information and the stimulation of business partnerships at all our on-site networking forums."

2020 at CERN

2020 sees the 20th version of the euspen annual event, from 8 to 12 June, and the organisers are pulling out all the stops to ensure that this will be a landmark event, the venue being announced as CERN in Switzerland, home of the world's largest particle physics laboratory.

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	6 April 2020
Mechatronics System Design - part 2 (MA)	5	HTI	4 November 2019
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	25 September 2019
System Architecting (S&SA)	5	HTI	30 September 2019
Design Principles for Precision Engineering (MA)	5	HTI	22 June 2020
Motion Control Tuning (MA)	6	HTI	27 November 2019
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	29 October 2019
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	19 November 2019
Thermal Effects in Mechatronic Systems (MA)	3	HTI	to be planned (Q2 2020)
Summer school Opto-Mechatronics (DSPE/MA)	5	HTI	upon request
Dynamics and Modelling (MA)	3	HTI	25 November 2019
Manufacturability	5	LiS	4 November 2019
Green Belt Design for Six Sigma	4	HI	16 September 2019
RF1 Life Data Analysis and Reliability Testing	3	HI	18 November 2019
Ultra-Precision Manufacturing and Metrology	5	CRANF	16 September 2019
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	29 October 2019
Advanced Optics	6.5	MC	19 September 2019
Machine Vision for Mechatronic Systems (MA)	2	HTI	11 November 2019
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	20 September 2019
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	13 September 2019
Tribology	4	MC	29 October 2019
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	4 November 2019
Experimental Techniques in Mechatronics (MA)	3	HTI	10 December 2019
Advanced Motion Control (MA)	5	HTI	18 November 2019
Advanced Feedforward Control (MA)	2	HTI	9 October 2019
Advanced Mechatronic System Design (MA)	6	HTI	to be planned (2020)
Passive Damping for High Tech Systems (MA)	2.5	HTI	19 November 2019
Finite Element Method	5	ENG	in-company
Design for Manufacturing – Design Decision Method	3	SCHOUT	in-company



ECP² program powered by euspen

The European Certified Precision Engineering Course Program (ECP²) has been developed to meet the demands in the market for continuous professional development and training of post-academic engineers (B.Sc. or M.Sc. with 2-10 years of work experience) within the fields of precision engineering and nanotechnology. They can earn certification points by following selected courses. Once participants have earned a total of 45 points, they will be certified. The ECP² certificate is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills, and allows the use of the ECP² title.

WWW.ECP2.EU

Course providers

- Engenia (ENG)
  WWW.ENGENIA.NL
- High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LISACADEMY.NL
- Schout DfM (SCHOUT)
  WWW.SCHOUT.EU
- Holland Innovative (HI)
  WWW.HOLLANDINNOVATIVE.NL
- Cranfield University (CRANF)
  WWW.CRANFIELD.AC.UK
- Univ. of Huddersfield (HUD)
  WWW.HUD.AC.UK
- National Physical Lab. (NPL)
  WWW.NPL.CO.UK

Content partners

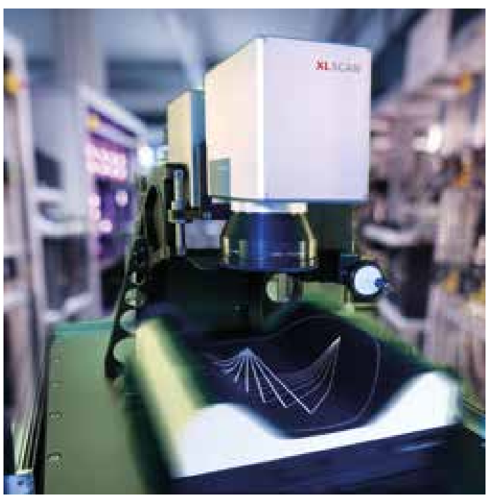
- DSPE
  WWW.DSPE.NL
- Mechatronics Academy (MA)
  WWW.MECHATRONICS-ACADEMY.NL
- Technical Training for Prof. (T2Prof)
  WWW.T2PROF.NL
- Systems & Software Academy (S&SA)

Limitless scanning with integrated ultra-dynamic Z-axis

In June, at the LASER World of Photonics 2019 tradeshow in Munich, Germany, leading galvo-based scan solution provider Scanlab presented its XL SCAN, for the first time with an additional axis. Jointly developed with ACS Motion Control, this innovative scan system processes workpieces of practically unlimited size by combining a 2D scan head with an XY-positioning stage. What's new is the added ultra-dynamic Z-shifter that enables highly precise surface processing of 3D-shaped workpieces in nearly any size.

Numerous laser processing applications are constrained by the scan system's image field size. Large workpieces thus typically require stepwise processing of individual surface sections. But this approach produces relatively long process times and bears the risk of stitching errors. To eliminate those shortcomings, Scanlab and ACS Motion Control designed the XL SCAN. This scan solution synchronises one or multiple excelliSCAN scan heads and one or two mechanical XY-stages, each with two servo axes. That turns the system into a highly dynamic scan solution for micromachining large workpieces at maximum accuracy.

In Munich, an XL SCAN was shown for the first time with an integrated excelliSHIFT Z-axis. Because this galvo-based Z-axis works completely without transmissive elements, it keeps up with the scan head's fast dynamic performance and flexibly guides the laser spot. This will allow users to precisely process even 3D-shaped large-area workpieces. The user inputs the desired three-dimensional contour and can let processing be simulated beforehand. Potential applications include processing of windshields and surface structuring of mould tools. Initial test systems with integrated Z-axes will be deliverable starting in 2020.



WWW.SCANLAB.DE

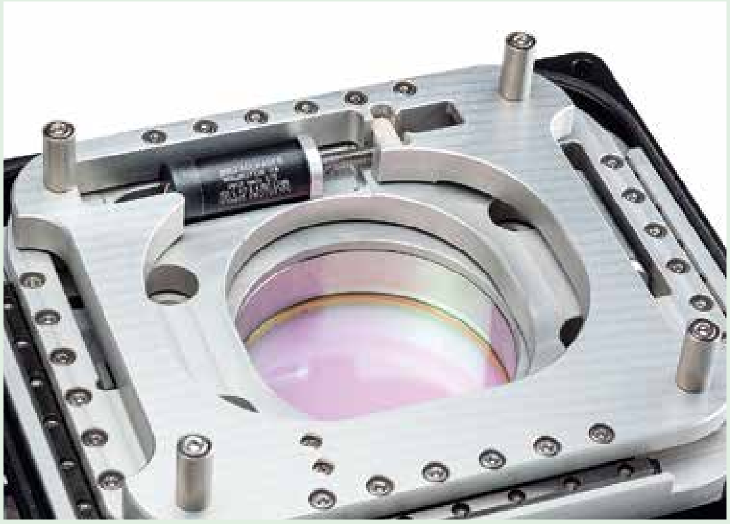
Multispot optics for laser soldering and welding

Laser beams can melt and even vaporise metals highly efficiently and very precisely. For this reason, they are increasingly used as a tool for joining components, namely for welding and soldering, e.g. in the automotive industry. Normally, laser devices – like conventional welding torches – have a single focal point or 'spot'. Laserline has now developed multispot optics for laser soldering and welding, which also allows particularly difficult materials to be processed. Motors from Faulhaber help to ensure that the spot energy is distributed correctly.

An optics module is responsible for ensuring precise alignment of the spots. It contains various optical elements that selectively modify the laser beam. The collimation lens aligns the divergent laser beams leaving the fibre-optic cable, so that they run parallel to each other. A so-called homogenisation array generates a square-shaped main spot, while other optical elements split the beam and generate additional spots. In the case of soldering, two leading spots are generated to the front and side of the main spot. To obtain the desired clean seam at the end of the process, the power distribution between the main and leading spots as well as between the leading spots must be precisely set. How the laser power is distributed to these spots depends on the position of the optical elements. By moving these elements in the x- and y-axis, it is possible to achieve the precise distribution of laser power required for the task in question.

To deep-weld aluminium, for example, a small, intensive spot can be positioned inside the weaker large spot. To weld together metal sheets of different thicknesses, two spots can be adapted to the respective material. This can be done during the running process because the elements in the Laserline optics module are moved by motors. The edge length of this square-shaped module is 12 cm, with a depth of 5 cm. The optical elements and a sophisticated mechanical system are housed in this small space, so there isn't much room left for the motors. The primary requirement placed on the drives is therefore compactness.

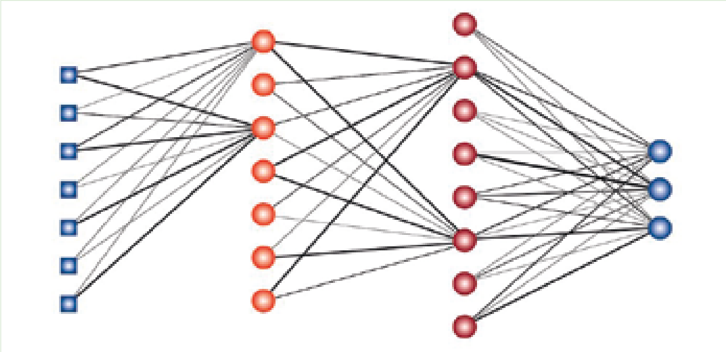
Brushless DC-servomotors of the 1226 B Faulhaber series with 12 mmm diameter were selected, with lead screws directly bonded to the motor shaft and without shaft coupling. This provides a very compact drive which nevertheless reliably delivers the required power and speed. The laser optics are mounted to a robot arm during soldering and welding; this robot arm moves the laser optics to the required position. The optics must withstand considerable dynamic loads that act on the motors and can trigger unwanted changes in position. This is no problem for the Faulhaber motor because it detects its current position using the integrated Hall sensor and if necessary readjusts – at the latest when the laser is positioned on the seam. This gives the certainty that any incorrect positioning is ruled out.



The edge length of the square-shaped Laserline optics module is only 12 cm, with a depth of 5 cm, so the primary requirement placed on the drives is compactness.

WWW.LASERLINE.COM
WWW.FAULHABER.COM

New deep learning training at High Tech Institute



Last June, High Tech Institute organised its first edition of the 'Introduction Deep Learning' training. Deep learning is one of the fastest developing fields in artificial intelligence. During the one-day masterclass participants were introduced to deep learning trends and techniques by lectures as well as exercises. The masterclass is intended for software and hardware engineers, application and process engineers, system architects and managers with a technical background. Prerequisites are basic mathematics skills and basic (Python) programming skills. The next edition will be on 19 November 2019, in Eindhoven (NL).

WWW.HIGHTECHINSTITUTE.NL/INTRODEEPLEARNING

Photonics Applications Week sneak preview

The DSPE Optics Week (see page 72) is part of the Photonics Applications Week, which takes place from 30 September to 4 October 2019 in Eindhoven (NL). Below a sneak preview of other highly interesting events that are organised during this week.

30 September: Internet of Things and Li-Fi Event
Workshop about how Li-Fi enables Internet of Things (IoT) in providing networked mobile communication using light. Optical Wireless Communication (OWC) is very well positioned to provide high-speed, latency-free communication. By networking multiple OWC-enabled access points, one can build a new mobile communication system integrated with lighting. At the moment, first generations of Li-Fi systems, based on visible or infrared LEDs, are being rolled out, but the potential for OWC goes much further.

1 October: Photonic Integration Conference
During this one-day executive conference (5th edition), global experts will explain why integrated photonics is vital to keep our world communicating and connected in the 21st century. The integration of optical components and functions into large-scale photonic integrated circuits will result in miniaturisation and a decrease of cost price, which will lead to more applications in agrifood, healthcare & life sciences, 5G, Internet of Things, M2M, manufacturing, autonomous systems, data centres, cloud computing, and more. It is the most energy-efficient technology to scale up services for all these applications.

1 October: Agrifood Photonics Workshop
Foodtech Brainport and ZLTO will organise an event where the agrifood and the photonics industry will meet and discuss the photonics-related needs of agrifood professionals.

2 October: Automotive Photonics Conference
Conference about photonics-based developments in all automotive areas; from powertrain, through lighting to driver assistance and vision systems. Presentations will feature, among others, lidar, solar panels, wireless Terahertz-communications, and smart displaying.

3 October: Workshop How photonics helps to improve Health
The benefits of photonics in healthcare are plentiful. The technology is non-invasive and has no adverse side effects, as it only deploys a light beam for diagnosis and treatment. Medical devices based on photonics technology are small and easy to handle, making the treatment highly portable.

WWW.PHOTONICSAPPLICATIONSWEEK.COM
WWW.IOTEVENT.EU
WWW.PHICONFERENCE.COM
WWW.AUTOMOTIVEPHOTONICSCONFERENCE.COM

UPCOMING **EVENTS**

16-18 September 2019, Nantes (FR)
SIG Meeting Advancing Precision in Additive Manufacturing
Special Interest Group Meeting hosted by euspen in collaboration with ASPE, focusing on, a.o., dimensional accuracy and surface finish from AM, design for precision, standardisation, metrology, and integration of AM into an overall holistic manufacturing process.

WWW.EUSPEN.EU

23-26 September 2019, Rhodes (GR)
MNE 2019
The 45st international conference on micro- and nanofabrication and manufacturing using lithography and related techniques is devoted to progress in advanced patterning, nanofabrication for functionality, nanodevices/MEMS and nanofabrication for life sciences (lab-on-a-chip).

WWW.MNE2019.ORG

25 September 2019, Eindhoven (NL)
Software-Centric Systems Conference
Devoted to complex software development.

WWW.SOFTWARECENTRICSYSTEMS.COM

30 September, 1-3 October 2019, Eindhoven/Delft (NL)
Optics & Optomechanics Week
Unique event comprising the DSPE Optics and Optomechanics Symposium & Fair, on Monday 30 September, and a new three-day optomechanics system design course, on 1-3 October. For more information, see page 72.

WWW.DSPE.NL

1 October 2019, Eindhoven (NL)
Photonic Integration Conference
Fifth edition of conference that covers the integration of photonics with micro-electronics, cases in a variety of application areas, business models, and tools for development and packaging. Part of the Photonics Applications Week, also featuring the Photonic Integration Conference, the Automotive Photonics Conference, and workshops on IoT and Li-Fi, agrifood photonics, and photonics helping to improve healthcare. See also the News section on page 79 ff.

WWW.PHICONFERENCE.COM

WWW.PHAPPSWEEK.COM

8-10 October 2019, Karlsruhe (GE)
DeburringEXPO
Third edition of trade fair for deburring technology and precision surface finishing. See also the article on page 53 ff.

WWW.DEBURRING-EXPO.COM

9-10 October 2019, Glasgow (UK)
SIG Meeting Precision Engineering for Sustainable Systems
Euspen's first Special Interest Group (SIG) Meeting on the role of precision engineering for renewable energy covers four themes: wind, solar and oceanic energy as well as energy storage.

WWW.EUSPEN.EU

21-22 October 2019, Delft (NL)
Adaptive Optics school
Part of the XII Workshop on Adaptive Optics for Industry and Medicine (21-25 October). Focus of the school is on the fundamentals of adaptive optics and emerging applications in opthalmology, microscopy, space and lithography.

WWW.AOIMXII.ORG/DELFT/SCHOOL

22-24 October 2019, Stuttgart (DE)
Parts2clean 2019
International trade fair for industrial parts and surface cleaning.

WWW.PARTS2CLEAN.COM

28 October - 1 November 2019, Pittsburgh (PA, USA)
34th ASPE Annual Meeting
Meeting of the American Society for Precision Engineering, introducing new concepts, processes, equipment, and products while highlighting recent advances in precision measurement, design, control and fabrication.

WWW.ASPE.NET

4-8 November 2019, Leiden (NL)
LiS Academy Manufacturability course
5-Day course targeted at young professional engineers with a limited knowledge of and experiences with manufacturing technologies and associated manufacturability aspects. See also page 46 ff.

WWW.LISACADEMY.NL

7 November 2019, Delft (NL)
TNO Optical SATCOM Day
This conference features recent developments, future challenges and technology roadmaps for optical satellite communication, inluding high-throughput optical ground stations, free-space QKD systems, multi-beam optical terminals and integration of satcom into 5G.

INFO-OPTICALSATCOMEVENT@TNO.NL

13-14 November 2019, Veldhoven (NL)
Precision Fair 2019
Nineteenth edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum.

WWW.PRECISIEBEURS.NL

21 November 2019, Utrecht (NL)
Dutch Industrial Suppliers & Customer Awards 2019
Event organised by Link Magazine, with awards for best knowledge supplier and best logistics supplier, and the Best Customer Award.

WWW.LINKMAGAZINE.NL

27-28 November 2019, Berlin (DE)
SIG Meeting Micro/Nano Manufacturing
SIG Meeting hosted by euspen, focusing on novel methodological developments in micro- and nanoscale manufacturing, i.e., on novel process chains including process optimisation, quality assurance approaches and metrology.

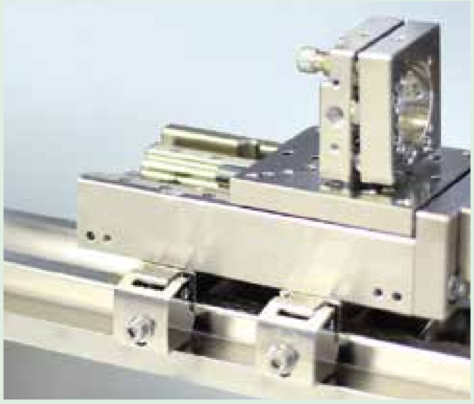
WWW.EUSPEN.EU

Towards extreme-ultra-high vacuum

OWIS®, a German supplier of optical beam handling systems and positioning systems, is consistently expanding its portfolio of vacuum-compatible products. The foundation was laid in 1980 with a standard product range of positioners and optical components. At the beginning of the 2000s, OWIS started developing products for vacuum applications in the pressure range of $1 \cdot 10^{-6}$ mbar, followed by products for the pressure range of $1 \cdot 10^{-9}$ mbar and, since this year, of $1 \cdot 10^{-11}$ mbar, the so-called extreme-ultra-high vacuum (XUHV).

The product line for the entire vacuum range includes, inter alia, manual and motorised linear stages as well as optical components, rails and slides. Customised solutions are also possible. All parts are cleaned, mounted, measured, tested and packed in the OWIS cleanrooms, and each delivered unit is accompanied by a certificate which attests the vacuum qualification.

WWW.OWIS.EU



Fast alignment for photonics-fibre coupling

In the packaging and testing of photonic components, the optical alignment must be repeated at multiple process steps and, therefore, plays a decisive role in production economics. PI's new F-712.HU1 fibre alignment system speeds up this process and is particularly suited for coupling entire fibre arrays to silicon photonics structures and photonic integrated circuits. Speed and, therefore, the economic efficiency of coupling processes are improved by typically two orders of magnitude whether during testing or in packaging.

The system combines the proven H 811 hexapod for large travel ranges with the fast-acting P 616 NanoCube® nanopositioner for accuracies in the single-digit nanometer range. In combination, the two subsystems offer nine degrees of freedom (DoFs) for motion purposes. The high dynamics and wear-free working principle of the NanoCube also allow continuous tracking for dynamic compensation of drift effects during coupling or curing of adhesives.

The inherent parallel-kinematic design of the hexapod provides high system stiffness in all its six DoFs. The brushless DC motors in the struts of the hexapod allow for travel ranges of ± 17 mm or tilting of up to ± 21°. The pivot point can be freely defined by using software, allowing rotations about an optical axis, focal point, beam waist or other desirable position. The P-616 NanoCube, which also has a parallel-kinematic design, offers travel ranges of up to 100 µm in X, Y, and Z direction with a bidirectional repeatability of below 15 nm. Flexure guides and all-ceramic PICMA® actuators guarantee a long lifetime.

PI's sophisticated scanning routines are firmware-based, that is, they are integrated directly into the controllers of the two motion systems. In comparison to PC-based software, this makes the entire scanning process significantly easier and quicker as there are practically no more command latencies. All calculations for position control are carried out in the controllers with the servo clock rate. The integrated rotational scanning routines also make the optimisation of fibre arrays with all channels possible. Multiple alignments can proceed in parallel, eliminating time-consuming sequences and loops.

WWW.PHYSIKINSTRUMENTE.COM

Telescopic cleanroom for CERN

Part of CERN's Prevessin site in France is dedicated to producing beam intercepting devices, to be used in different particle accelerators across its world-leading particle physics laboratory. This involves the assembly of highly specialised parts such as collimators to clean the halo of proton beams, beam stoppers and beam dumps to absorb the energy of particles. These beam intercepting devices are built in sections to allow parts to be decommissioned and removed for servicing & maintenance.

With these highly calibrated pieces of machinery there is a risk that exposed parts could be affected by particulate contamination during assembly or servicing. Conducting the assembly inside a cleanroom would reduce the risk of particulate contamination – but some parts are up to 6 m in length and 30 tonnes in weight.

Collaborating with CERN scientists, Connect 2 Cleanrooms designed a telescopic cleanroom with three moveable modules that extend on guide rails from a closed position, tripling the floor space. So, when the larger beam intercepting device sections have been craned into the servicing bay, the cleanroom can be extended, laterally enveloping the part. Doors can then be closed and locked in position for safety and integrity. In its closed position the cleanroom can be used for work on smaller parts, so all the beam intercepting device components can be assembled in the same environment. The softwall cleanroom houses six HEPA filter fan units in total, to maintain the clean air integrity no matter what the configuration.

WWW.CONNECT2CLEANROOMS.COM

VDL system architect named as first fellow at UT

Jaap Brand, working at VDL ETG, has been appointed fellow in the Precision Engineering chair held by professor Dannis Brouwer, Faculty of Engineering Technology at the University of Twente (UT). He is the first official fellow starting at the UT. Brand is going to conduct research into design principles for accurate positioning and movement.

Together with Ph.D., PD.Eng. and M.Sc. students, Brand will continue to try making the design principles methodology into science. In addition, he is going to reinforce the wider cooperation between the UT and VDL Group. Both parties expressed their intention to eventually establish a strategic cooperation. As a system architect at VDL ETG Technology & Development in Almelo, Brand is concerned with the development of new machines for VDL customers. He is also working at further developing the competencies of vacuum technology.

From left to right; Geert Jakobs (managing director VDL ETG Technology & Development), Jaap Brand (fellow and system architect, UT and VDL ETG), Dannis Brouwer (professor of Precision Engineering, UT) and Victor van der Chijs (president Executive Board, UT).

WWW.UTWENTE.NL/EN/ET/MS3/RESEARCH-CHAIRS/PE
WWW.VDLETG.COM

KMWE acquires ATM

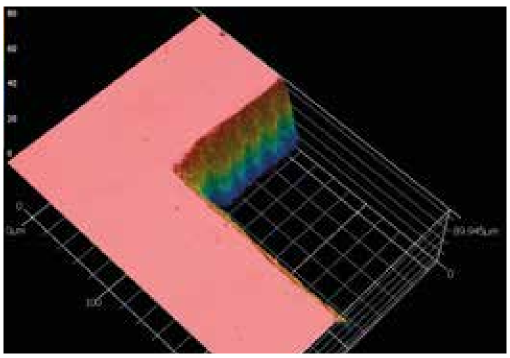
KMWE, headquartered at the Brainport Industries Campus in Eindhoven (NL), has acquired ATM, located in Oirschot (NL). After its recent relocation and rapid growth, ATM had been looking for a partner that could help shape its future development. The acquisition is the next step in realising KMWE's strategy to further grow and bring in different areas of expertise. ATM will continue to operate independently under its own name.
KMWE offers solutions for the engineering and assembly of high-grade modules and systems and the production of complex components. ATM specialises in high-quality surface treatments of aluminium, stainless steel and titanium, as well as the high-precision cleaning of various materials.

WWW.KMWE.COM
WWW.ATMOIRSCHOT.NL

Wide-range taper angle control in ultrafast laser micromachining

6-D Laser, a member of ALIO Industries' motion control and micromachining family of companies, has developed an integrated ultrafast laser micromachining system that combines high-speed galvo scanning with the novel positioning capabilities of ALIO's Hybrid Hexapod®. This hexapod takes a different approach to traditional 6-DoF (6 degrees of freedom) positioning devices, and exhibits much higher performance at extremely competitive prices. Rather than 6 independent legs (and 12 connection joints), ALIO's approach combines a precision XY monolithic stage, tripod, and continuous rotation theta-Z axis to provide superior overall performance, so ALIO claims.

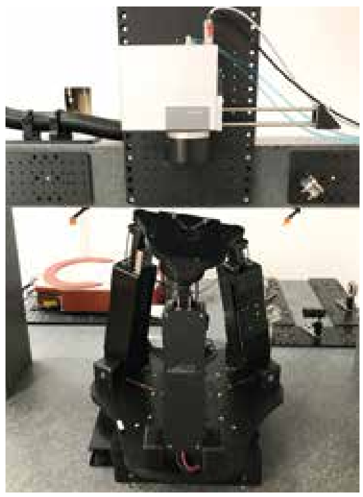
The combination of serial and parallel kinematics at the heart of ALIO's 6-D Nano Precision® is characterised by orders-of-magnitude improvements (when compared to traditional hexapods) in precision, path performance, speed, and stiffness. The hybrid hexapod also has a larger work envelope than traditional hexapods with virtually unlimited XY travel and fully programmable tool centre point locations. It has less than 100 nm Point Precision® repeatability, in 3D space.



3D laser-scanning confocal microscope image of a sapphire wafer (450 μm thick). A square feature was machined in the wafer with an ultrafast laser while controlling the AOI with the hybrid hexapod. The result is a wall taper angle of less than 0.5° degrees over a total feature size of 10 mm x 10 mm.

Introducing an integrated ultrafast laser micromachining system that combines the positioning capabilities of the hybrid hexapod, with high-speed optical scanning, leads to a system that can process hard, transparent materials with wide-range taper angle control for the creation of high-aspect-ratio features in thick substrates, without limitations on the feature or field size.

Ultrafast laser ablative processes, which remove material in a layer-by-layer process, result in machined features that have a significant side-wall taper. For example, a desired cylindrical hole will have a conical profile. Taper formation is difficult to avoid in laser micromachining processes that are creating deep features (> 100 μm). Precision scanheads can create features with near-zero-angle side walls, however, they are limited to small angles of incidence (AOI) and small field sizes by the optics in the beamline. 6-D Laser's micromachining system controls the AOI and resulting wall taper angle through the hybrid hexapod motion system, and the programmable tool centre point allows for the control of the AOI over the entire galvo-scan field, enabling the processing of large features.



High-speed galvo scanning with the novel positioning capabilities of the ALIO Hybrid Hexapod.

WWW.ALIOINDUSTRIES.COM

Ultra-clean vacuum knowledge in high demand

There is a continued interest in high-quality practical design knowledge for ultra-clean systems. This is the conclusion of High Tech Institute and Mechatronics Academy based on the increasing number of participants they are welcoming for their training "Basics & design principles for ultra-clean vacuum".

Last April, the training partners organised a new tailor-made in-company version of their ultra-clean vacuum training for an onboarding program of a large OEM in the south of the Netherlands. This exclusive edition is the first of a series and it received excellent marks, because of, e.g., the good balance between theory and practice.

"Designing modules for use in ultra-clean vacuum is a challenging task", says Adrian Rankers of Mechatronics Academy. "Our training is a valuable source for getting up to speed in that field. Our trainers are working full-time in the industry, and I am very happy that they want to share and transfer their valuable knowledge with such great enthusiasm."

Topics include vacuum fundamentals, flow of gases, total and partial pressure, pumps, leak testing, engineering aspects, mechatronics in vacuum, design for qualification and system design and budgeting. Next open-enrolment edition will start on November 4, 2019.

WWW.HIGHTECHINSTITUTE.NL/UCV

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Cleanrooms

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Brecon Group can attribute a large proportion of its fame as an international cleanroom builder to continuity in the delivery of quality products within the semiconductor industry, with ASML as the most important associate in the past decades.

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SEGULA Technologies Nederland BV develops advanced intelligent systems for the High Tech and Automotive industry. As a project organisation, we apply our (engineering) knowledge to non-linear systems. This knowledge is comprised of systems architecture and modelling, analysis, mechanics, mechatronics, electronics, software, system integration, calibration and validation.

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The LiS is a modern level 4 MBO school with a long history of training Research instrumentmakers. The school establishes projects in cooperation with industry and scientific institutes thus allowing for professional work experience for our students. LiS TOP accepts contract work and organizes courses and summer school programs for those interested in precision engineering.

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MTA is an high-tech system supplier specialized in the development and manufacturing of mechatronic machines and systems.
Our clients are OEM s in the Packaging, Food, Graphics and High-tech industries.

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MI-Partners is active in R&D of high-end mechatronic products and systems. We are specialised in concept generation and validation for ultra-fast (>10g), extremely accurate (sub-nanometers) or complex positioning systems and breakthrough production equipment.

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Etchform is a production and service company for etched and electroformed metal precision parts.

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Micro Drive Systems

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maxon motor is a developer and manufacturer of brushed and brushless DC motors as well as gearheads, encoders, controllers, and entire precision drive systems. maxon motor is a knowledge partner in development. maxon drives are used wherever the requirements are particularly high: in NASA's Mars rovers, in surgical power tools, in humanoid robots, and in precision industrial applications, for example. Worldwide, maxon has more than 2,500 employees divided over sales companies in more than 40 countries and eight production locations: Switzerland, Germany, Hungary, South Korea, France, United States, China and The Netherlands.

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Micro Drive Systems

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FAULHABER specializes in the development, production and deployment of high-precision small and miniaturized drive systems, servo components and drive electronics with output power of up to 200 watts. The product range includes brushless motors, DC micromotors, encoders and motion controllers. FAULHABER also provides customer-specific complete solutions for medical technology, automatic placement machines, precision optics, telecommunications, aerospace and robotics, among other things.

Physik Instrumente (PI)
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Motion Control Systems

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Aerotech's motion control solutions cater a wide range of applications, including medical technology and life science applications, semiconductor and flat panel display production, photonics, automotive, data storage, laser processing, electronics manufacturing and testing.

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Newport Spectra-Physics B.V. is a subsidiary of Newport, a leader in nano and micro positioning technologies with an extensive catalog of positioning and motion control products. Newport is part of MKS Instruments Inc., a global provider of instruments, subsystems and process control solutions that measure, control, power, monitor, and analyze critical parameters of advanced processes in manufacturing and research applications.

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Motion Control Systems

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Opt for state-of-the-art motion control systems from the world's leading provider PI. Developed, manufactured and qualified in-house by a dedicated and experienced team. Our portfolio includes a wide and deep range of components, drives, actuators and systems and offers infinite possibilities in motion control on a sub-micron and nanometer scale.

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Optical Components

molenaar optics

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As Application Centre we possess the required knowledge to support our clients in every phase of development and process selection.
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Piezo Systems

HEINMADE supplier piezo system solutions

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As partner for piezo system solutions, HEINMADE serves market leaders in the high tech industry. Modules and systems are developed, produced and qualified in-house. HEINMADE distributes Noliac piezo components.

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Piezo Systems

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High-precision piezo systems and applications that perform on a sub-micron and nanometer scale: world leader PI develops, manufactures and qualifies these in-house. With a broad and deep portfolio with infinite possibilities in components, drives, actuators and systems at hand, our experienced team is dedicated to find the best solution for any motion control challenge.

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Ultra-Precision Metrology & Engineering

IBS Precision Engineering

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IBS Precision Engineering delivers world class measurement, positioning and motion systems where ultra-high precision is required. As a strategic engineering partner to the world's best manufacturing equipment and scientific instrument suppliers, IBS has a distinguished track record of proven and robust precision solutions. Leading edge metrology is at the core of all that IBS does. From complex carbon-fibre jet engine components to semiconductor chips accurate to tens of atoms; IBS has provided and engineered key enabling technologies.

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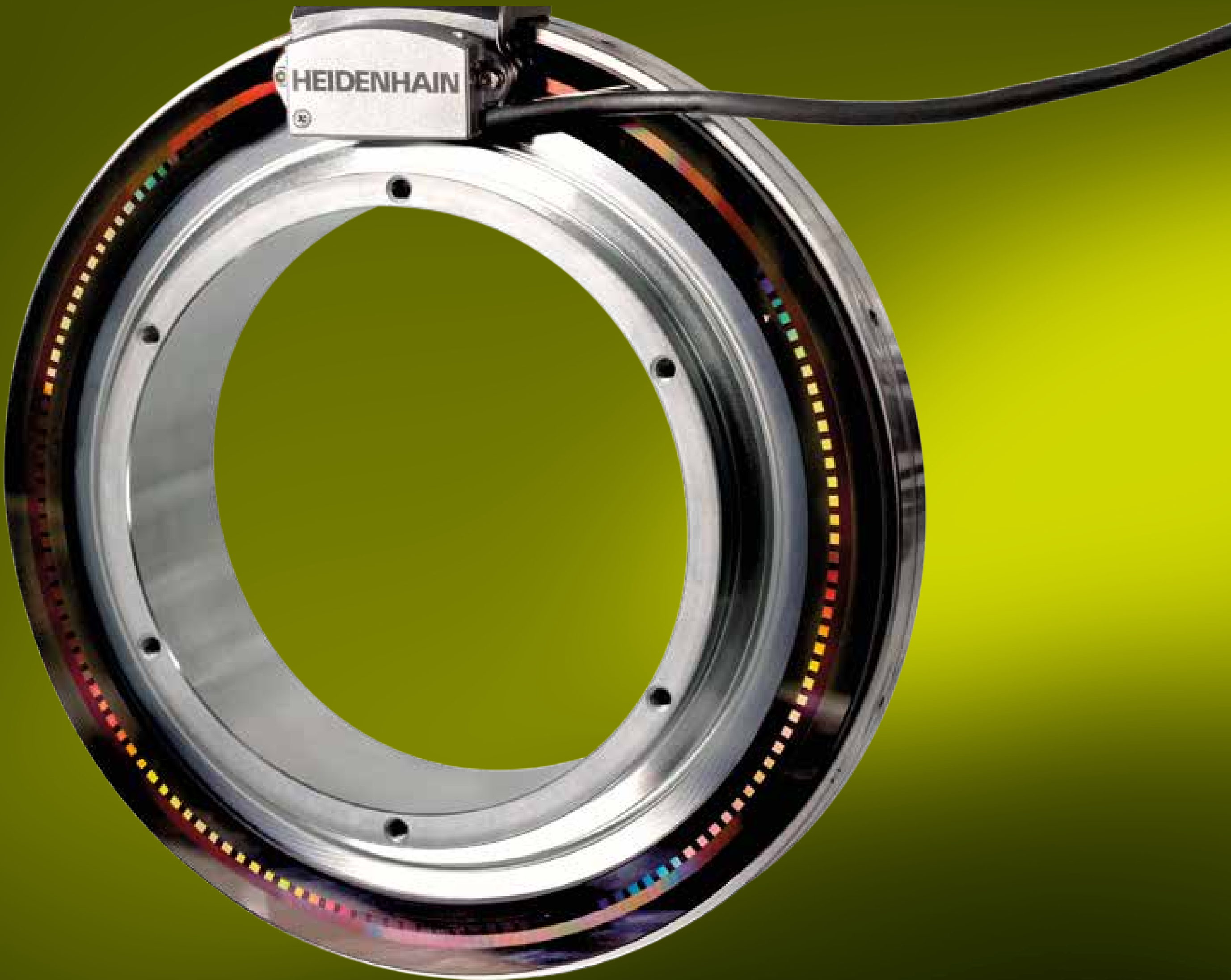
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