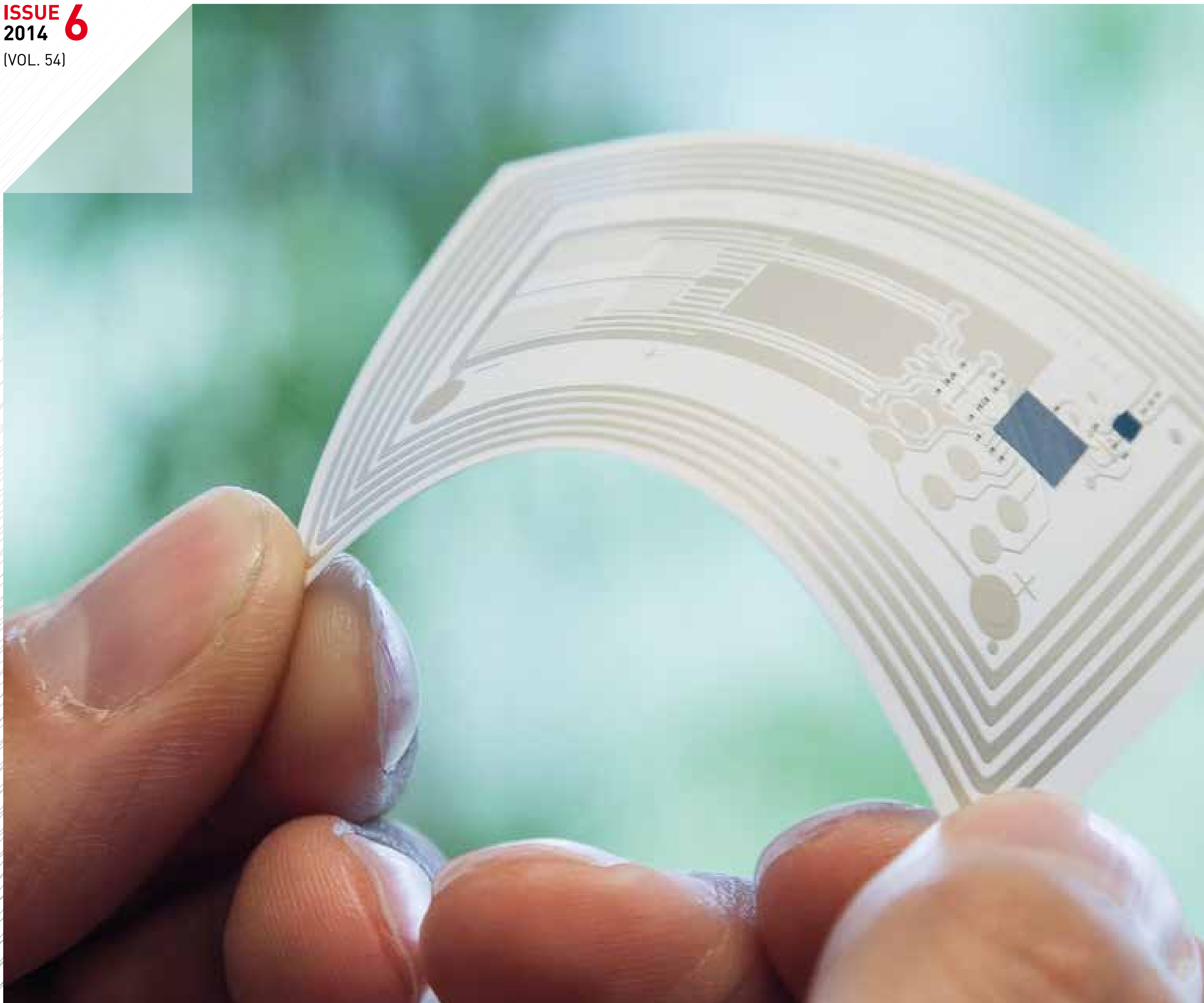
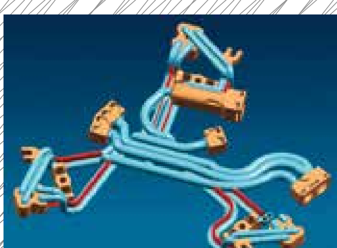
PROFESSIONAL JOURNAL ON PRECISION ENGINEERING

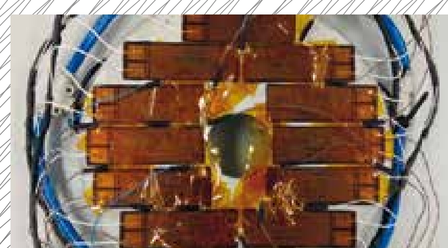
µ MIKRONIEK

ISSUE 6
2014
(VOL. 54)



- SPECIAL ISSUE: **ADDITIVE MANUFACTURING** – DESIGN AND REALISATION
- **2014 PRECISION FAIR** REPORT
- **ULTRASOUND** PRECISION CLEANING





Mikroniek is a publication of the DUTCH SOCIETY FOR PRECISION ENGINEERING www.dspe.nl

DSPE

PUBLICATIONINFORMATION

Objective
Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics.
The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

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Subscription costs

The Netherlands	€ 70.00 (excl. VAT) per year
Europe	€ 80.00 (excl. VAT) per year
Outside Europe	€ 70.00 + postage (excl. VAT) per year

Mikroniek appears six times a year.

ISSN 0026-3699

The main cover photo (flexible circuit with flip-chipped components) is courtesy of Marc Koetse/Holst Centre.

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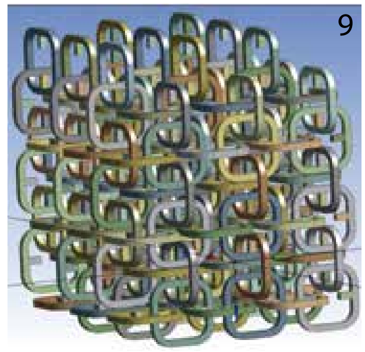
ISSUE 6
2014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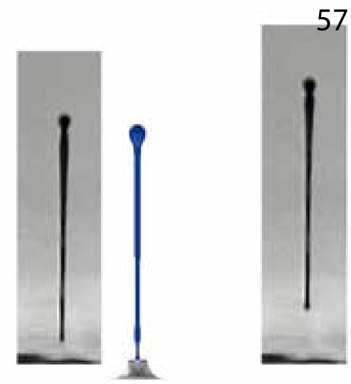
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FEATURES

YOU CAN ALWAYS GET WHAT YOU WANT

Most parts currently applied in production machines and equipment are manufactured in a 'traditional' way; a sequence of machining process steps, executed on various metal working machines. This sequence will lead from a block of raw material towards a high-quality machine component. Numerous part shapes are possible; however, limitations apply with regard to the construction and geometry of the machine tools used. So, you can't always get what you want! But things are changing…

Developments in Additive Manufacturing (AM) are occurring rapidly and will enable us to overcome geometrical limitations as outlined above. The latest 3D printers enable components with almost unlimited freedom in design. These opportunities require a new way of thinking by the designer, taking advantage of the new possibilities on offer. Most engineers and designers have grown up with knowledge of conventional production technology (subtractive manufacturing) and are unfamiliar with the features of AM technology.

Additive Manufacturing enables tailor-made (personalised) components, like fashion and art articles, but also custom-made medical implants and prostheses. The freedom in shape as offered by AM technology yields components of variable material density (topology) and curved holes. AM also reduces special manufacturing tooling (moulds, jigs, fixtures) and keeps work preparation data to a minimum, enabling a considerable reduction in time-to-market.

Moreover, AM enables integration of components. As a result it will be possible to replace multiple machined components including accurate interfaces with a single integrated component where only the functional surfaces might require additional machining. This will not only lead to cost savings, but also has the potential of bringing part functionality to a higher level. Consider the possibilities for spatial trusses to locate bearings and linear guides in both a light and stiff way.

To make engineers aware of all AM benefits re-education is necessary. New initiatives are being undertaken at universities and technical colleges for this purpose; consider the many FabLabs (approx. 60 in the Benelux countries), the Centres of Expertise at universities of applied sciences (approx. 15 in the Netherlands) and the recent FieldLabs initiative (approx. 10 in the Netherlands). Initiatives have been undertaken to develop 3D printers for organic substances (food, drugs, organs, body parts), electronics (printed electronics), aircraft and buildings.

Further improvements to 3D printers for polymers or metals are expected with respect to increasing print accuracy, improving surface finish quality, increasing build speed, enabling multi-material (hybrid) printing, and integrating (printed) sensors and actuators. New business models are needed to take full advantage of this 3D printing revolution. And, now you can buy a software package at Amazon that enables you to design your own favourite gift on your own PC. Then you can upload your design and you will receive your printed gift in a week's time. You can always get what you want!

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INNOVATING, CREATING AND MANUFACTURING IN ADDITIVE STYLE

Additive Manufacturing (AM), or 3D Printing (3DP), is without doubt the most innovative range of emerging computer aided technologies within an ever expanding 'smart industry'. Numerous, widely differing 'building methods' enable digital development of better products, with faster launch times. Today's high-performance AM is even eclipsing yesterday's limits in producing components near net shape, both for industrial and DIY (art or hobby) purposes. For a long time, hype floating on thin air, however, AM is now well on its way up within the professional and high-end consumer markets.

AUTHOR'S NOTE

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JAN WIJERS

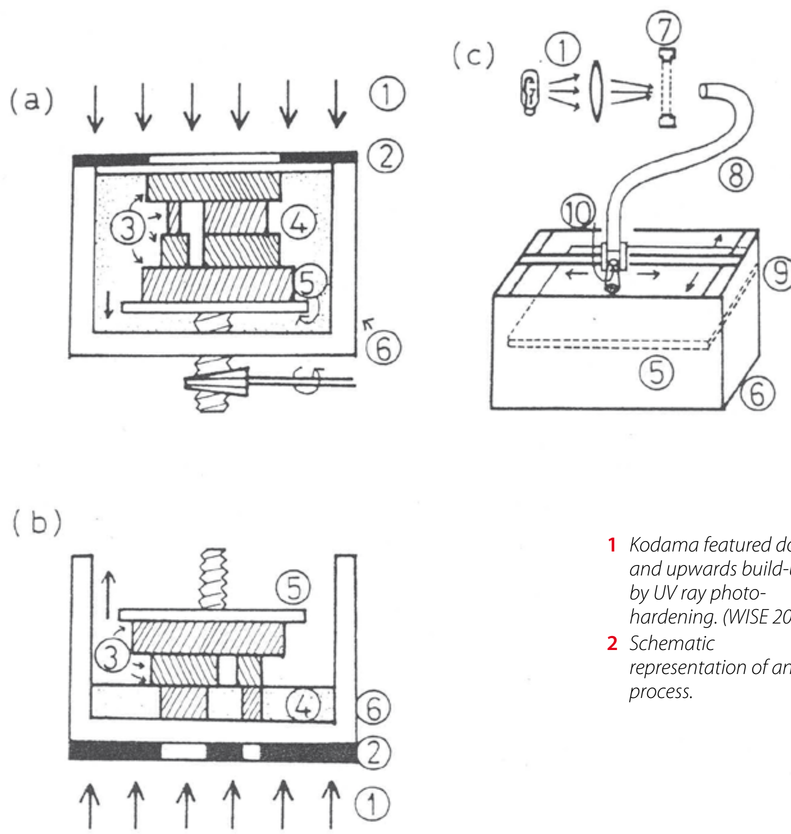
Sequential layering principle

For a Rapid Prototyping and Manufacturing (RP&M), AM or 3DP operation the initial, easy-going start of data generation occurs digitally. Generally, a 3D CAD-model originates from a surface or solid modelling software package. Furthermore, a CT, MRI or optical scan can supply the geometrical data (cloud) needed. This set of data is converted to an STL file – an unambiguous description of the total product volume based on a mesh of triangular facets – and sliced into horizontal plies, corresponding to a specific layer thickness. Fine triangles allow for improved accuracy; larger ones for faster component build-up. Next, an AM system is able to make the build-up sequence by repeatedly depositing, or binding from the bottom-most cross section up.

(Source: EOS)

With this kind of innovative manufacturing the user has full control of the complete process chain, whether in fabricating a personalised one-of-a-kind product, special designs or small-scale production on-demand. No expensive, prefabricated tools as moulds or dies with long lead-times are needed, as in traditional mass-production of relatively cheap, identical components. Most additive processes in the 21th century are a far cry from mere prototyping; they even manufacture near-net-shape products – approximately up to 99.5% solid. In an absolute sense though, they do not excel in pure (building) speed, only when taking into account the full life cycle.

The major difference between most of the widely accepted AM processes nowadays can be found in the basic way the layer-wise build-up action is actually performed; the process-specific 'tool' (laser beam, UV light, extrusion system, etc.); and the basic material being used – either powder, liquid, paste, polymer resin or sheet material.



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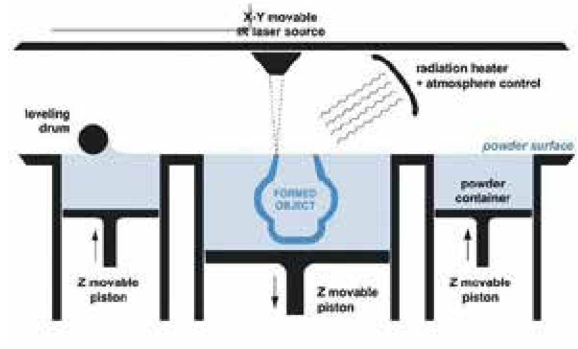

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1 *Kodama featured down- and upwards build-up by UV ray photo-hardening. (WISE 2000)*
2 *Schematic representation of an SLS process.*

History

Basically, one of the main principles of additive processes – the curing of a chemical material – was already patented some thirty years before the first patent was granted to Chuck Hull for a functioning stereolithography machine (1986). Shortly after laying hands on his original corporate cornerstone he founded 3D Systems, still one of the American forerunners in industrial and consumer solutions (recently acquiring Phenix Systems (Fr) and LayerWise (Be), to expand the metal AM section). That Hideo Kodama's new Japanese method for automatically fabricating 3D plastic models was already received for publication on 2 August 1981 is not widely known (Figure 1).
Henceforth, over many, many years, forecasts were made by involved players and RP&M 'addicts' about the upcoming explosive growth inside the AM technology branch, regards machine tools and applications and the rapid decline of the price of expensive apparatus and basic materials. Expectations which were barely realistic, and only since a few years a fact within the DIY and artistic fields, with assembly kits such as 'MakerBot' or 'MultiMaker'.

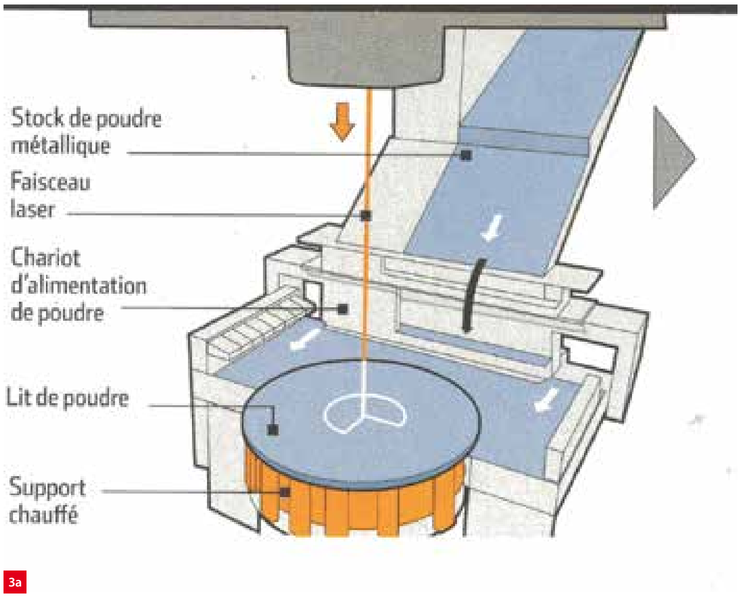
In the early days this new type of 'machine' was based on existing paper printer technology: on the outside a neat desktop design, but on the inside sophistication and precision were lacking, with vibration and no stiff machine configuration. Just one process – SGS: Solid Ground Curing from Cubital – made it to an expensive and rather service-unfriendly, but professional, configuration. The exclusive license of Maho – the 'M' in DMG – actually proved that.

This sophisticated and parallel working system functioned like some high-end plain copiers with an electrostatic toner mask on a glass disc through which a complete layer of plastic powder was exposed to UV light for solidification. The Solider had all the necessary features of an autonomous industrial AM machine, including even nesting capability to use the total volume for a mix of different products in one run. Actually, it was one of the very early types of hybrid machinery, as the resin was extracted after which the remaining openings were filled with a water soluble wax as support-structure and mechanically milled down to 100 μm thickness.

Gradually RP&M became more and more popular as an effective way to reduce costs and time in producing models, prototypes (to see, feel, fit, test and validate) and pre-series products before rapidly launching products successfully onto the market. Over these 25 years quite a number of breakthroughs have been achieved regarding efficiency and quality up to professional 3DP standards of producing almost any shape in any material. With this smart design-driven tool for innovation, mastering complexity regards geometry and structure isn't an issue anymore, no matter which one of the long line of AM techniques does the job. For example, 'bionic' titanium components – designed after nature – are now flying in the Airbus 350XWB.

Industrial breakthrough

Owing to low-priced, self-assembled installations resembling the early primitive SLS (Selective Laser Sintering, see Figure 2) and LOM (Laminated Object



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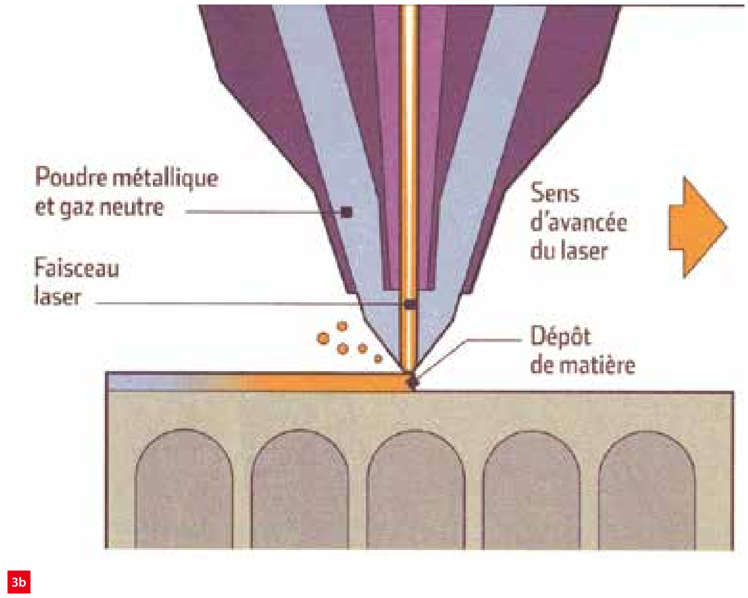

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Manufacturing) prototypes, high-performance computers, open software and expanding cyberspace, consumer 3DP is now exploding within the media.

One indication that state-of-the-art AM is coming of age in a more industrial way is the fact that numerous front-runners – in aerospace, medicine, motorsports, high-tech industry, machine tool building and automotive – recently brought their AM offsprings out in the open, in one way of the other; spreading out to the die & mould industry. Just to name a few: a ballistically tested printer was sent to the International Space Station; GE announced the production of AM components in their future Lean aircraft engine; HP has just launched its next-generation printer (Multi Fusion Jet) which will be available early next year.

Another rapidly spreading hybrid development (Figure 3) is selective laser powderbed melting or laser cladding (> 5 times faster deposition rate) of a metallic object and milling it down on the same, sophisticated 5-axis multi-tasking machining centre, to the high precision and mirror-like surface quality required by the customer.

Aside from standard stand-alone systems, an amazing number of high-ranking AM players (e.g. EOS and Arcam with Electron Beam Melting) and established machine-tool brands are introducing, almost simultaneously, this year either new 3DP or fairly mature hybrid configurations. For example, Matsuura, Mazak, DMG (Figure 4), Sodick and Hurco showed the ability to exchange standard cutters for a dedicated AM or laser head on a specific adapter out of the tool magazine, which lowers initial costs considerably. Government sponsored R&D projects in Germany, the USA, UK and Japan absolutely contributed in setting the sails to the wind. Or is it just speculation to picture a future of solely near-net-shaping, combined with mechanical finishing on one machine tool?

Comparison subtractive – additive

The respective strengths of either conventional machining or AM can easily be deducted in a 1:1 comparison regards several crucial aspects. Certainly an advantage is the mature spot that chipping has attained in industry after more than a century in action, with regard to high-end machine tool engineering, availability of precision up to XXL sizes, high productivity during roughing and superior geometrical and surface quality while finishing.
On the other hand, AM is rather young and still in full evolution regards available systems, technology and applications. It excels in the almost automatic generation of an adequate tool path and corresponding machine commands. A layer-by-layer work piece is produced by

3 *Hybrid developments. (Source: Usine Nouvelle)*
(a) Selective laser powderbed melting.
(b) Laser cladding.
4 *DMG Mori LaserTec65 'growing' an AM workpiece.*

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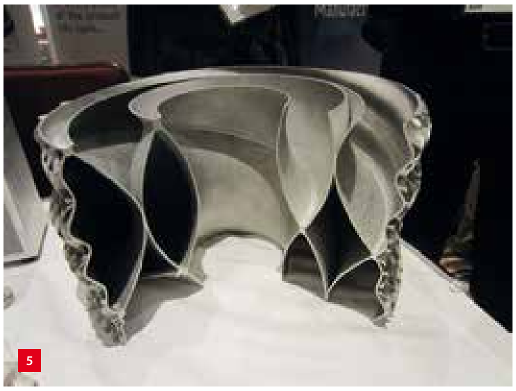


5 *Optimised heat exchanger manufactured with additive help.*

bringing material only where it is wanted and in a near-net-shape state on a single machine, without any clamping problems. It gives the user extreme freedom in material (hard/soft, conducting, insulating, etc.) design, multi-colour, scale and location of production. If finishing is required for highest tolerance, lowest roughness and finest detail, only re-clamping onto a traditional machine tool will provide the solution.

Promising future

Quite a number of unthought-of promises and potentials do exist for the future of AM in a real world-wide digital network – whether or not on shared 'big' data, in a protected 'cloud'. Certainly, the way through the 'magic of additive manufacturing' could also be a perfect medium to attract our youth of today to technology. This despite the basic principles of 'making things' only being superficially touched upon. In reality, several constraints and possible pitfalls require a solution concerning processing, materials and applications. More robustness of the processes will be required. For example, by inline monitoring and some kind of quality assurance the reproducibility and acceptance could increase. Increasing demand for larger components leads to 3D printers with bigger dimensions.

The search for higher deposition or building rates leads to a switch in laser sources onto high-powered fibre lasers and even multiple parallel diode laser heads. Concerning processes that use a heat source causing internal stresses in components, heat treatment is necessary as post-treatment. By cleverly adjusting the build strategy – or the machine settings – while 'growing' a product, thermal effects can be reduced considerably. Shared transfer of knowhow and experience isn't normally an issue, but could become a restraining factor inside the 'internet of things'.

At the moment a substantial number of validated and certificated materials are available as powders (in different sizes ranging from 20 to 100 μm), liquids and pastes. Graded or hybrid material compositions, smart types featuring active and self-healing behaviour, additional coatings on AM surfaces for decoration, or for example, as an additional way of stiffening components, are all being globally researched.

Especially new, complicated, open structures such as lattices and scaffolds that traditionally were impossible to machine in one piece (see the heat exchanger (Figure 5), have to be watched closely, regarding metallurgical properties under actual stress, because of the anisotropic structure of all laminated components. Finally, the low status of standardisation – no matter how complex an issue it is – is being tackled across the globe, already resulting in preliminary and definitive ASM and ISO standards.

As, nowadays, three-dimensional scanning of complete components is widespread, the re-engineering of existing components for rebuilding or upgrading is almost a normal activity, although with the danger of counterfeiting built-in. The challenge is how to manage themes like legal rights, intellectual ownership, privacy, ICT security and costs. The general consensus is that the industry urgently needs more technicians who have in-depth expertise of all mechanical, advanced metallurgical, software and design aspects of AM.

Conclusive remark

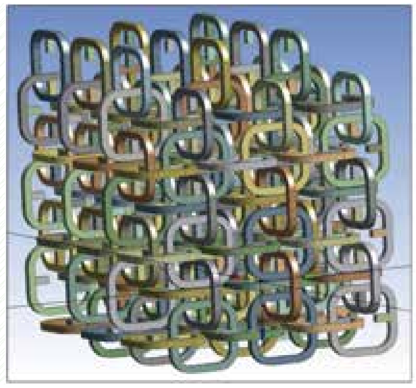
An appropriate prediction is that Additive Manufacturing has a long way to go before – as US president Barack Obama said in February 2013 – "the inherent potential will change the world". It already is changing our world on a relatively small scale: not as the predicted rule breaker in overturning existing economical, manufacturing and logistical business models, but more as a 'game changer'. ■

REFERENCE

Wohlers Report 2014, "3D Printing and Additive Manufacturing State of the Industry", www.wohlersassociates.com

AM FOR HTS PERFORMANCE

Typical system requirements for many precision equipment applications are stated in terms of extremely accurate motion and positioning of a substrate, combined with substrate (thermal) stability within stringent limits. Known bottlenecks in such motion systems concentrate around moving mass, thermal non-uniformity and system complexity. This article presents initial attempts to answer the question as to how AM-enabled freeform design can provide precision mechatronics solutions to such bottlenecks, and pave the way to breakthroughs in system performance.



GREGOR VAN BAARS, JEROEN SMELTINK, JOHN VAN DER WERFF, MAURICE LIMPENS, MARCO BARINK, JAN DE VREUGD, OLEKSIY GALAKTIONOV AND GERT WITVOET

Introduction

Additive Manufacturing (AM) is a rapidly evolving technology [1], with increasing relevance for high-precision systems development. In particular, the inherent freeform nature of AM offers new design possibilities for system engineering [2]. It is well known that High Tech Systems (HTS) roadmaps demand continuous improvement of equipment performance and capability (primarily in terms of accuracy, productivity, and increasing substrate size). It is also well known that the underlying disciplines, mechatronics design and system engineering, are encountering problems pertaining to increasing moving mass, internal deformations, thermal non-uniformity, and overall complexity.

Rapid developments within AM offer great potential for high-tech equipment, mainly because of the freeform possibilities that come with this production technology. However, exploiting freeform for system performance is a mechatronics design challenge, which should lead to new architectures and design principles for lightweight & stiff advanced thermal cooling topologies, integrated parts and mechanisms. (See also the contributions from ASML, Denis Loncke, page 17 ff., and VDL ETG, Gerrit Oosterhuis et al., page 36 ff.) This has been envisioned in a previous article [2]. As a follow-up, this article will present initial research orientation and intermediate results, as a first step towards exploring the potential added value of AM for high-precision systems.

First, some insights and ideas starting at system level will be presented, and a tangible mechatronics research orientation will be proposed for starting the exploration of AM-enabled freeform precision mechatronics. Next, a variety of preliminary results will be presented, outlining the contours of the potential of freeform mechatronics.

Freeform design approach

In [2] three main routes are proposed where AM could support mechatronics/precision engineering to overcome current or foreseeable performance limitations:

- Open structures to achieve lightweight system designs with favourable mechanical and dynamical properties.
- Sophisticated mechanisms and flexures that can be manufactured in one piece. Solving the problem of tedious assembly, delicate alignment, etc., of a large number of small parts (not to mention the compiled sequence of tolerances).
- Freeform flow and thermal solutions, designed to enable thermal performance.

A summarising illustration is presented in Figure 1.

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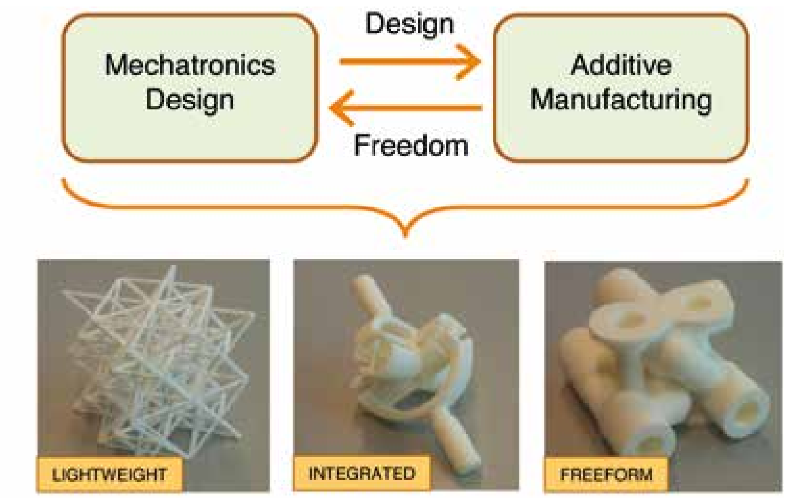

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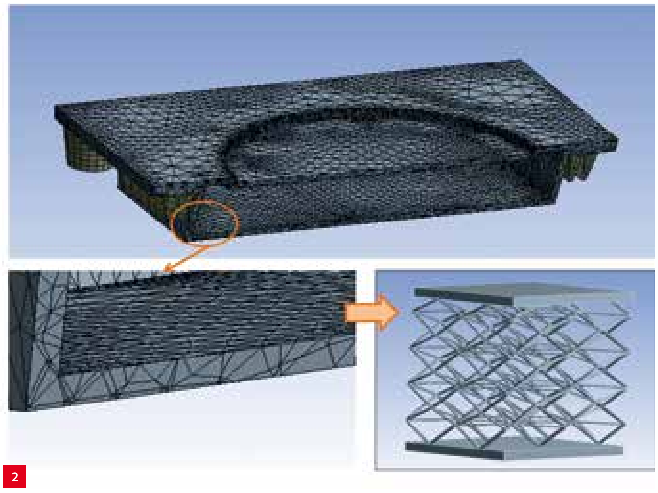

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1 AM-enabled freeform mechatronics routes.
2 Lightweight motion component with internal lattice structure.

Developments towards multi-disciplinary and system level performance specifications are still conceptual in terms of development and research, but awareness is rising among system architects and mechatronics designers that freeform AM design may be of significant impact.
In pursuit of breakthrough solutions to these multi-criteria and multi-physics based design challenges, topology optimisation is a very promising area of research. Starting with separate endeavours regarding lightweight and thermal design optimisation explorations respectively, the ultimate demand will expand to serving both in a combined optimisation design approach.
Taking freeform design even a step further, first explorations towards multi-material, spatial distribution of mechanical/dynamical properties across a component, provide interesting ideas. In particular, this will be considered for obtaining preferable properties in terms of thermal expansion behaviour.

Freeform mechatronics research progress

Here, a variety of freeform mechatronics research orientations will be presented. Some are more evolved and closer to application than others. This variety has intentionally been chosen to give an impression of the wide range of possibilities within the total solution space defined by the combination of AM and freeform mechatronics design.

Lightweight motion system component

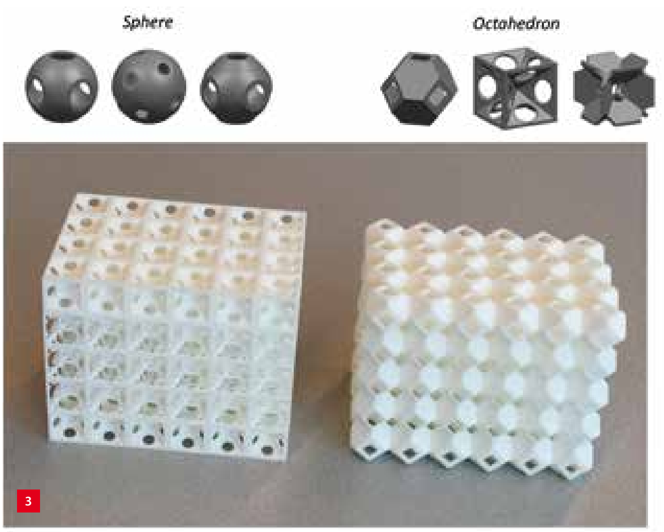
Looking for options to design lightweight motion systems is not a new activity. Open structures with lattices are being explored, e.g. within the aircraft industry. Also, structural topology optimisation studies to find model-based design solutions for balancing lightweight with high stiffness requirements are known. (See the contribution by TU Delft, Gijs van der Veen et al., page 28 ff.) With the rising capabilities of industrial AM, however, the possibility of actually manufacturing those components is now, to some extent, within reach. This stimulates designers to really start thinking about design approaches for fulfilling high-precision demands and come up with design breakthroughs.

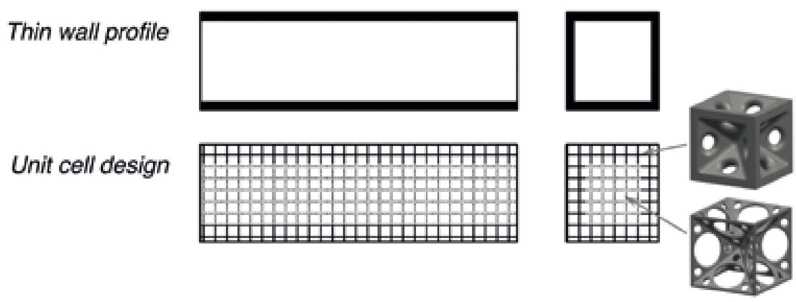
Figure 2 illustrates a design study on a lightweight motion system component (typically basic rectangular box shape of a substrate carrier), where the aim was to reduce mass whilst preserving the first resonance frequencies close to that of a massive component.

The idea has been to build the inner section based on a lattice structure and geometry that could be manufactured with AM. In this instance C-SiC was chosen as the material with assumed properties: ρ = 2,650 kg/m^3, E = 238 GPa.
A mass reduction of a factor of two was achieved, while the resulting modes ($f_{torsion}$ = 1,100 Hz, f_{saddle} = 1,300 Hz) have been kept very close to those of the massive monolith benchmark component. Mass reductions of this range are naturally interesting for motion systems, since they reduce the mass spiral and associated problems throughout the whole system.

Unit cell exploration

From the rather simplified example, as presented above, the question arises as to which open structure is best suited in the search for lightweight, and at the same time, stiff components. To gain insight, we concentrate first on unit cells as building blocks. In literature many structures (mostly 2D patterns) can be found, each with specific benefits. In return, such structures suffer from weak points when loaded otherwise than in the optimised case. For example, some structures are very stiff when compressed, but perform poorly when subjected to shear forces. This is





3 *Lightweight unit cell structures (top) and printed samples of blocks built from repeating unit cells (6 x 4 x 5 cells) of approximately 6 mm size (l x w x h).*

4 *Unit cell based topology optimisation example. For a lightweight, but stiff, structure a typically thin-walled profile is expected (upper part). The available volume has been gridded to accommodate unit cells of various wall thicknesses.*

obviously unacceptable in many high-tech system applications.

Here, the following starting points were taken into account in the unit cell exploration:

- 3D structure as building blocks, with repeatable geometry to be able to build 3D objects.
- Unit cell geometry should be AM-printable without internal supports, and powder must be removable after build.
- Primary target is mass reduction (per unit volume) without sacrificing mechanical properties. Scalable mechanical properties are desired, for example, through varying wall thickness within the unit cell structure.
- Analysis on strength, stiffness and isotropy under various load cases.

As a result of the exploration, sphere-shaped and octahedron-type cells remained the most interesting for further studies (see Figure 3). Many other cell structures fail to satisfy all criteria simultaneously.

Figure 3 shows also printed samples of repeating cells. The right block is built from cells which are all identical. The left block has an upper and lower layer of cells with thicker walls than the inner layers, just to illustrate the possibilities.

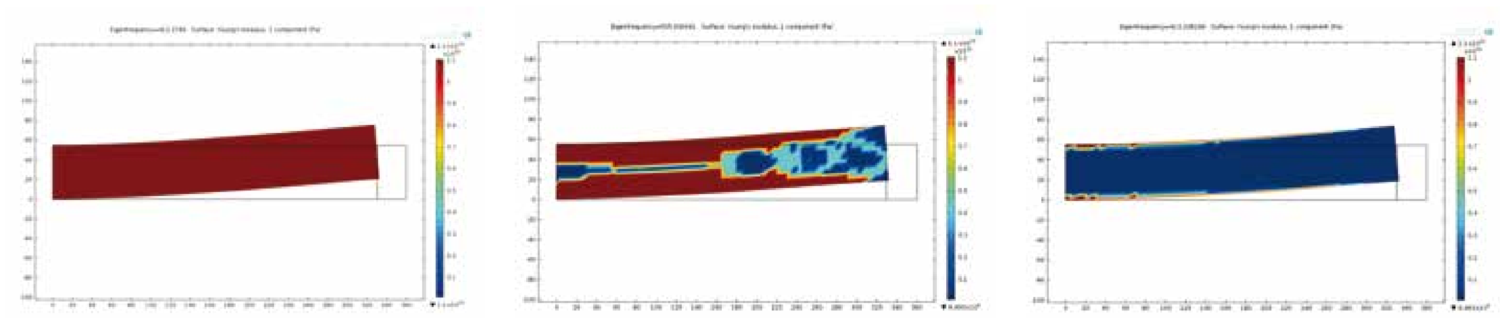
Unit cell based topology optimisation

As mentioned above, topology and shape optimisation are considered as powerful tools in solving complex, multi-specification design problems, especially when such freeform design space is available as with AM. Already impressive lightweighting examples based on topology optimisation can be found (see [3] and the contribution from ASML, Denis Loncke, page 17 ff.), but handling the tools requires skill and experience to avoid solutions which make no sense and are far from optimal. With the danger of optimisations getting stuck in local minima, it is self-evident that results are far from unique, but dependent on, for instance, the initial design and the volume gridding prior to optimisation.

Here, an alternative approach has been taken. Since the unit cells can be scaled with wall thickness, and they therefore tailor the mechanical properties of a cell, it is proposed to offer a family of different cells with different wall thicknesses (e.g. thin, medium, and thick) in addition to the regular choices of void or solid.
Now, a component design volume can be gridded, in accordance with unit cell dimensions, and the idea is to let the topology optimisation algorithm decide which type of cell to place at each grid position, such that the resulting component properties are optimal with respect to the optimisation targets and boundary conditions.
This way, the probability of ending up in local minima is reduced; mainly due to a limited optimisation scale (the number of unit cells to be placed is by far less than with regular topology optimisation over much finer grids). This idea has been tested in a simplified case, as depicted in Figure 4.

Results of two optimisations are shown in Figure 5. The middle graph (Figure 5b) shows that, compared to a solid reference component (Figure 5a), both weight can be reduced and resonance frequency can be increased. Figure 5c shows that a spectacular reduction in weight can be achieved (82% less) whilst keeping the resonance frequency at the same value.

The latter is obviously not of very practical value, because stiffness is much too low. As with other model-based optimisations, only useful engineering results will emerge when all relevant criteria have been put in the optimisation problem. Otherwise, the algorithm will seek the optimum without compromise. So, for this simple case the designer is confronted with the question how to balance the trade-off



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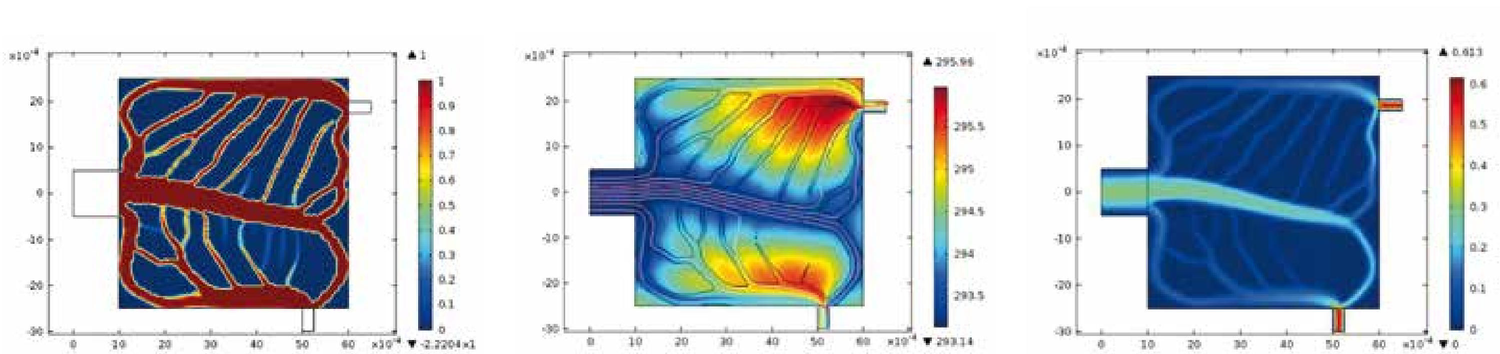


6a 6b 6c

between mass, stiffness and resonance frequency in this new, AM-enabled, freeform design space.
Of course, issues and drawbacks are associated with this pragmatic approach. For example, how to deal with curved product volumes and the minimum number of unit cells within a component cross section. Dedicated software tools are available to adapt typical lattice structures to curved shapes. It will be interesting to evaluate these in the next phase when we will aim for application-oriented design cases.

Freeform optimised cooling topology for substrate conditioning

Thermal conditioning of substrates during processing is critical to performance in many high-precision systems. Active cooling is required to achieve the required temperature uniformity. Limitations in the cooling channel design are often due to manufacturing constraints. Again, the freeform potential of AM appears to open up new possibilities to design dedicated and optimum cooling channels for thermal management. See, for instance, the contribution by VDL ETG, Gerrit Oosterhuis et al., page 36 ff., for already convincing results in thermal conditioning.

An initial topology optimisation study has been carried out combining flow and thermal domains (see Figure 6). A square cooling body, subject to a uniform and continuous heat load, has been taken as an example with the cooling fluid inlet (left) and outlet (right and bottom) positions chosen arbitrarily.

The resulting cooling channel, obtained from optimisation (Comsol Multiphysics), shows vein-like branches of variable width. From an engineering perspective this makes sense, but without the aid of model-based design tools a designer would probably never have drawn such a channel layout.

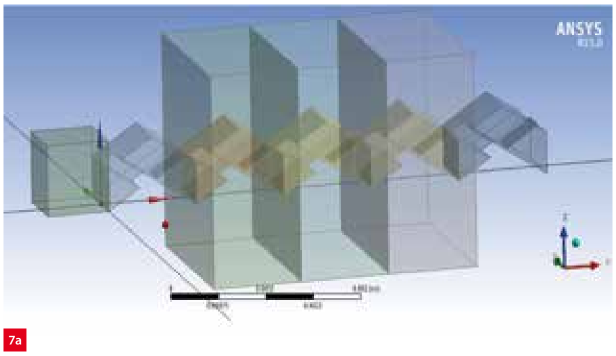
Especially when considering flow and thermal design problems, it should be noted that underlying models in the optimisation schemes should cover all relevant phenomena. If the model is too simple, incomplete, or used outside validity regions, the outcome of optimisation can never render an optimal design.

Flow mixing

Starting from existing engineering reality, the conventional cooling channels exhibit more basic shapes, mainly determined by design-for-manufacturing constraints. A freeform, yet rather simple idea is to design channels that enforce flow mixing and thus make better use of the cooling fluid flow through the channels. See Figure 7 for the basic idea, where a kind of corkscrew-shaped channel is shown which could be manufactured with AM. Because of the spiralling shape, the flow is mixed internally along the main

5 *Unit cell based topology optimisation results.*
(a) Solid component, for reference.
(b) A result with increased resonance frequency and reduced weight.
(c) Maximum weight reduction whilst keeping the resonance frequency the same.

6 *Thermal cooling channel topology optimisation study.*
(a) Channel pattern.
(b) Thermal performance.
(c) Flow speed across conditioning body.



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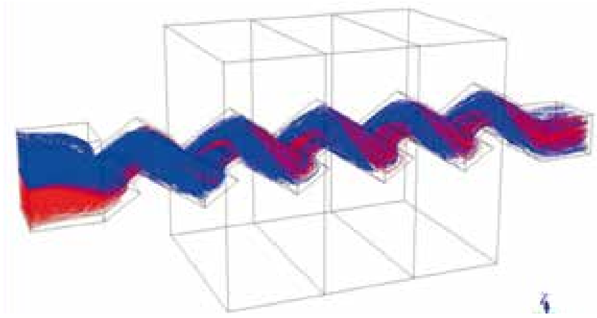

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channel direction (going from left to right, the initially separated blue and red flow volumes are clearly being mixed).

From preliminary flow and thermal analysis we observed that preheated water is continuously refreshed with initially cooler water in the stream, whilst preserving laminar flow. The results indicate that heat transfer can be significantly improved (even to values comparable with turbulent flow), depending on the flow velocity through the channel (Reynolds number). Additional pressure drop along the channel appeared limited.

Thermal pixel

The next freeform idea also did not originate from optimisation, but from the engineering insight that upward flow towards surfaces that require high-performance thermal control should result in enhanced, local cooling performance. The elementary principle is illustrated in Figure 8a.

This was translated into various freeform design concepts; see for example Figures 8b and 8c. A top surface can be obtained from repeating the elementary unit (which we call a thermal pixel). One way of organising cooling flow for each individual thermal pixel is via an orthogonal set of parallel supply and return pipes (see also Figure 8d).

7 Flow mixing example; flow direction is from left to right.
(a) Basic flow geometry.
(b) Flow analysis results.

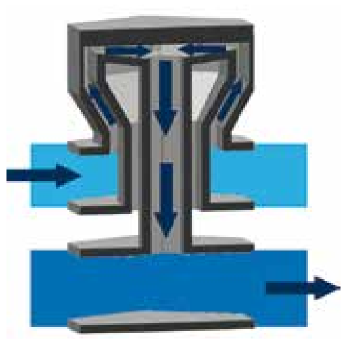
8 Thermal pixel development.
(a) Basic idea starting point.
(b) One of the design concepts.
(c) Printed sample with multiple thermal pixel.
(d) Possible supply and return channels to feed each thermal pixel with cooling flow.

Currently this idea is under development, so design changes and refinements can be expected. Especially the potential of dedicated, local cooling flow control can be very interesting in dealing with dynamic thermal loads that only affect part of a substrate area. This requires active control of cooling flows at each individual pixel of course. Studies are currently being conducted to find the best way of steering separate supply and return channels.

Obviously, this is heavily application-case dependent, but before proceeding with this design concept it is important to know whether local addressing of separate pixels with controlled flow can be achieved. Initial results are promising, so confidence prevails that this issue can be tackled.

Multi-material substructures for favourable thermal properties

More long-term, but already very appealing in terms of possibilities and potential benefits, is multi-material AM for high-tech applications. An interesting area for AM research is seeking smart combination of materials, e.g. in micro-



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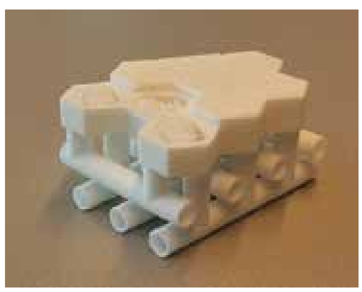

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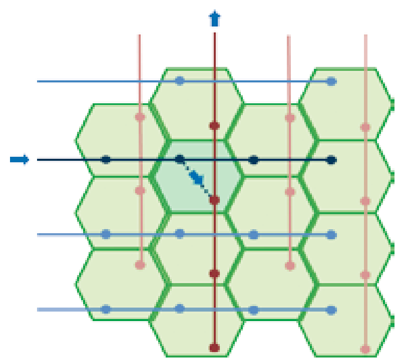

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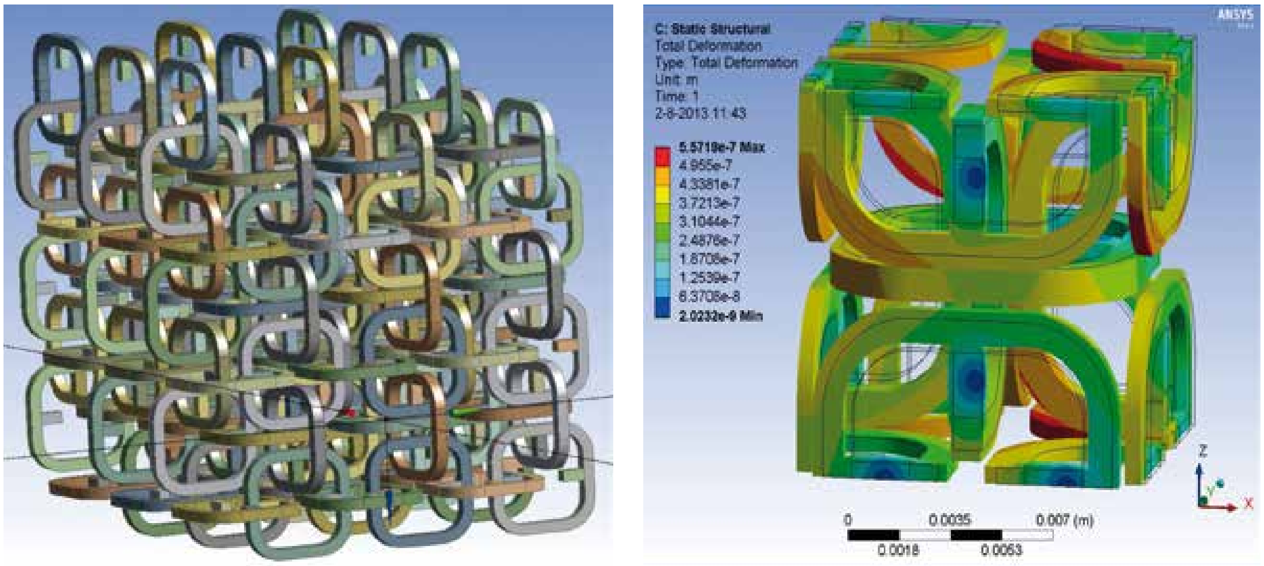

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9 *Multi-material substructure design (left) and cell analysis for zero-expansion macro properties (right).*

structures, resulting in components with desirable properties at macro level. Academic examples in 2D setting are known, e.g. aiming towards zero thermal expansion, typically considering exotic materials with, for instance, negative thermal expansion coefficients.
Here, some explorative 3D design studies are presented combining different materials. Starting with materials, all with positive thermal expansion, a geometrically repetitive microstructure is conceived with zero thermal expansion, but also having acceptable mechanical properties, and without too high internal stress levels. Just for illustrative purposes, see Figure 9 (although final designs look rather different).

All elements in the structure will expand when the temperature rises, but through intelligent interconnections the boxed envelope around the structure will remain constant in size.
Note that these explorations and studies are still far from completion and real application, but nevertheless, they show some of the potential to conceive meta-structure properties with multi-material AM.

Multiple segment, leaf spring-hinged tip/tilt mechanism

The potential of AM to manufacture complex shapes and mechanisms out of one piece is really appealing within precision engineering, for instance because it avoids delicate assembly of a large number of small components, and the alignment of the resulting mechanism. Typical examples are leaf-spring parallel guides, cardan hinges, etc., out of one piece.

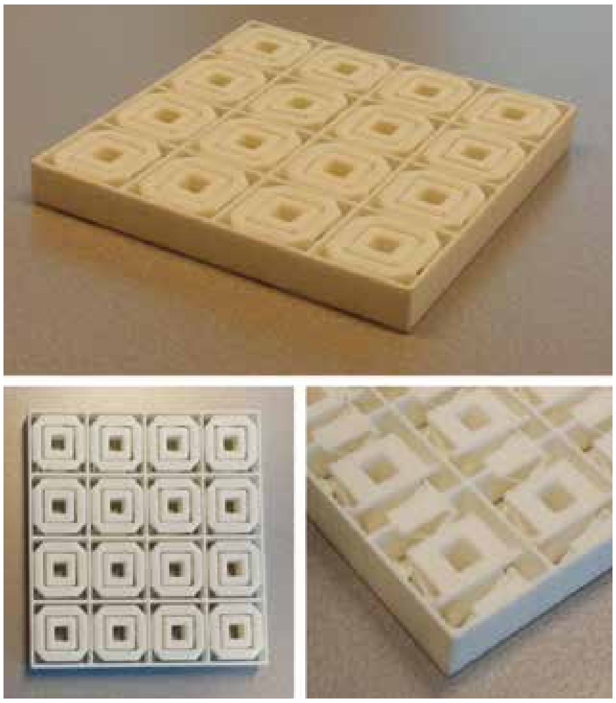
See Figure 10 for an illustrative example of an integrated mechanism consisting of multiple segments that are suspended with delicately designed leaf springs that allow for individual tip/tilt movement per segment. Through AM, the component is derived from one piece, so no assembly is involved in mounting the separate square segments.

Although this mechanism has only been designed as a study case, and has been Additively Manufactured with SLS using plastic, the potential is immediately apparent. For instance, a mechanism enabling local substrate manipulation for levelling at the area of performance instead of having to manipulate the whole substrate carrier body in Rx and Ry. Experimental evaluation has to be carried out to understand the influence of building orientation on mechanical properties. For instance, motion hysteresis should be improved to allow for performance-critical application in precision systems.

Conclusions

This article has touched upon the potential benefits of high-tech Additive Manufacturing for high-precision system solutions. From a system performance driven perspective, some research orientation has been presented on how the freeform nature of AM opens up new opportunities in terms of lightweight, optimised dynamics, thermal management and integrated mechanisms.

Preliminary research results have been presented on a range of these research areas with a focus on design and mechatronics. The main conclusion that can be drawn is that confidence is growing and some aspects are already proven in practice (albeit in simplified settings for obvious



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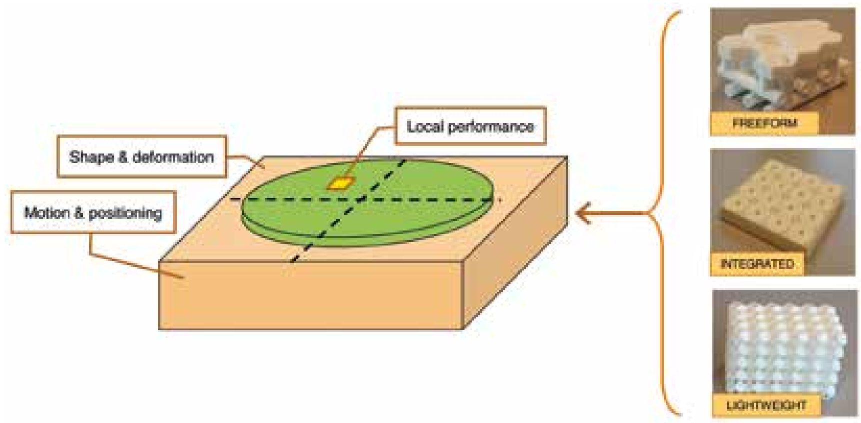

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10 *Integrated mechanism with 16 identical tip/tilt segments and tailored leaf-spring suspension. The lower right picture shows the rear, from which some detail of the double leaf springs can be observed.*

11 *Towards application-oriented research cases.*

research reasons). Yet, this development is only the beginning, and leading design principles are lacking or incomplete. It encourages designers to embrace the as yet unexplored opportunities of AM for performance solutions of high-tech systems.

Next steps

The next steps in future research will focus on application cases. The available freeform design concepts, of which a few examples have been presented in this article, are considered promising enough to proceed in that direction and find out how much value can be obtained at system level. Figure 11 visualises this ambition schematically.

The list of freeform, AM-enabled possibilities is not exhaustive. Furthermore, some ideas have only been suggested but remain unexplored. For example, spatial variations within a product or component, such as grading, deliberate anisotropy, and local damping are still to be investigated to be able to judge possible merits for high-tech systems performance.

Invitation

Interested readers are invited to participate, support, discuss, join forces, etc. They can contact the first author for comments, suggestions, or other constructive input. ■

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FOLLOWING MOORE'S LAW

ASML has been using Additively Manufactured (AM) parts in its NXT systems since 2007, starting with polycarbonate parts and followed by titanium parts in 2009. From the first introduction until today, ASML has increased the use of AM technology to a total of over 30 production parts and had to deal with a number of challenges that come with introducing new technologies.

DENIS LONCKE

ASML is the world's leading provider of lithography systems for the semiconductor industry, manufacturing complex machines that are critical to the production of integrated circuits or chips that power a wide array of electronic, communications, and information technology products. With every generation, the complexity of producing integrated circuits with more functionality increases following Moore's law.

AM for industrial parts

With the increasing complexity of integrated circuits, the complexity of the equipment to produce these chips also increases; see Figure 1. To deal with these challenges, ASML development is continuously looking for new solutions [1] [2]. Often, these solutions are limited by the available manufacturing technologies or the cost for manufacturing complex structures and parts.

The freedom of design that comes with AM takes away a number of these limitations opening a way to new design solutions. AM is not a single technology but a denominator for technologies that build up a part layer upon layer.

1 *NXT 1950i, ASML's first system in which AM parts were used.*

Abbreviations

AM	Additive Manufacturing
WAAM	Wire Arc Additive Manufacturing
LOM	Layered Object Modelling
FDM	Fused Deposition Modelling
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SLA	Stereolithography
VAT	stands for a process taking place in a vessel

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The collaboration within the ASML AM competence team and with ASML Research is greatly appreciated. Special thanks to Fred de Vreede (material and process release), Bart Gysen (lightweight and stiff design, designing for AM), Radu Donose (thermal control) and Rogier den Breeje (reducing disturbance forces) for supplying the innovative ideas and materials.

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Technology	Metal	Polymer	Ceramic	Properties
Directed Energy Deposition	Cladding, WAAM parts, repair			Higher / Rougher / Lower
Sheet lamination	LOM Proto's		LOM Parts	
Material Extrusion		FDM Parts & Proto's	Slurry extrusion (R&D phase)	Durability / Finish / Detail
Powderbed Fusion	SLM Parts	SLS Parts & Parts	SLM possible but low density	
Binder Jetting	Binder jetting Proto's	Binder jetting Parts & castmoulds		
Material Jetting		Material jetting Casting patterns		Lower / Smoother / Higher
VAT Photo-polymerization	VAT (R&D phase) [illegible]	SLA Proto's	VAT (R&D phase) [illegible]	

2

Figure 2 gives an overview of the available technologies which are described by the ASTM International Committee F42 on AM, in combination with a high-level indication of the properties. The technologies ASML currently uses to manufacture parts are highlighted in green; in yellow the processes that are under investigation.

For manufacturing its parts, ASML has selected material/technology combinations together with the suppliers based on the largest potential for meeting the part requirements successfully. Together with these suppliers we look at the possibilities of the process and the requirements and develop a product, process settings and finishing methods in order to meet the agreed requirements.

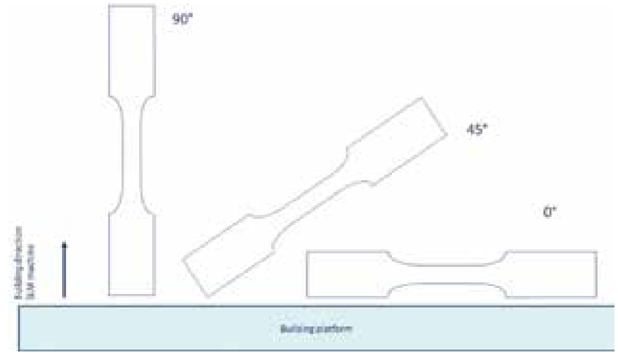
For metal parts we use Ti grade 5 with SLM, for polymers we use polycarbonate with FDM and polyamide with SLS. These materials and technologies have been released for certain application areas in the ASML systems. Stereolithography is only used for rapid prototyping by ASML using various materials available. For ceramics, research is in a relative early stage where we are currently experimenting with alumina in a VAT process.

Material and process standardisation

Material properties and surface finish can vary with the process parameters used in AM. Together with the possibility to generate complex structures that come with the freedom of design, this demands for a new set of standards on material properties, surface finish, and quality verification.
Since these standards were not yet widely available at the time ASML started with AM, we had to define these standards ourselves in order to provide our designers with the needed design guidelines.

It is commonly known that material properties like yield strength and fatigue strength of a 3D printed part can also vary depending on the direction from which the material is added. The same holds for the surface roughness. For this reason we have tested a number of samples with different layer orientations and measured these parameters (Figure 3).

For powder-based processes like SLM and SLS the issue of particle contamination needs to be solved. Since particles on the outer surface of a layer can only be partially melted, they can easily detach (Figure 4). Loose particles can become airborne, for instance by gas flows through SLM/SLS manufactured channels, and cause defects on integrated circuits if they end up on the wafer surface. In order to prevent these particles from coming loose in an application they should be either mechanically or chemically removed or re-melted with the part.
When printing cooling channels in a part or cooling plate, it is often necessary to reduce the wall thickness of the channel to a minimum for optimum heat transfer or mass



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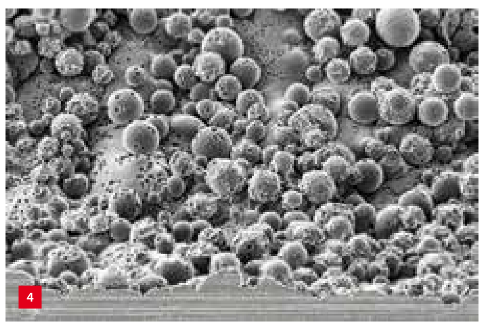

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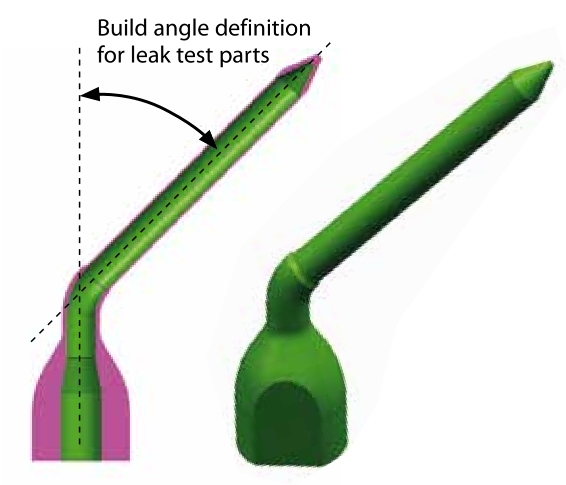
2 *Overview of AM technologies used for ASML [3] [4].*
3 *Testing 3D printed parts. (a) Tensile test samples with varying layer orientation. (b) Roughness sample.*
4 *View of Ti SLM surface before surface finish.*



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reduction. Because the AM processes are based on building layer upon layer, the minimum wall thickness for a 3D printed part may be different than for conventionally machined parts. For this reason the minimum allowed wall thickness for a reference pressure needs to be determined experimentally for different building angles. These tests were executed for Ti grade 5 alloy; results show that a wall thickness of 0.2 mm was still He leak tight with a maximum leak rate of $1 \cdot 10^{-9}$ mbar·l/s.

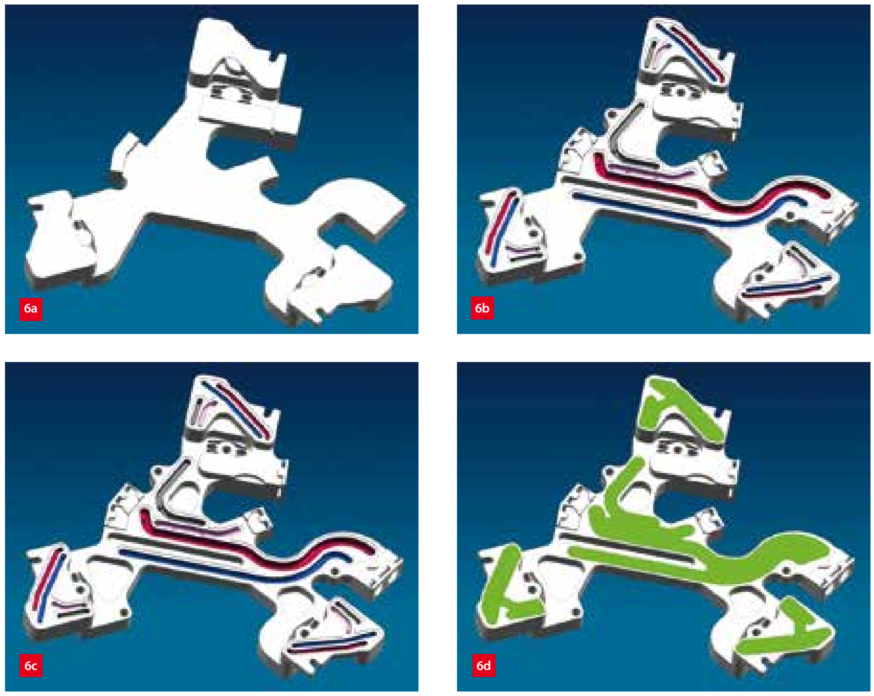
Designing for AM

AM technologies come with a large freedom of design that enables producing complex shapes which are hard or impossible to realise with conventional manufacturing technologies. It creates the opportunity to realise lightweight products using lattice structures, freeform shapes with multiple undercuts, and complex organic shapes. The conventional way of designing starts with a predefined volume from which material is removed. With AM a designer can truly start from a blank page adding the minimum amount of material only where it is needed.

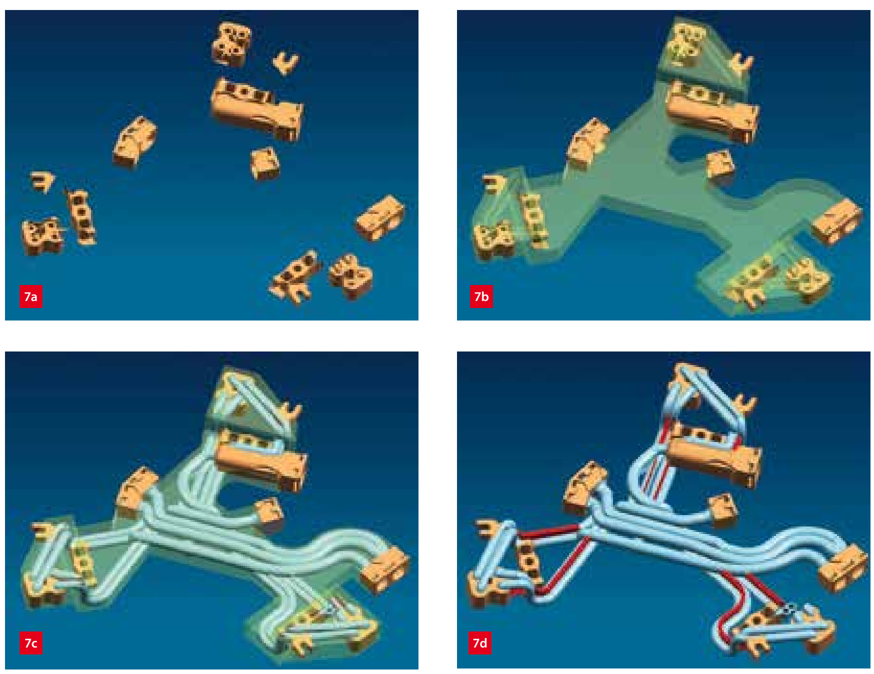
Figure 6 shows an example of the conventional way of designing a manifold, where the starting point is the maximum allowed envelope. Within this volume first the interfaces with the surroundings are defined, next the functional features are added, in this case the channels. Because of the limitations of conventional manufacturing technologies, the channels originally are open and need to be closed by a separate production step. When mass requirements are stringent, excessive mass can be removed and the part can be finalised, in this case adding the closing lids.

Figure 7 shows an example of designing for AM, where the starting point is the definition of the interfaces and the envelope. The next step is adding material for the functional features and the last step is finalising the part with supporting features like reinforcement structures in order to meet all requirements.

AM has also opened the way for topology optimisation, a computational



5 Test sample used for minimum wall thickness tests.
6 Traditional way of designing.
(a) Volume and interfaces.
(b) Functional features.
(c) Mass reduction.
(d) Finalise part.
7 Designing for AM.
(a) Interfaces.
(b) Check volume.
(c) Functional features.
(d) Finalise part.



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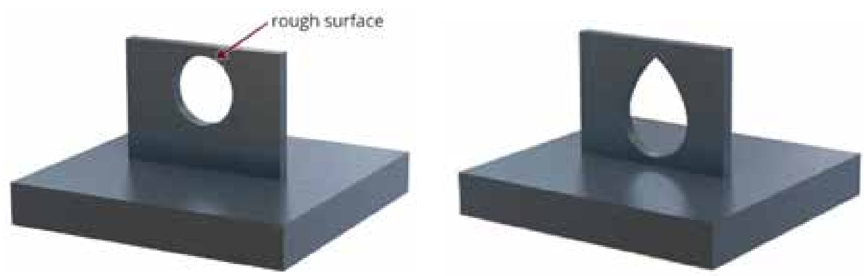

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8 *Example of a topology optimised structure.*
9 *Solution for circular cross sections [5].*
10 *Integrating support structures [5].*
11 *Schematic overview of a positioning stage.*

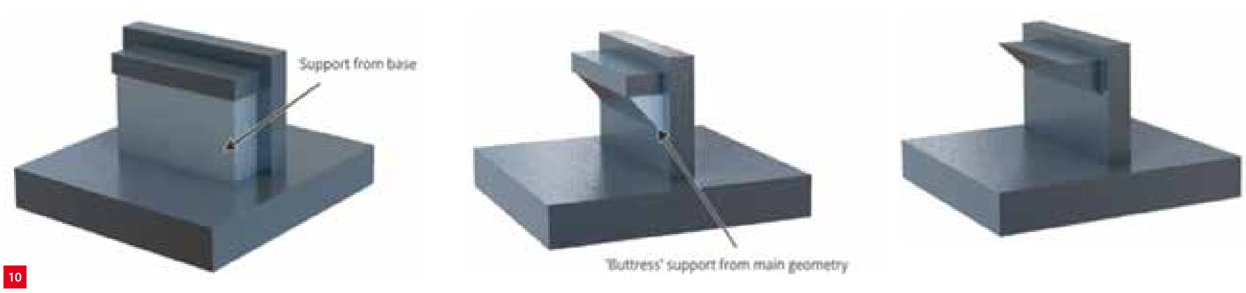
optimisation method which generates optimised designs in a certain domain (mass, stiffness, thermal, flow, ...) in the form of material distributions in 2D/3D space based on given input and output constraints. The result of such an optimisation is an organic 3D shape which cannot be manufactured in a conventional way. Figure 8 shows the result of a structure that has been optimised for mass and stiffness; it was printed as a demonstrator part using stereolithography.

Although the design possibilities with AM seem endless, there are a number of limitations and design rules that need to be taken into account. One of these design limitations is printing large overhangs and circular cross sections. Because an overhang and the top part of a circular section are supported only by powder and by not a structure below, they tend to sag and create a rough and irregular finish. This can be solved by changing the circular section to a droplet or a hexagon shape where the top comes together under an angle of 90° or less (Figure 9).

Another consideration when using overhangs is the use of a support structure to prevent sagging. This support structure can either be removable or, if possible, it can be integrated in the design (Figure 10).

Driving Moore's law

Lithography is driving Moore's law. The challenges on lithography are the continuous shrink, requiring improved resolution (determined by the smallest feature, usually a line width that can be printed), and increased productivity in order to reduce cost per function and increase the efficiency of the lithography tool. In addition to improved optics, this also requires better stages with increased precision, dynamics and thermal control (Figure 11).



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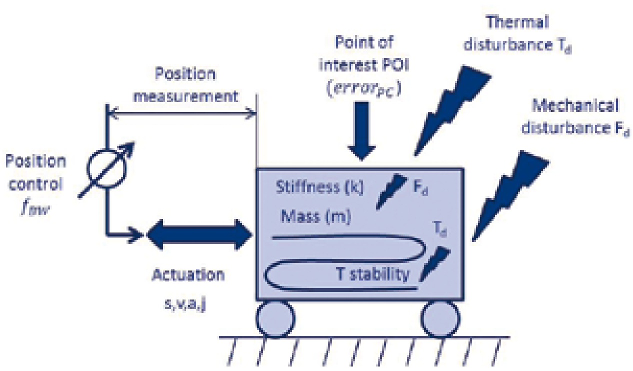

$$F_{act} = m.a$$

$$f_{BW} \sim f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

$$\frac{error_{PC}}{F_d} = \frac{1}{0.5.m.(2\pi f_{BW})^2}$$

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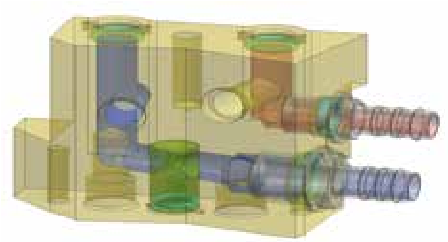
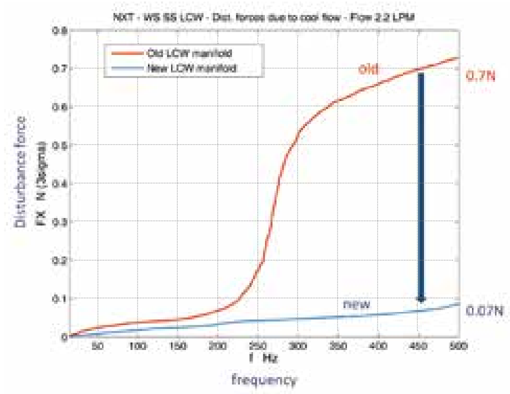

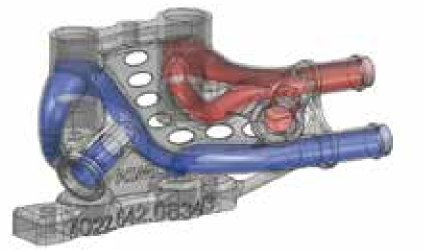

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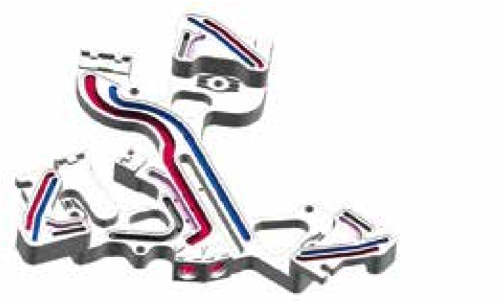
To deal with these increasing challenges, ASML development is continuously looking for new solutions. Often these solutions are limited by the available manufacturing technologies or the cost for manufacturing complex structures and parts.
The freedom of design that comes with AM takes away a number of these limitations opening a way to new design solutions. Challenges such as shrink and productivity can be translated into stage design parameters such as precision and speed. These are in turn impacted by factors including disturbance forces acting on the stage, dynamics of the stage itself, and the thermal influences on the stage. These three aspects can be improved using the freedom of design that comes with AM.

12 *Example of reducing disturbance forces caused by turbulent flow. See text for explanation.*

13 *Example of design for AM.*
(a) Original design.
(b) Lightweight and stiff design.



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Reducing disturbance forces

Disturbance forces originate from both internal and external sources. One of the possible sources of position disturbance in a high-precision stage is flow-induced vibration caused by turbulent flow of a cooling medium. A flow in a channel can become turbulent when the transitions in cross sections or the direction of the flow change in a discrete way instead of gradually.

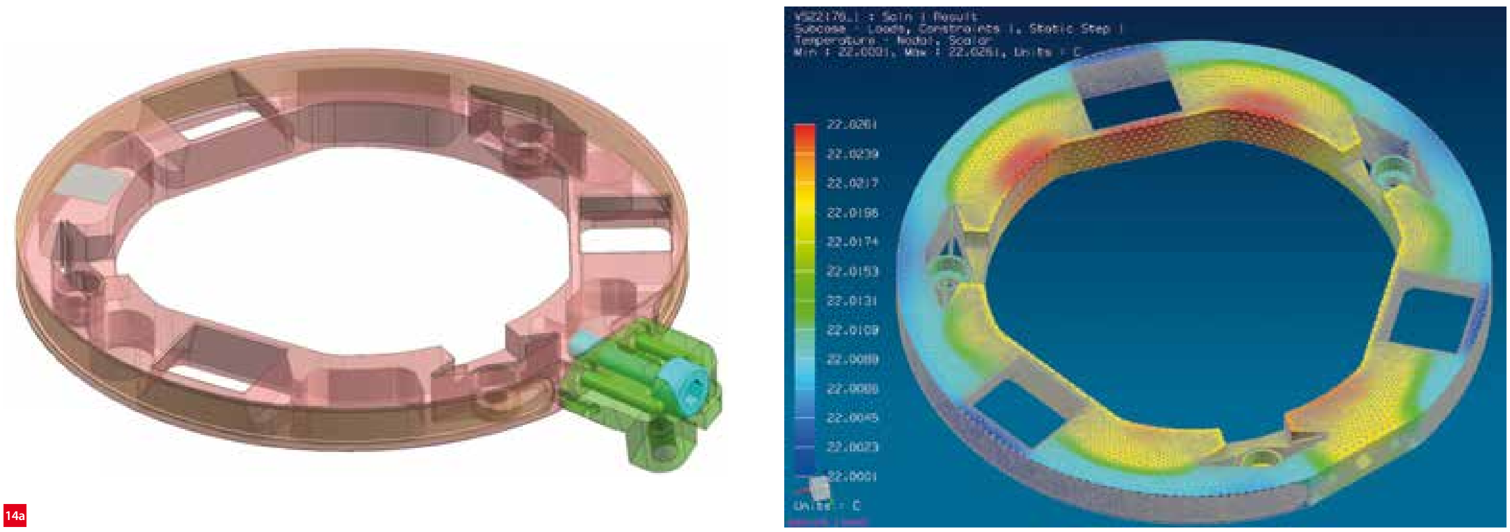
The example on the left in Figure 12 depicts a water distribution manifold made out of PEEK (polyether ether ketone), where the channels are drilled perpendicular to each other, thereby creating sharp corners and transitions. These transitions cause turbulence-induced vibration forces up to 0.7 N, which is too high for maintaining nanometer-level position control. This problem cannot be solved with conventional technologies, not even by using casting technology, because of the small feature size. The freedom to design smooth channels in case of AM dramatically reduces turbulence and pressure drop in the channels. The resulting disturbance forces were reduced by a factor of 10, bringing them down to an acceptable level.

Lightweight and stiff design

The changed philosophy of designing for AM automatically delivers low-weight designs as described above. The designs in the example of Figure 13 have the same functionality and dynamic performance, the manufacturing cost price is 20% higher for the AM part, but the main gain can be found in the mass reduction from 200 g to 100 g.

Improved thermal control

The final example in Figure 14 is a thermal conditioning ring with a circular cooling channel milled on the outer circumference. The channel needs to be closed by welding a cover on the outer surface. Conventional machining limits the uniform distribution of the water channels across the entire cooling ring surface. This results in a temperature



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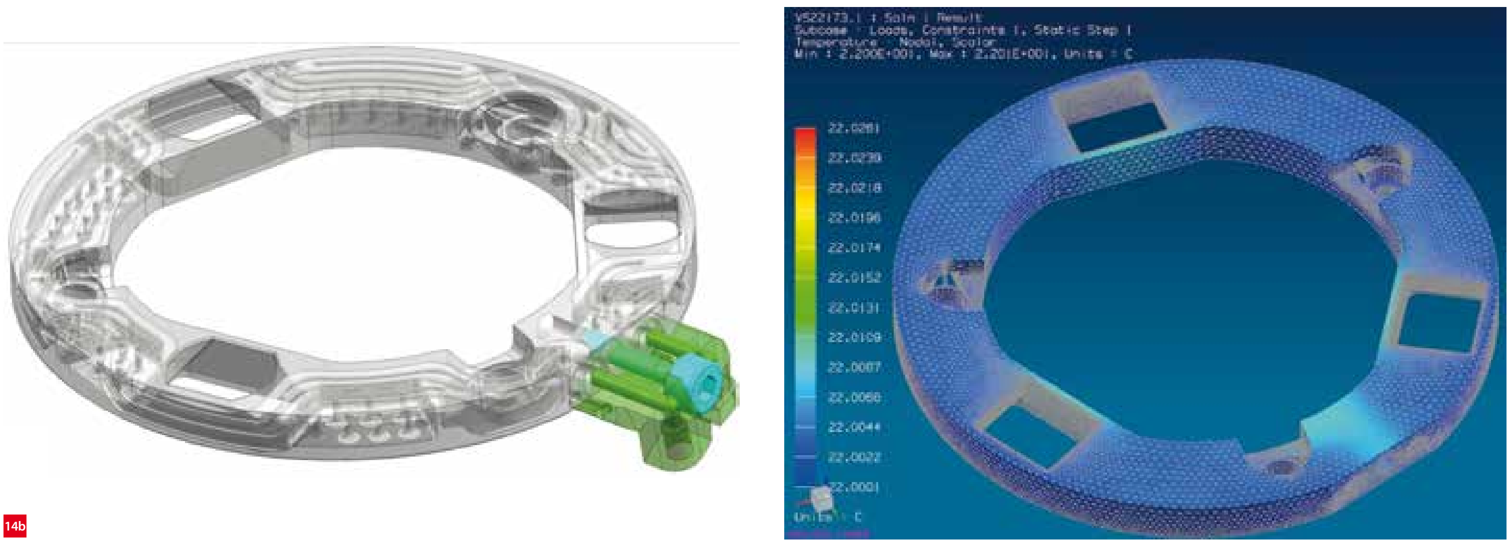

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distribution ΔT with an average of 14 mK over the top surface and a gradient of 22 mK over the height of the part. Using AM, the design can be modified and optimised. As a result, an improvement of 6x was obtained in thermal performance.

14 *Example of optimised thermal control.* *(a) Conventional design: average ΔT at top surface: 13.8 mK (left); temperature gradient: 22 mK (right).* *(b) AM design: average ΔT at top surface: 2.3 mK (left); temperature gradient: 3.7 mK (right).*

Moore's law in AM

The industry today is investigating the possibilities of using AM for their parts. The focus here is on metal parts and the main resistance to start using this technology comes from the high cost, limited accuracy or resolution, and unknown repeatability of part quality. The high cost is mainly determined by the production speed of the tools.

Additive Manufacturing and the semiconductor industry have similar goals in their drive for more productivity to reduce cost and improved resolution for printing smaller features with more accuracy. As a high-tech industry, we should drive the roadmap for AM in the same way Gordon Moore did for the semiconductor industry. ■

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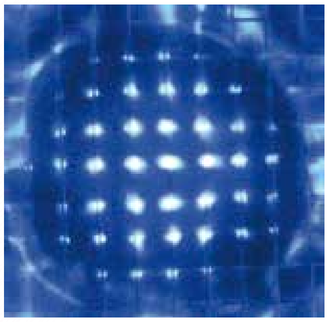
REMOVING 'ADDITIVE' CONTAMINANTS

Ultrasonic cleaning, a well-known technique, is of interest for the Additive Manufacturing (AM) community. In AM processes performed with industrial printers, the resulting objects can have printing material, such as unsintered nylon powder or non-cured polymer, sticking to their surface. These contaminants need to be removed ultrasonically to ensure proper functioning. However, simply placing an object inside an ultrasonic bath is not always sufficient for cleaning precision mechanical objects. New ultrasonic technologies can improve the cleaning process.



BRAM VERHAAGEN AND DAVID FERNANDEZ RIVAS

Ultrasonic cleaning has been used for 70 years already for the daily cleaning of items such as jewelry, dental instruments, laboratory items, semiconductors, 3D-printed objects and precision mechanical objects. Gears, bearings, tubes, connectors and similar high-precision parts often carry contaminants from the production process, including oil and chips of material. However, simply placing an object inside an ultrasonic bath is not always sufficient for cleaning precision mechanical objects.

Working principle

The cleaning mechanism of an ultrasonic bath is not the ultrasound itself. Rather, the ultrasonic pressure waves lead to the formation of bubbles (cavitation) that are doing the actual cleaning [1]. These bubbles are created from gas that is already present in the liquid. The ultrasonic pressure waves make these bubbles grow and collapse, and this collapse is so violent that huge mechanical forces are exerted on a very small scale (micrometers), through the generation of jets and shockwaves as well as several other effects. It is still under debate what the exact physical cleaning mechanism is [2], but for practical purposes, the main point is that cavitation bubbles are formed and can perform cleaning (see Figure 1).

The major requirements for cavitation to take place are the presence of a pocket of gas and sufficient pressure. These conditions are not always fulfilled, mainly because the pressure inside an ultrasonic bath is not uniformly

AUTHORS' NOTE

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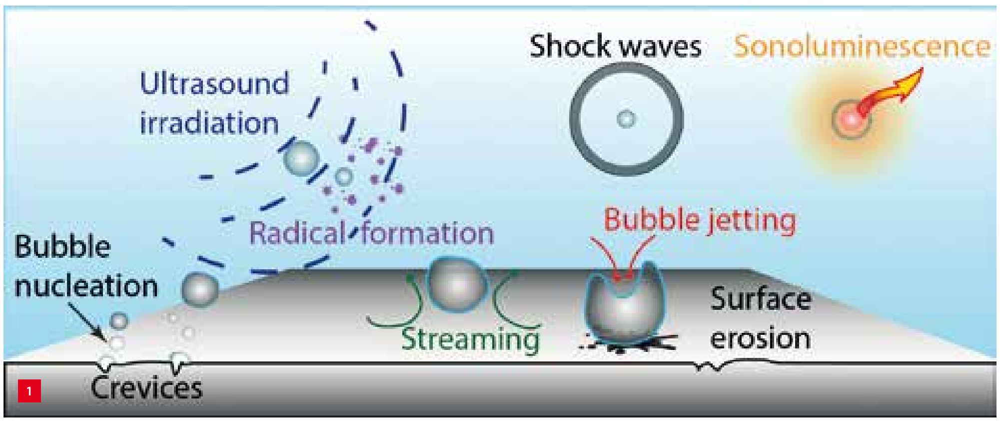
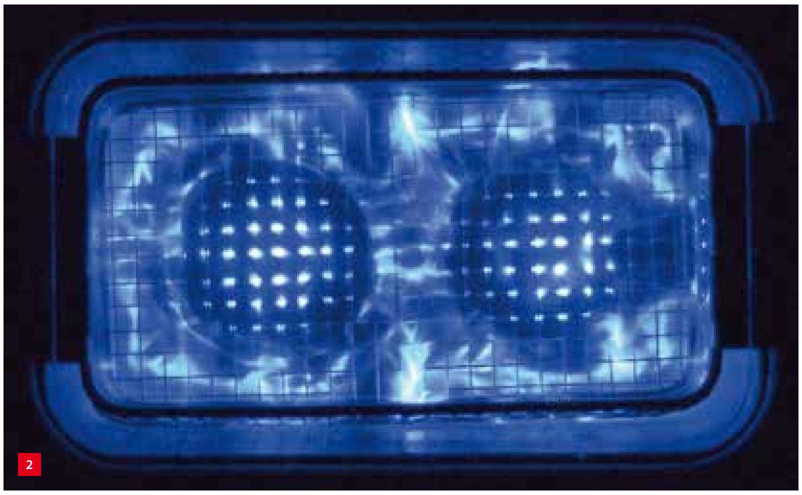


1 *An overview of the various phenomena that occur when bubbles collapse. The main cleaning mechanisms are thought to be jets and shock waves, however there is also streaming, radical formation and sonoluminescence. The bubbles grow out of crevices (gas pockets) on the surface.*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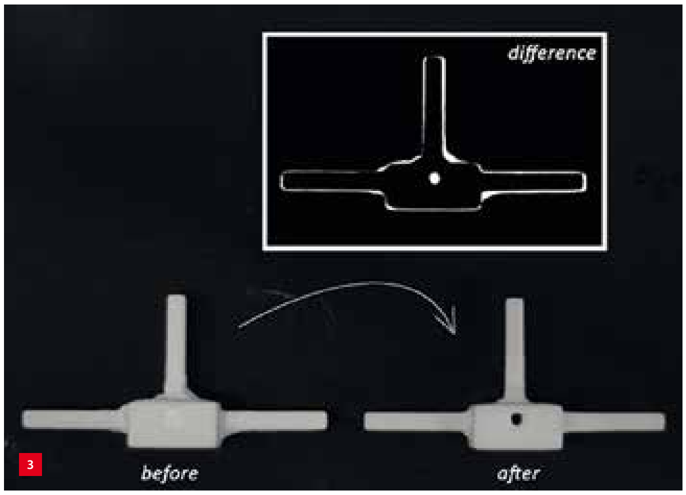


3

distributed (see Figure 2). Making a map of the cavitation activity of an ultrasonic bath can help to determine where to place an object that needs to be cleaned. This is important information when many miniature components need to get the exact same cleaning treatment in a large ultrasonic bath.

A second issue with ultrasonic baths is that 'acoustically hard' objects will not transmit sufficient ultrasound pressure to the interior of objects: a metal surface will reflect a lot of the ultrasound. Therefore, there is less cavitation or cleaning inside hollow metal objects. One example where this is a problem, are robotic arms used for surgery. These are expensive, complex mechatronic systems consisting of many small features and narrow lumina, in which tissue contamination can resist conventional ultrasonic treatment.

Objects made of plastic face another challenge for ultrasonic cleaning. Bubbles generally collapse toward the surface of an object, but because of the acoustic properties of plastic, this collapse is much weaker than it would be for metal. Plastic objects are therefore generally difficult to clean, rendering ultrasonic cleaning not suitable for 3D printed plastic items with the current techniques (see Figure 3). We are working on new techniques to make ultrasonic cleaning work better for Additive Manufacturing.

The fact that cavitation relies on the random presence of a gas pocket is the main reason why, in typical applications, the cleaning process of ultrasonic baths is uncontrolled and inefficient. Gas pockets often exist on dirt particles that float in the liquid volume. This is not an issue for low-tech cleaning applications, but for precision mechanics the cleaning is often more demanding.

2 Cavitation map, showing in top view the distribution of cavitation (blue) in an ultrasonic bath. The two transducers can be recognised, as well as a basket.

3 Ultrasonic cleaning of a 3D model, printed using Selective Laser Sintering. Small features such as the hole and the corners near the poles' bases are difficult to clean using standard ultrasonic equipment.

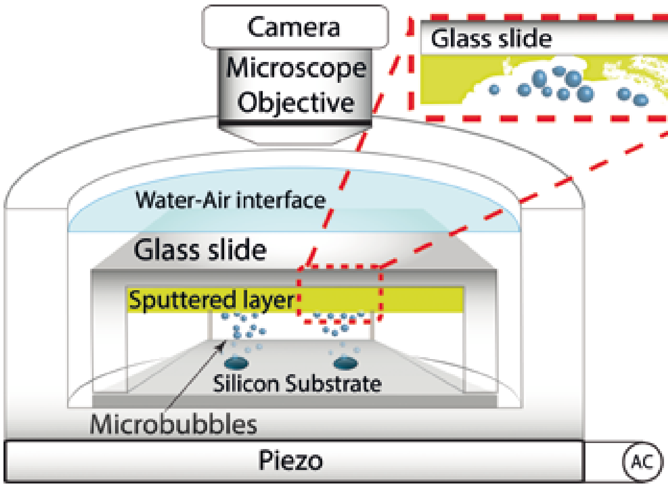
We have shown recently that a good level of control over cavitation can be achieved by making artificial gas pockets [3] (see Figure 4). These gas pockets were micromachined in a silicon surface, and air was entrapped upon submersion in water. By ultrasonically vibrating the silicon surface, cavitation bubbles could be generated at a specific place and time, and very precise cleaning could be performed. This has potential for cleaning delicate parts or specific areas of wafers, contact lenses, 3D printed objects, etc.

The size of the cavitation bubbles is mainly determined by the ultrasound frequency, with higher frequencies leading to smaller bubbles. This automatically sets a limitation to the size of object features that can be cleaned: tiny features on complex gears or other precision mechanical parts can only be cleaned by small bubbles, which requires high frequencies. In general, smaller bubbles have milder effects, i.e. they collapse less violently. Gentle cleaning is favourable for delicate and miniature objects such as microchips in semiconductor wafers. Megasonic systems are available that operate at MHz frequencies for this purpose.

Construction of ultrasonic baths

Not much has changed in the construction of ultrasonic baths since their invention in the 1930s, except for recent digitalisation of the electronics and controls [4]. The ultrasonic bath consists of a liquid-containing tank with volumes ranging from 1 L to 90 L and even larger. To this tank several piezoelectric transducers can be attached, which convert an electronic driving signal into ultrasonic motion. This results in ultrasonic waves that travel through the liquid (see Figure 5).

The frequency of operation of ultrasonic baths is typically 20-40 kHz, although other devices operate at 80 or 135 kHz,



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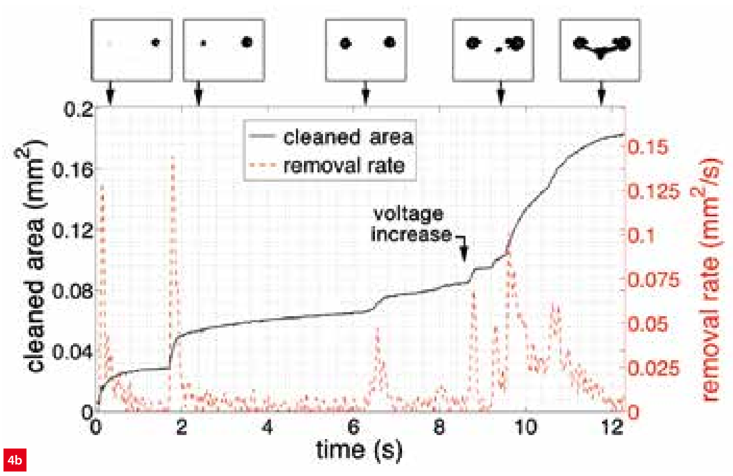


4b

or even higher. Modern ultrasonic baths often come with a sweep function, in which the frequency is varied a few kHz around the main ultrasonic frequency. The advantage of a frequency sweep is that standing waves in the liquid volume are reduced and a more homogeneous pressure distribution is obtained. A more homogenous exposure to the ultrasound can also be obtained with automated motion of an object through the tank.

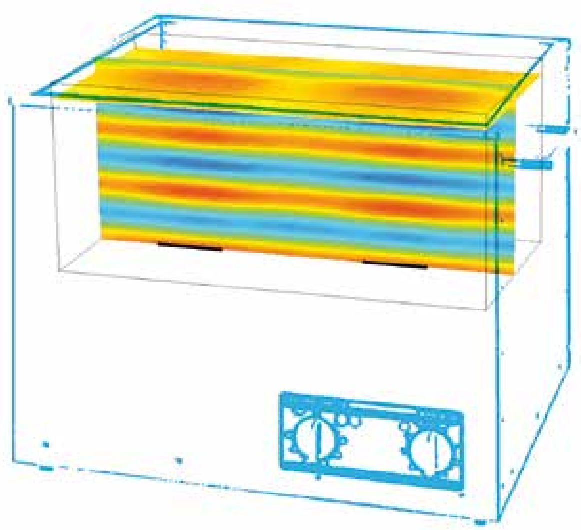
There is not much to improve in the ultrasonic bath design, but rather we try to improve the cleaning process, by having more control over the cavitation bubbles. Steering these cavitation bubbles is crucial for high-tech applications where the standard ultrasonic baths are not sufficient.

Specific applications

The choice of cleaning equipment is often made based on the size of the object that has to be cleaned. However, the operating frequency is equally important, since smaller features require higher frequencies for cleaning. A 'Sweep' type of functionality can be beneficial to reduce the occurrence of hot spots. Additionally, the acoustic power determines the pressure available for generating cavitation. Acoustic powers for table-top ultrasonic baths are typically around 25-50 W/L; industrial baths can have more power.

Besides the ultrasonic bath, it is important to choose the right liquid for a specific cleaning application. While plain water may often be sufficient, some cleaning applications require the addition of a surfactant or strong chemicals such as acetone or ethanol, for example to remove glue from nozzles, or in cleanroom photolithography processes. The cleaning then takes place through a combination of chemical dissolution and mechanical forces by cavitation bubbles. There are many water-based chemicals available, depending on the type of contaminant (grease, soot, glue, etc.) and object material (metal, plastic, etc.). These chemicals have an optimal temperature, both for their chemical action and for cavitation to occur. Many ultrasonic baths therefore come with a built-in heater that can warm up the liquid to 80 °C.

Because of the many variables in the cleaning process, there is no straightforward cleaning system and protocol (object position, time) for a specific purpose. Preferably, we carry out specific tests to confirm the suitability of an ultrasonic bath and chemical for a certain cleaning purpose, and establish a cleaning protocol.



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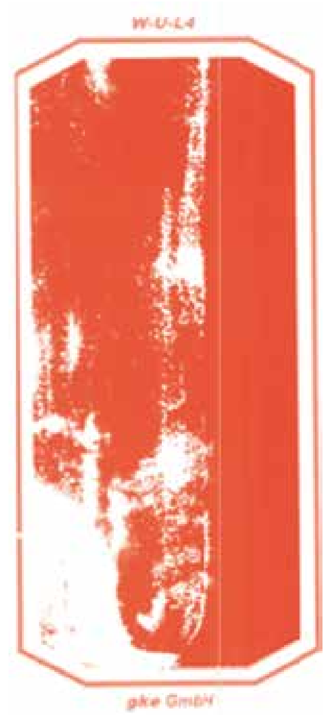
4 Controlling cavitation [3].
(a) Set-up for generating cavitation bubbles locally. Two artificial gas pockets, spaced 1 mm apart, were micromachined in a silicon surface. Cavitation bubbles were generated upon ultrasonic vibration, and started to clean the nearby surface with gold contamination.
(b) The cleaned area as a function of time was measured, and a good level of control over the location and timing of cleaning was demonstrated.

5 Simulation result for the acoustic pressure generated by two transducers (represented with black lines) in an ultrasonic bath. A standing wave arises, consisting of a pattern of high (red and blue) and low (yellow) pressures. At the water surface, two 'hot spots' (dark red) can be recognised.

6a



6b

6 *Cleaning indicators for ultrasonic baths.*
(a) There are four levels of cleaning indicators, which represent increasing difficulty of contamination (yellow to red).
(b) Placing such a cleaning indicator in an ultrasonic bath allows for quantitative monitoring of the ultrasonic cleaning process.

Using ultrasonic equipment

After selection of an ultrasonic bath, a suitable protocol and proper maintenance are required in order to fulfil its full potential. For example, the optimal filling level of the bath, which is liquid- and temperature-dependent, needs to be determined and maintained. Further optimisation can be achieved by placing the object at the location of maximum acoustic pressure. Roughly speaking, this is above one of the transducers, but a full cavitation map can give more insight into hot spots and dead zones.

However, anything placed inside the ultrasonic bath (containers, the basket, the objects to be cleaned) will affect the acoustic field and therefore the cleaning process. We have several specialist tools and probes to make a cavitation map and find the hot spots for cleaning. For a large cleanroom facility, we used these tools to characterise the effectiveness of their ultrasonic equipment for specific cleanroom processes [5]. This allowed us to measure the influence of stainless steel, glass or plastic containers on the processing of silicon wafers, and deduce the optimal place for these containers and the silicon wafers.

Ultrasonic baths tend to degrade over time. One main cause is that the adhesive with which the transducers are fixed to the water tank reduces in strength, often due to the ultrasonic bath not being filled to the right level. Another cause for bath degradation is damage of the inside of the liquid tank, because of objects or dirt on the bottom of the tank. It is therefore recommended to regularly check the functioning of ultrasonic baths. There are several methods available, including the basic aluminum foil test and more advanced cleaning and cavitation indicators (see Figure 6). We have cleaning indicators available that can periodically provide more information on the technical state and functioning of an ultrasonic bath.

The use of such cleaning indicators can also be used to validate that all of the cleaning parameters (duration, temperature, liquid levels, surfactant level) have been met in each cleaning treatment. This is relevant for applications such as healthcare or high-tech components of medical products, where reproducible cleanliness levels are required.

To conclude

Despite the fact that ultrasonic cleaning is not a new technology, it remains a valuable tool for cleaning of various items. However, for challenging objects such as medical instruments, precision parts and detailed 3D printed objects, innovations are required in the way the bubbles clean. ■

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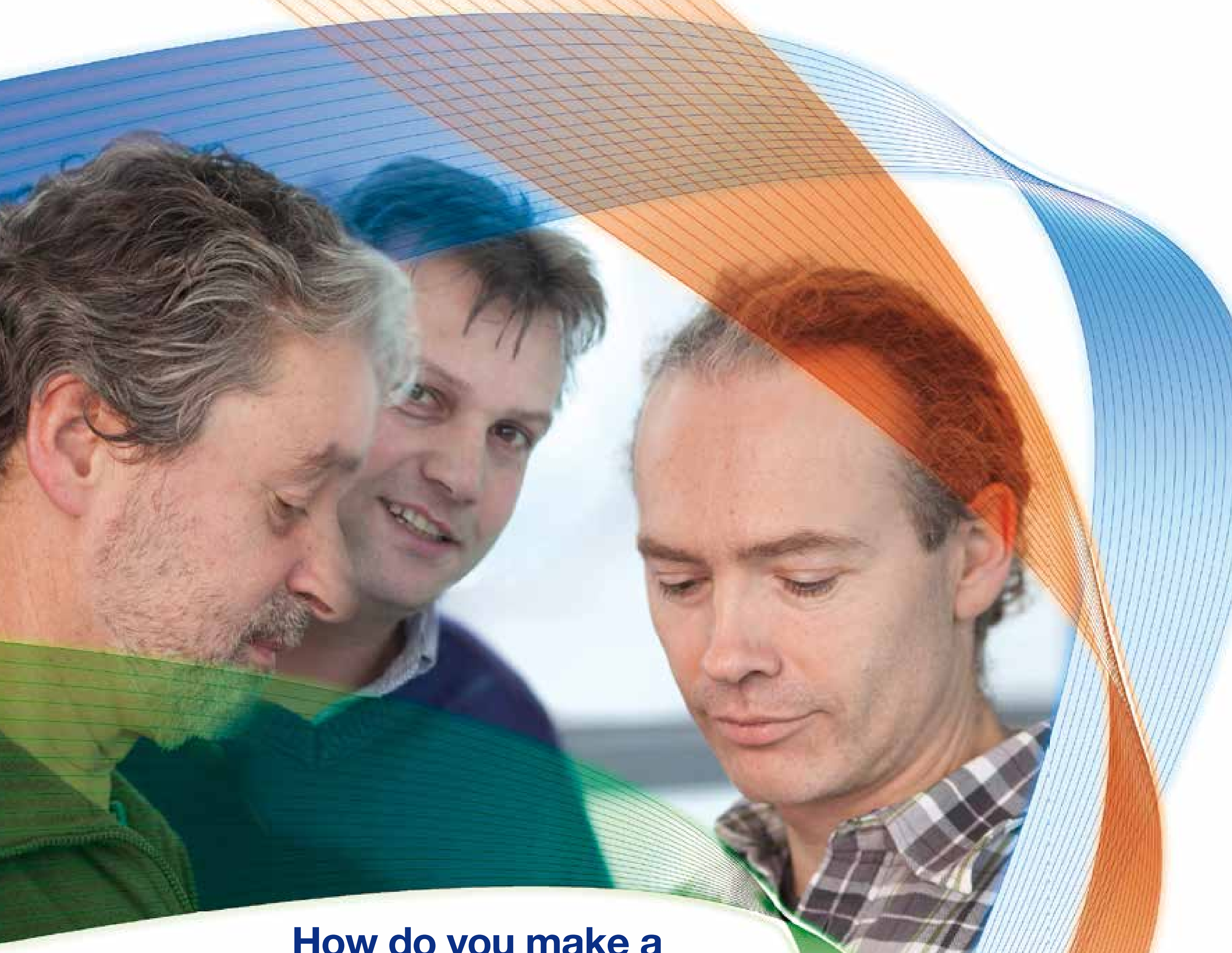
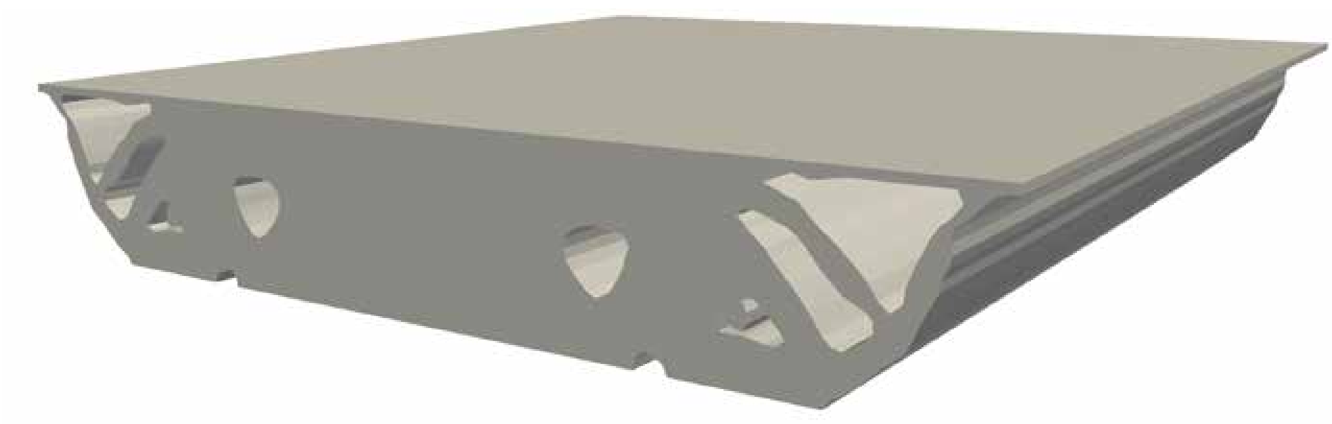


THE LINK BETWEEN TOPOLOGY OPTIMISATION AND ADDITIVE MANUFACTURING

The design case of a simplified motion system serves to demonstrate the potential of topology optimisation (TO) techniques for improving the performance of such systems. The presented methodology allows the extensive design freedom offered by topology design to be explored and results in a conceptual design. The intrinsic capability of TO of coming up with complex geometries suggests a very natural and powerful link with Additive Manufacturing techniques that can realise such geometries with few restrictions.

GIJS VAN DER VEEN, MATTHIJS LANGELAAR AND FRED VAN KEULEN



Introduction

Improving the closed-loop performance of precision motion systems relies to a large extent on changing the mechanical properties (e.g. mass, stiffness, damping) of their components. For instance, certain flexible modes may limit the achievable control bandwidth. While mechanical design guidelines usually lead to designs that are a useful starting point for subsequent mechanical and control design iterations, it is of interest to investigate whether the overall performance can be improved by including the

AUTHORS' NOTE

The authors belong to the Structural Optimisation and Mechanics (SOM) group, part of Precision and Microsystems Engineering at Delft University of Technology. The group is headed by Professor Fred van Keulen. Matthijs Langelaar is Assistant Professor, specialising in topology optimisation. Gijs van der Veen is undertaking postdoctoral research on combined topology and control system optimisation of motion systems.

The authors gratefully acknowledge the support of Agentschap NL and MI-Partners. They wish to thank Dick Laro (MI-Partners), Jan van Eijk (MICE) and Pascal Etman (Eindhoven University of Technology) for their valuable input regarding this research.

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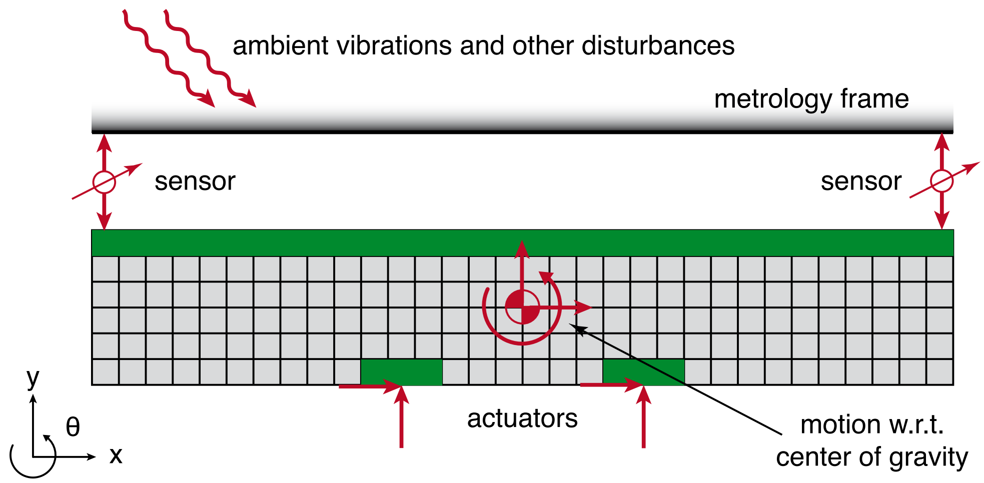


1 *A platform is positioned with respect to a metrology frame within three degrees of freedom, x, y and θ. The grey elements of the platform can be removed or added, to change the topology. The question is what the optimal structure should look like. The platform is 60 x 60 x 10 cm³. The assumed actuator and sensor locations are indicated by the arrows.*

closed-loop performance demands as objectives from the outset.
In anticipating the availability of Additive Manufacturing (AM) techniques for high-precision devices, it is particularly important to develop tools that can exploit the unprecedented design freedom these manufacturing techniques offer. This design freedom is difficult to fully explore by even the most experienced of mechanical designers, and therefore we develop optimisation-based tools to come up with conceptual designs of components, as a starting point for further design and development.

In this article the focus is on optimisation techniques that determine a certain material distribution within the user-specified geometrical boundaries of a component, i.e. topology optimisation. This topology is optimised with the direct aim of improving the controlled closed-loop performance of the system by taking into account the dynamic interaction between the component and the control system. We will discuss some basic aspects of the developed techniques and show some examples to highlight their potential. The article will conclude by listing a number of challenges on the roadmap, from proof of concept to industrial use.

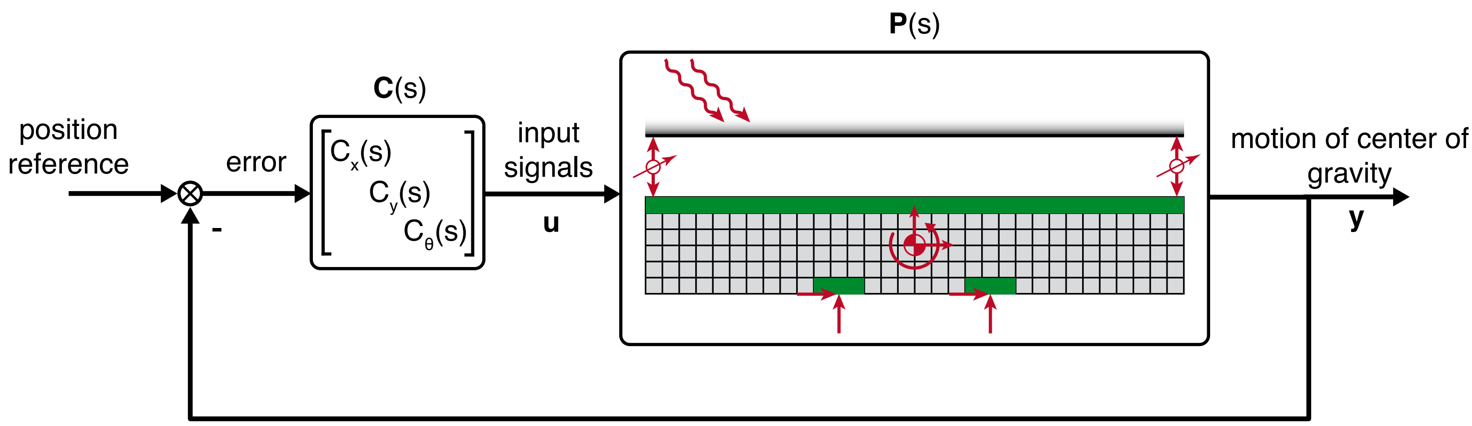
Topology optimisation

Topology optimisation (TO) refers to a category of optimisation techniques which can be used to conceptually design structures or components within many engineering contexts. Since its development in the Eighties, it has found industrial application in the automotive and aerospace industries in particular. The ideas behind topology optimisation will only be briefly outlined here. The interested reader is referred to [1], related to topology optimisation for thermo-mechanical systems, and [2], [3].

To define TO, we discuss some typical aspects that are involved with a TO problem. First, a design domain is specified that defines the geometrical limits of the sought design. This domain is equipped with the boundary conditions (i.e. connections to the environment) as well as loads pertaining to the problem to be solved. Then, the interior of this design domain is meshed and discretised using finite elements. The material distribution is controlled by assigning a design value between zero and one to each finite element. A value of 0 indicates no material whereas a value of 1 indicates solid material.

A schematic illustration of the motion control problem considered throughout this article is presented in Figure 1. Note that due to the number of finite elements one may easily have thousands of design values for 2D models and millions of design values for 3D models. Given this design value for each element, we have a fully-defined finite-element model of our problem. Next, an optimisation process is used to determine the optimal values for each of the density values, in order to maximise or minimise a certain objective function. In order to solve such a large-scale optimisation problem, it is necessary to use gradient-based optimisation techniques. In combination with adjoint design sensitivity analysis the gradients are efficiently computed.

The intrinsic capability of TO of coming up with complex geometries suggests a very natural and significant link with AM techniques that are able to realise such geometries with few restrictions. Furthermore, we do not make any a priori assumptions on the design or its parametrisation, other than the coarseness of the mesh, so that unexpected designs can be found.



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In literature, objective functions for topology optimisation are mostly concerned with the static performance (stiffness, compliance) or the dynamic performance (natural frequencies, frequency response) of structural designs. We will show the additional possibility of directly linking the objective to closed-loop performance within a motion system context.

Closed-loop system model

The closed-loop system model is used to predict the performance of the controlled motion system. The control system is laid out as depicted in Figure 2. The mechanics are assumed to be linear and discretised (e.g. using finite elements). This finite-element model is used to create a reduced-order model on the basis of a set of natural vibration modes. We assume the mechanical behaviour to be expressed as a transfer function:

$$y(s) = \mathbf{P}(s)\, \boldsymbol{u}(s) \qquad (1)$$

Here, $\boldsymbol{u}$ denotes the inputs to the motion platform and $\boldsymbol{y}$ denotes the outputs. Important to note is that this transfer function includes the allocation of actuator forces to nodes in the finite-element model and determination of the centre-of-gravity motions x, y and θ. Furthermore, the actuator forces are allocated so as to ensure that the rigid-body motions are completely decoupled in a static sense. That is, an input $\boldsymbol{u} = [1\ 0\ 0]^T$ will generate a pure x-motion and an input $\boldsymbol{u} = [0\ 0\ 1]^T$ will generate a pure θ-motion. The different sensor signals are also combined in such a way that the output signal $\boldsymbol{y}$ contains, respectively, the pure x, y and θ displacements of the centre of gravity. This allows us to approach the controller design as a problem that is largely decoupled.
The controller for each motion axis (x, y or θ) is assumed to be an independent PID controller with a fixed structure, commonly used in the control of motion systems [4].

2 *The control system layout examined in this study. The motion system is controlled within three degrees of freedom by independent PID controllers. The aim is to reject disturbances acting on the system in order to keep the platform positioned accurately.*

3 *A plot of the sensitivity function for a typical motion system. The arrows indicate the objective: minimise disturbance sensitivity within this frequency range. The red lines indicate the constraint, which limits the responsive overshoot.*

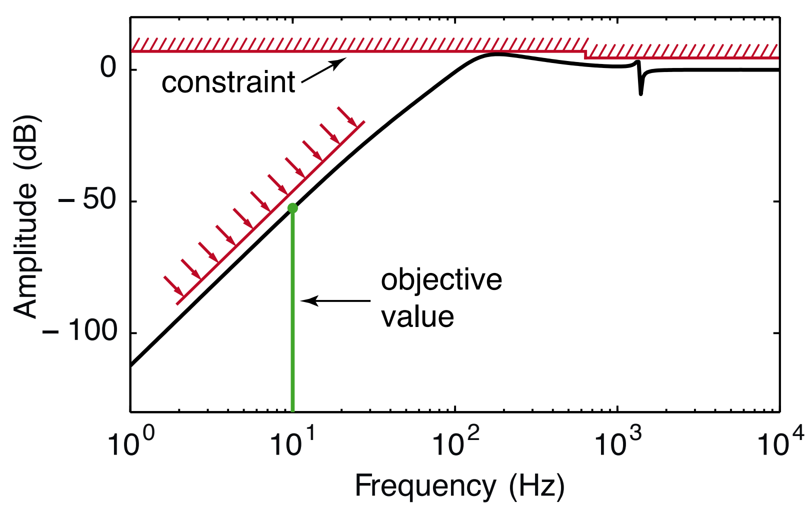
Hence, each motion control loop has a controller of the form:

$$C_i(s) = k\,\frac{s+\frac{1}{5}\omega_B}{s}\,\frac{3s+\omega_B}{s+3\omega_B}\,\frac{5\omega_B}{s+5\omega_B} \qquad (2)$$

This controller involves integral action for zero tracking error, lead compensation for stability and robustness, and roll-off; all governed by a bandwidth ω_B and a gain k.
To investigate performance of the closed-loop system, we focus on the disturbance rejection performance, which is governed by the sensitivity function:

$$\mathbf{S}(s) = (\mathbf{I} + \mathbf{P}(s)\,\mathbf{C}(s))^{-1} \qquad (3)$$

This function describes how disturbances acting on the motion system affect the outputs and is a performance function frequently used in control design. A typical example of a bode magnitude plot of the sensitivity function is shown in Figure 3. The information shown in this plot



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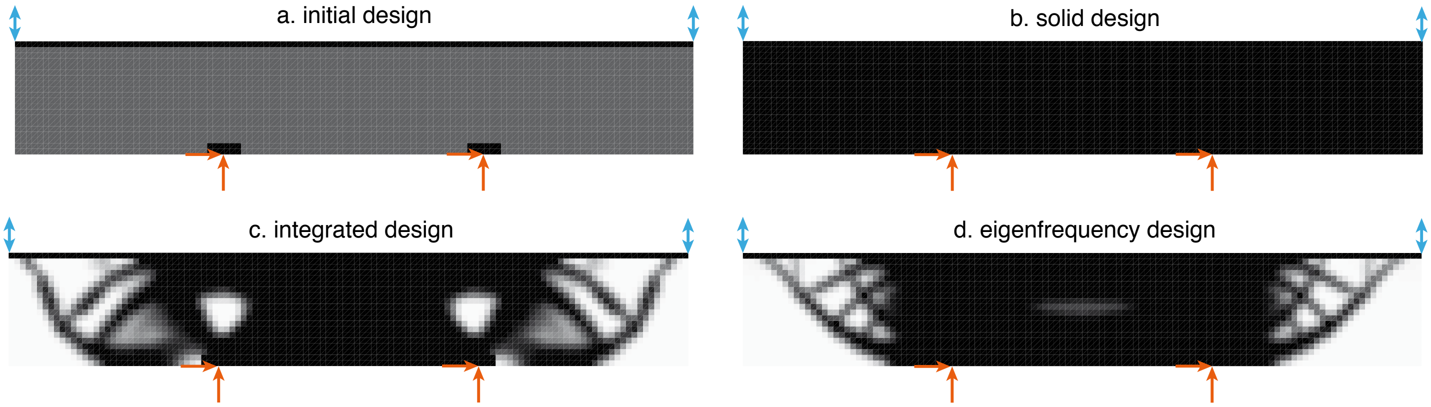

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allows us to formulate objectives and constraints for the topology optimisation problem. In words, the objective is to minimise the amplitude of the sensitivity function at low frequencies.
In the example discussed here a frequency of 10 Hz is chosen at which the sensitivity should be minimised. Since there are multiple control loops (three in this example with three rigid-body degrees of freedom), each of those will have a sensitivity function value at the frequency of 10 Hz (i.e. governed by (3)). The sum of these is minimised. To avoid the appearance of lightly damped closed-loop motions, we determine that the sensitivity functions cannot exceed a certain threshold value (i.e. 6 dB for the main sensitivity peak and 2 dB for the lightly damped subsequent peaks, see Figure 3). For single-loop control systems this also implies a degree of robustness. Finally, we determine all closed-loop poles of the system to be stable (i.e. in the open left-half plane).

How topology affects performance

We mentioned before that each finite element is assigned a design variable that varies between zero and one. To describe the properties of such an element for intermediate values of this variable, material interpolation models are used; see the article earlier this year for more details [1].

Here, it suffices to mention that an intermediate design value in a certain element results in a specified combination of physical material density and elasticity modulus for that finite element. In this way, changing the variables assigned to the elements affects the mass and stiffness matrices of the mechanical model. This, in turn, affects the dynamics of the mechanical system, allowing flexible modes and natural frequencies to be modified. By changing the topology and the controller parameters at the same time in an intelligent way, we are able to improve the performance criteria whilst meeting the constraints.

Design case

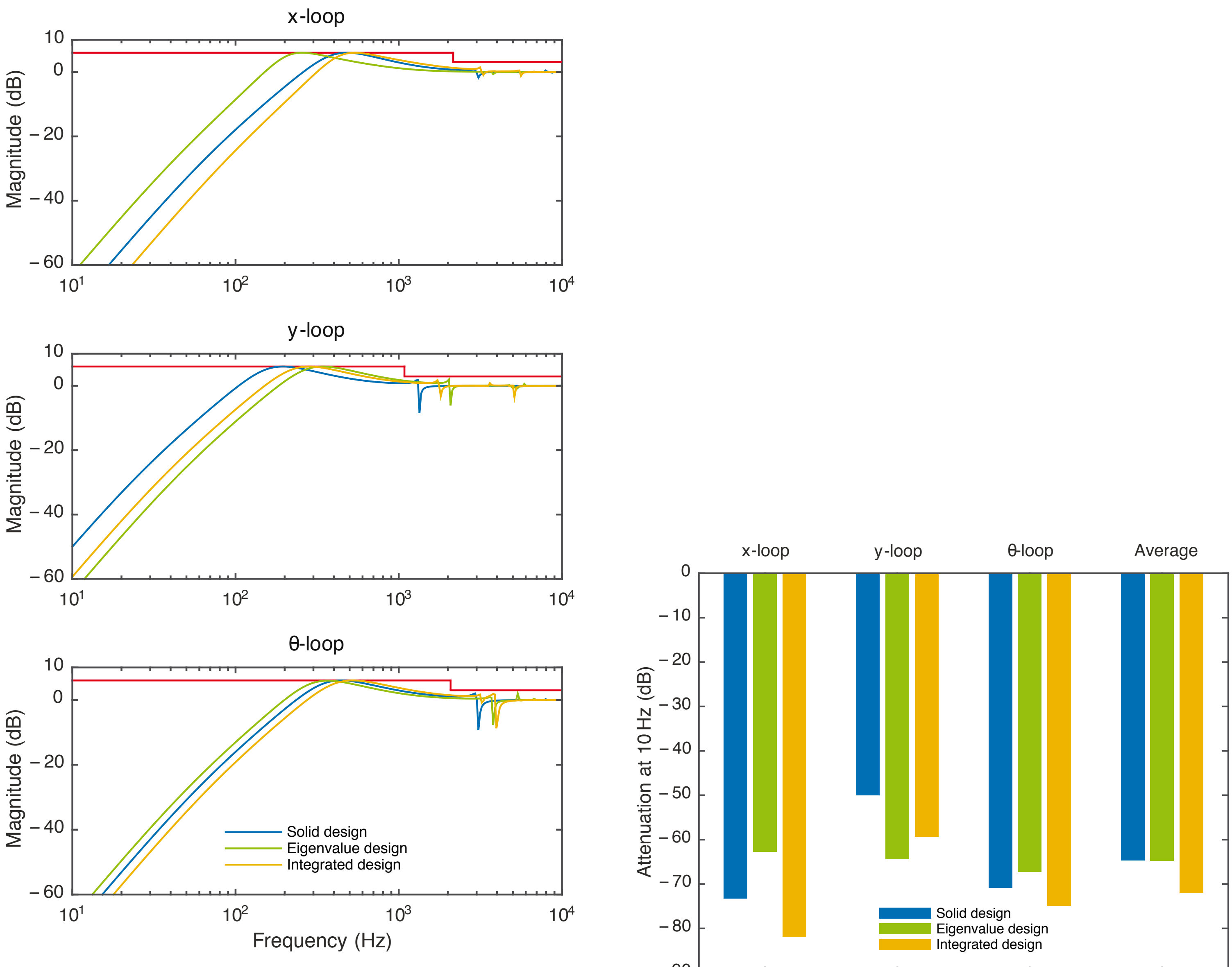
For the design case, the motion system depicted in Figure 1 is again investigated. The platform is constructed of aluminium, and fixed sensor and actuator locations are considered, as indicated by the arrows. The design of the top layer is fixed to provide a useful working surface, but the structure underneath (the meshed area in Figure 1) can be changed by the topology optimisation process. We will design the system twice over, each time with a distinct objective in mind.

One of the design rules for high-performance systems is to create mechanical parts with high natural frequencies. These natural frequencies are often a limitation in increasing controller bandwidth. This design heuristic, however, does not convey any information about mode shapes and, hence, whether a mode is a performance-limiting factor or not. Therefore, the question is asked: does an eigenfrequency-optimised design yield similar performance within closed-loop as a fully integrated design?

To summarise, the following cases are compared:
- Objective 1 (*Integrated design*): For the problem of positioning in three degrees of freedom (x, y and θ), maximise the disturbance rejection at 10 Hz in all three positioning loops, subject to stability and sensitivity overshoot constraints.
- Objective 2 (*Eigenfrequency design*): Maximise the sum of the first three natural frequencies of the system.

All optimisations are initiated from a design in which the design variables are set to 75% (see Figure 4a). One could have started with a 100% solid design, but that would not allow certain areas in the domain to be strengthened with respect to other areas in the first few design iterations, thus restricting the design freedom.

4 *Compared designs: The optimisations were started from the 75% gray initial design (a). Designs for maximum eigenfrequencies (d) and for best closed-loop performance (c) are compared to the performance achievable with a solid design (b).*



5 *Performance comparison of the three designs in terms of disturbance sensitivity of the three motion-control loops (left) and the disturbance attenuation at 10 Hz within these three loops (right, lower is better).*

The closed-loop system model is used to evaluate the objectives and constraints and to compute their gradients with respect to the design variables (density variables and controller parameters). This means that for each parameter in the system (either an element's design variable or a controller parameter) we examine how a small change in that parameter changes the performance and constraints. This gradient information is supplied to an optimisation algorithm, in this case, a sequential quadratic programming (SQP) algorithm, as described in [5]. The algorithm computes a design update with which the objectives and constraints can be re-evaluated.
This process is repeated until convergence. Due to the complex and nonlinear nature of the objectives and constraints, the process will likely converge to a local optimum. Nevertheless, this optimal design can be a significant improvement over the original one in terms of performance.

Figure 4 shows the designs to which the closed-loop performance is compared. The solid design is used as a reference design, Figure 4b. Then, the performance of a design that was optimised for maximum eigenfrequencies (Objective 2) is analysed, Figure 4d, and compared to a design for closed-loop performance (Objective 1), Figure 4c.

Figure 5 shows the sensitivity functions of the three positioning loops, to compare how the three designs perform. Note that the objective was defined as the disturbance rejection at 10 Hz, averaged across the three control loops. This is summarised to the right of Figure 5. Note that on average the three control loops perform best for the integrated design. For the solid design, the y-positioning loop performs quite poorly due to the dominant first bending mode of the structure that is directly activated by a vertical motion. This situation is improved for the eigenfrequency-optimised design, since the frequency of this mode is much higher. Ultimately, however, the fully integrated design delivers the best trade-off when all three control loops are equally important.

Note that this equal weight assigned to each of the control loops is just one possibility. Assigning different weights to the control loops, for instance based on real disturbance characteristics, allows more flexibility in formulating the objective and focusing the design towards a specific use case.
In terms of mass, both the eigenfrequency design and the integrated design use only about 70% of the mass of the solid design. The integrated design converged in 55 iterations, which took under 10 minutes on a pc. The eigenfrequency design required 88 iterations, but only took about 5 minutes due to lower computational complexity.

Outlook

The design case of a simplified motion system served to demonstrate the potential of topology optimisation techniques for improving the performance of such systems. The presented methodology allows the large design freedom offered by topology design to be explored and results in a conceptual design. This is still one of the early proofs of principle and various aspects require further investigation. A challenge to be addressed is to extend the method to 3D configurations whilst retaining feasible computation times. This is necessary to make the methodology applicable as a design tool for realistic cases. The tools will also be further refined by including various application-specific constraints (e.g., required stiffness or allowable deformation) in the design formulation.

In current and future research projects in the Structural Optimisation and Mechanics group at Delft University of Technology, these aspects will be developed further in collaboration with end-users. This will be part of a larger effort to develop TO design tools relevant to other issues within the precision industry, such as thermal design, and to incorporate the link between design tools and the actual Additive Manufacturing process. ■

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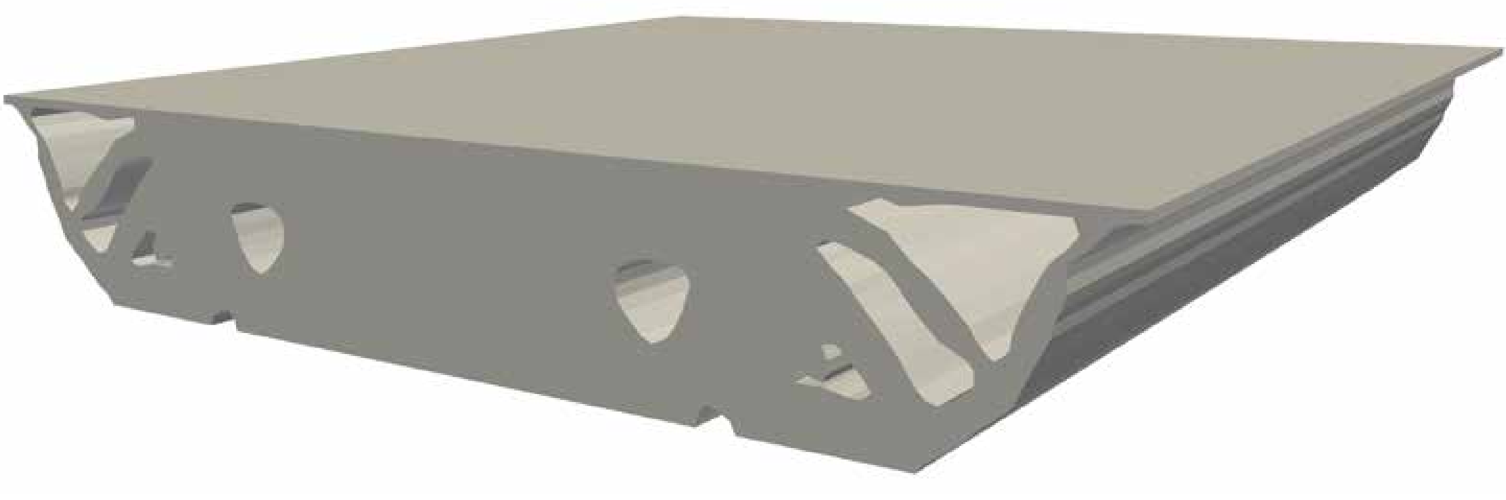


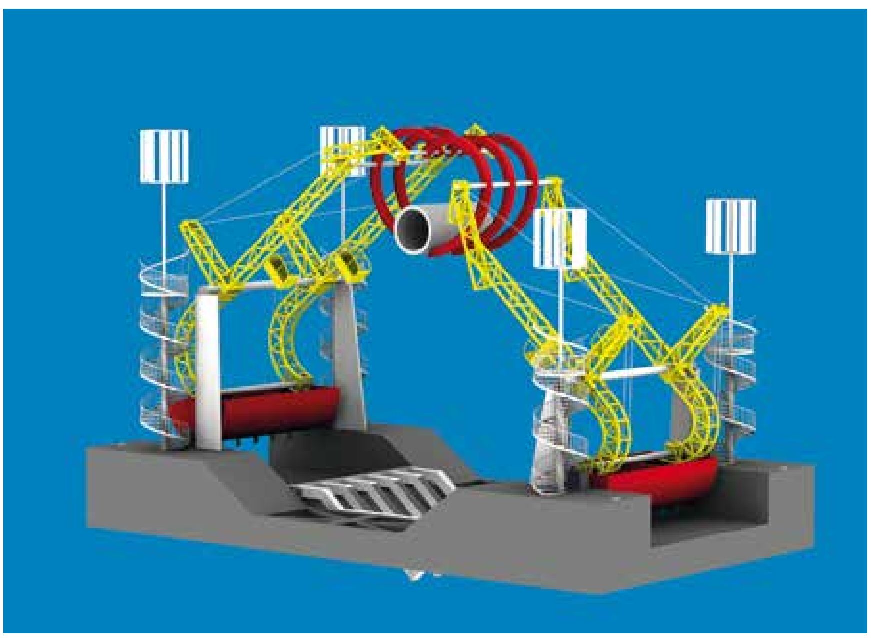
INSPIRATIONAL '60 YEARS' EVENT

To celebrate the 60th anniversary of DSPE, a special event was organised on the second day of the 2014 Precision Fair in Veldhoven, the Netherlands. The inspirational event offered a mix of historical reflection and presentations by young technological and artistic talents.

60th anniversary DSPE YOUR PRECISION PORTAL

■ *DSPE President, Hans Krikhaar, kicking off the special DSPE '60 Years' Event at the 2014 Precision Fair. (Photos: Jan Pasman)*

DSPE President, Hans Krikhaar, kicked off the event with short musings on the function and ambitions of DSPE as an independent professional branch organisation for all precision engineers in the Netherlands. Following a short overview of activities he outlined DSPE's broad remit, from precision mechanics and manufacturing technology to mechatronics and systems engineering, and then introduced the new domains that DSPE has started to cover, including additive manufacturing, robotics and photonics. He depicted DSPE as a guild society of precision engineers with the mission to cherish young professionals and ensure that the passion, knowledge and craftsmanship of experienced professionals is shared with the young.



■ *Design of the 'Taaie Tiller' by Volkert van der Wijk. (Illustration: Kinetic Art)*

Nobel Prize roots

Dick Harms, board member of DSPE and Director of the Leiden Instrument Makers School, delivered a short historical account covering 60 years of DSPE. Since the founding of its predecessor in 1954, the Dutch Association for Precision Mechanics (N.V.F.T.), DSPE has been active in the diverse world of instrument makers, precision engineers and glass technologists. Harms disclosed that the true origins of DSPE even date back to 1901, when in Leiden Professor Heike Kamerlingh Onnes formalised having unpaid 'students' by establishing the 'Society for the Advancement of Instrument Maker Training'. DSPE thus appears to have Nobel Prize roots, because in 1913 Kamerlingh Onnes won the Nobel Prize for Science for the liquefaction of helium.

■ *Timo Overboom delivering his presentation on the Ceiling Robot.*

Kinetic art

Next, Volkert van der Wijk, Director of Kinetic Art and researcher in the Faculty of Electrical Engineering, Mathematics & Computer Science at the University of Twente, presented his design of a giant piece of kinetic art. The 'Taaie Tiller' (Tough Lifter) is a moving sculpture driven by wind and water power, a machine that encourages the spectator to never give up hope. The design is based on Van der Wijk's research on dynamic balancing of parallel manipulators. He demonstrated how his dynamic balance theory finds applications in precision engineering as well as in kinetic art & architecture.

A 1: 6 scale model of the 'Taaie Tiller' is currently under construction on the University of Twente campus. The full-scale object will be realised in the harbour of Rotterdam, on a floating pontoon measuring 40 m long, 22 m wide, and 5 m high; the lifting height will be 18 m above water level. Under normal wind conditions the cycle time (lifting an object and dropping it in the water, giving rise to a big splash) will be one day.

'Flying carpet' under the ceiling

Timo Overboom, Ph.D. student in the Department of Electrical Engineering at Eindhoven University of Technology (TU/e), concluded the DSPE '60 Years' Event with his presentation of an innovative so-called Ceiling Robot. The Ceiling Robot is the world's first 'flying' planar motor in which a robotic platform is magnetically and contactlessly suspended beneath a ceiling. A prototype of this unique and complex mechatronics system was constructed within the TU/e research group led by Prof. E.A. Lomonova. ■

■ *Design of the Ceiling Robot: an actuator moves underneath a stator. Magnetic attraction forces provide for the gravity compensation.*

INFORMATION

www.dspe.nl
www.lis.nl
www.kineticart.nl
www.taaietiller.com
www.tue.nl/epe

CHANNELS AND PILLARS

Thermal control is often a key enabler for high-precision functioning. Part of temperature control can be achieved through cooling channels. Conventionally, channels are machined first and then covered. However, using Additive Manufacturing technology yields significant added value for conditioning applications that require fast thermal behaviour with good thermal uniformity.

GERRIT OOSTERHUIS, ALEJANDRO VILLEGAS, JOHN VOGELS, MELTEM CIFTCI, JAN SCHUTTEN, TON PEIJNENBURG, ROLAND HANEGRAAF AND FRANS-WILLEM GOUDSMIT

Introduction

In high-end manufacturing, such as semiconductor electronics production, thermal control is a key enabler for high-precision functioning. Sub-micron machine positioning accuracy, as well as product (substrate) stability, is only possible under tight control of the temperature. Part of temperature control is done by liquid (mostly water) cooling channels at crucial locations.

As a rule, channels are machined first and then covered using adhesive, brazing or welding, sometimes combined with gun drilling. Such processes all consist of multiple processing steps which, in addition, are often sensitive to yield loss. In all cases, the channel shape and location will deviate from the optimum as a result of manufacturing constraints, such as wall thickness, seals, o-rings, heat-affected zones or large tolerances needed for brazing or welding. Also, liquid cooling solutions require many seals, hose couplings and manifolds. Each of which has a finite probability for failure, which leads to possible reliability issues.

Through the use of metal Additive Manufacturing (AM), these limitations of conventional cooling channels can be overcome as embedded voids can be realised without additional features and processing steps. We will illustrate this for a wafer conditioning table manufactured in a suitable aluminium alloy, using the Selective Laser Melting (SLM) process.

Benefits of metal AM

The freedom of design that is enabled by AM has a large potential for novel thermal solutions. First, AM-designed channels can provide for reduced flow resistance due to smoother shaping. Also, increased heat transfer is enabled by AM. The text box provides an explanation on how AM influences thermal transfer. See also multiple examples in the contribution by TNO, Gregor van Baars et al., page 9 ff. Here, a case study will be presented that illustrates the potential of AM for thermal control and proof of advanced functionality is also given.

Case: Thermal wafer conditioning

This case study focuses on thermal wafer conditioning for lithography, which means that uniformity, temperature offset and speed of conditioning (thermal time constant) are the key drivers.

Requirements & design challenge

Table 1 shows the thermal and mechanical requirements for the thermal wafer table. The wafer contact requires

Table 1 *Overview of typical requirements for a thermal wafer table.*

Wafer table size	300 mm
Flatness	< 50 µm
Initial wafer offset from the machine reference temperature	A few K
Cooling time	10 s
Remaining wafer offset from the machine reference temperature (residual temperature)	mK range
Wafer temperature uniformity after conditioning	mK range

AUTHORS' NOTE

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exceedingly high cleanliness and surface quality. To achieve good thermal contact to the wafer, currently two main solutions are used within the industry: a burl plate or a (pre-loaded) air bearing. This wafer contact layer will not be manufactured by AM, as in both cases this is a high-precision manufacturing step that is done with conventional technologies. Therefore, the thermal effect of the wafer contact layer is omitted in the current study. Thus, the focus in the project is on optimising the cooling water channel geometry in components produced with AM.

How does AM influence thermal performance?

For illustrative purposes, a wafer cooling table is schematically depicted in Figure 1a. This is a simplified model assuming a constant water temperature as a boundary condition, as well as good conduction through the metal. The wafer capacity and contact resistance are ignored. Figure 1b shows a typical cooling curve of the top surface after loading a hot object. Two aspects are important, the speed of cooling, i.e. the time constant τ, and the actual temperature at $t = t_1$ at the point of interest; in this case $T_{top}(t_1)$. These two aspects are elaborated upon below.

Speed of cooling (time constant)

The time constant (τ) of this system is determined by the resistance (R_{metal}) and the capacitance (C_{metal}) of the metal , as well as by the thermal transfer to the cooling water ($R_{convection}$):

$$\tau = f\,(R_{metal}\, C_{metal}\, ,\, R_{convection}\,)$$

First, the metal body properties are elaborated:

$$R_{metal} = L_{metal} \,/\, (\lambda A_{metal}) \;\rightarrow\; R_{metal} \sim L_{thermal}$$

$$C_{metal} = V_{metal}\, \rho c_p \;\rightarrow\; C_{metal} \sim V_{metal}$$

Here, λ, ρ and c_p are material constants. Hence, the thermal resistance of a given material is determined by a characteristic length $L_{thermal}$. Similarly, the thermal capacitance is determined by the volume of the table. Hence, to optimise τ, $L_{thermal}$ and V_{metal} should be minimised. The design freedom of AM enables further optimisation compared to conventional manufacturing by, for instance, very thin walls, complex 3D channel crossings, elimination of couplings and interfaces, in addition to open structures with minimal mass.

To further reduce τ, the convection resistance $R_{convection}$ should be minimised:

$$R_{convection} = 1 \,/\, (HTC \cdot A_{channel})$$

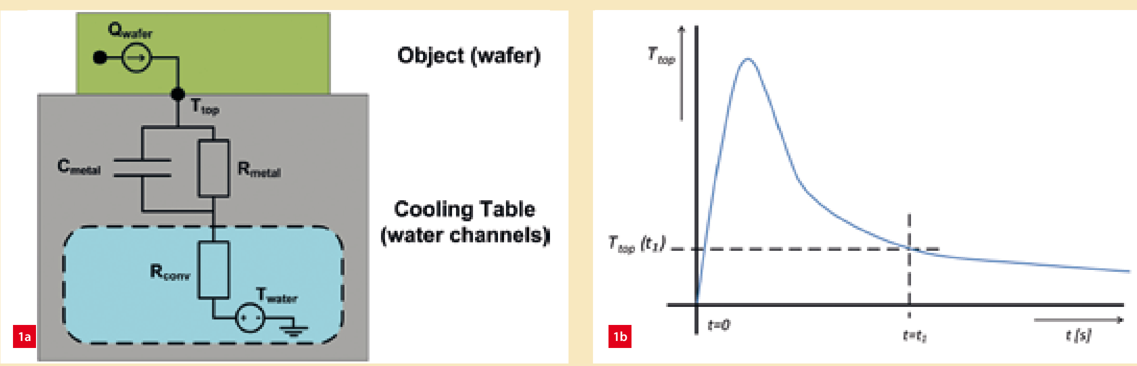
To reduce this resistance, the product of the heat transfer coefficient (*HTC*) and the channel surface area $A_{channel}$ should be maximised. This typically is a trade-off between maximum surface area ($A_{channel}$) on the one hand and optimal mixing and flow speed on the other hand, with both parameters determining *HTC*. AM can help to generate channel and surface properties that facilitate both parameters through, for instance, vorticity generators, complex heat exchange fins, multiple thin-walled channels, and pillar structures, etc.

Final temperature and uniformity

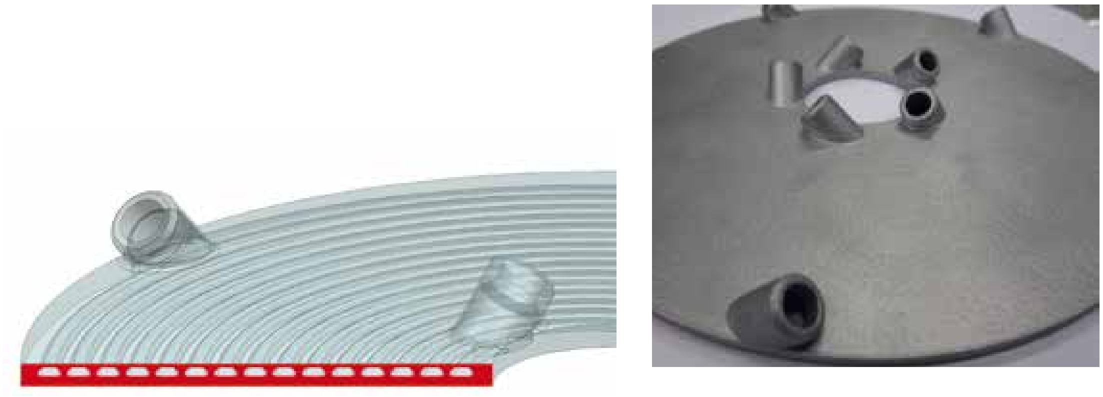
The final temperature of the top surface $T_{top}(t_1)$ in this simplified model is then determined by τ, the heat load $Q(t_1)$ and again R_{metal} and $R_{convection}$:

$$T_{top}\,(t_1) = f\,(R_{metal}\,,\, R_{convection}\,,\, \tau\,,\, Q_{wafer}(t_1))$$

As stated above, AM directly enables reduction of these parameters, hence improving the final temperature to be achieved. Finally, by an enlarged freedom to design the flow-guiding elements, AM also allows for an optimally distributed flow, hence better wafer table temperature uniformity.



1 *Wafer cooling table.*
(a) Simplified model.
(b) A typical cooling curve.



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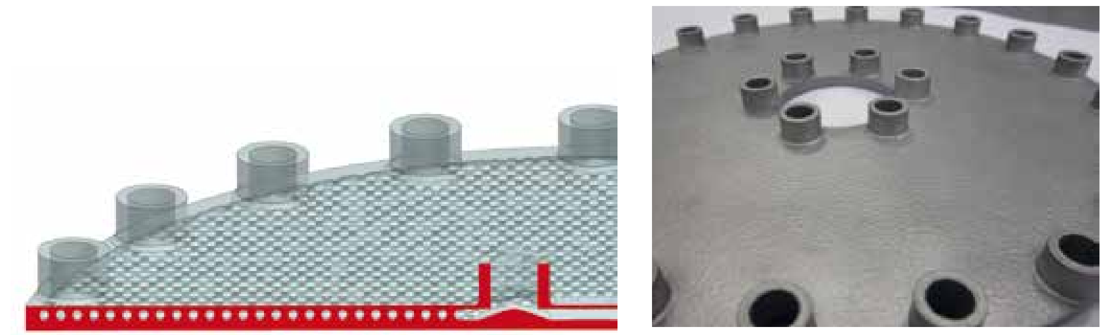


2b

2 *Drawings and test components (200 mm) manufactured by SLM in AlSi10Mg.*
(a) Channel concept.
(b) Pillar concept.

1D network model analysis

A simplified 1D network, or lumped-mass, model similar to the model in the text box has been used to study the feasible time constants that can be achieved. First, this preliminary model showed that a thermal conductivity like that of aluminium is needed to achieve the required performance; hence, aluminium was selected as the building material.

Further, in this analysis, the following water channel alternatives were compared, which do not all meet the requirements of Table 1:

- An existing thermal table design with o-ring seals, built from an aluminium alloy with approximately 100 W/mK thermal conductivity. This design has a time constant of 15-20 s.
- An optimised thermal table under development, built in a 170 W/mK alloy, with o-ring seals. This table shows a time constant of 5-7 s.
- A design optimised for AM, assuming a 100 W/mK printing alloy, without any seals and utilising minimal material usage, which leads to a time constant of 0.75-1.5 s.

It is clear that the use of AM significantly reduces the time constant of the thermal table. Therefore, it was decided to continue with a detailed 3D design & analysis, as well as with prototype testing to verify this result.

3D design and simulations

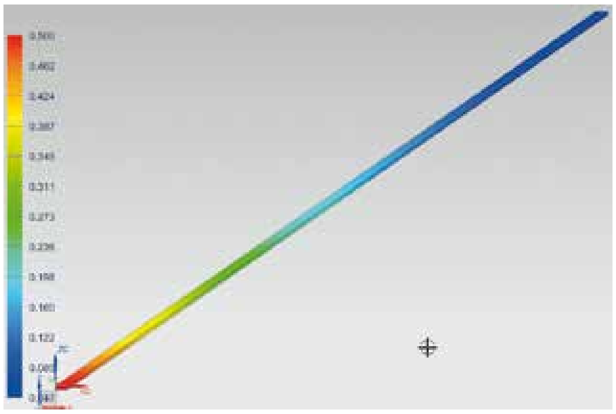
Based on general design considerations for AM [1], and the 1D model presented in the previous section, two starting points have been used for the design. One starting point was the classical approach using spiralling channels, which are easily scalable and lead to high uniformity by choosing a spiral definition that leads to an equal cooling area per channel length everywhere in the plate.

However, channels offer little possibilities to enhance the surface area or heat transfer coefficient (*HTC*, see the text box and for instance [2-4]). In parallel, a design has been made with a pillar structure (pillars) as starting point [5-7], which is promising because of the large surface area and many possibilities to enhance mixing, hence increase *HTC*. However, the performance of a pillar structure is less straightforward to predict.

This resulted in two concept designs based on turbulent flow, of which 200 mm example prototypes are shown in Figure 2. The channel concept exhibits multiple parallel spiralling channels, the pillar concept is a porous open structure, with top and bottom plate connected by many pillars. The geometries exhibit feature sizes and wall thicknesses down to 1-2 mm. Hence, both designs would be nearly impossible to realise with conventional manufacturing technologies.

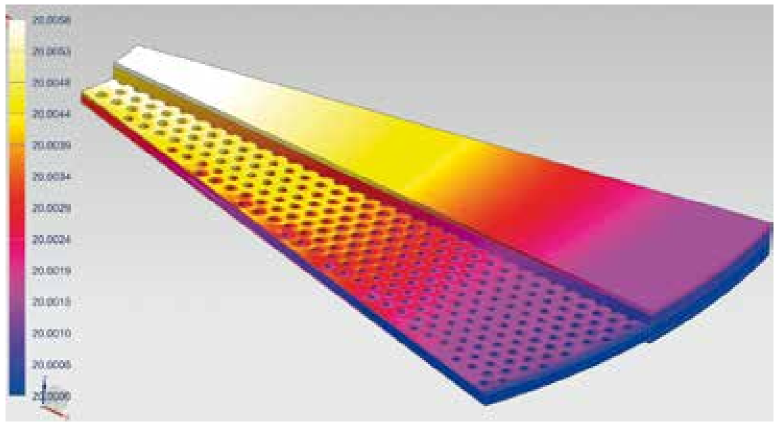
Channels

For the channel design, a straight channel was modelled, using analytical estimates of the Nusselt and Reynolds numbers, which together determine the thermal transfer



Flow	8	l/min
Average residual temperature	2.5	mK
Temperature non-uniformity (peak-to-valley)	5	mK
Pressure drop	590	hPa

3



Flow	10	l/min
Average residual temperature	3	mK
Temperature non-uniformity (peak-to-valley)	6	mK
Pressure drop	140	hPa

4

and water flow regime. In the wafer table, the vertical transport dominates the lateral transport. Therefore, the results of the straight channel can be considered to be representative for the full table performance. As such, a pragmatic and efficient modelling approach was possible.

The modelling software was NX Flow. Turbulent effects were taken into account using a k-ε model, and assuming a surface roughness of 0.1 mm. The channel results are given in Figure 3. It should be noted that in this approach the so-called 'local losses' (viscous and internal losses) are omitted; these relate to bends and corners in the flow. As a result, the calculated pressure drop will be slightly under-estimated. Thus, the residual temperature will be somewhat higher than modelled.

Pillars

For the pillar approach, there was scant literary reference for the given structure. In particular, further to literature, the determination of the Reynolds and Nusselt numbers was not possible. Hence, a more elaborate full CFD approach using the same software as for the channels was chosen, as can be seen in Figure 4. A circular segment was modelled, assuming a homogeneous inflow and outflow at the edges; a higher flow was possible due to the smaller pressure drop compared to the channel design.
To conclude, it can be asserted that the simulations show both designs are theoretically capable of meeting the required heat exchange performance. Both approaches seem to be capable of achieving the required conditioning down to a few mK, at an acceptable pressure drop. Especially the pillar design shows an exceptionally low pressure drop for the given water flow.

3 *Overview of the modelling results (scaled 100x, i.e. 0.5 degC equals 5 mK) for the channel design (the full 300 mm table contains eight pieces that are equally distributed). The simulated wafer temperature after 7 seconds is shown, for a flow of 8 l/min through the complete wafer table.*

4 *Overview of the modelling results for the pillar design. The flow is from the outside to the inside. The figure shows the simulated wafer temperature after 7 seconds, at a flow of 10 l/min through the complete wafer table.*

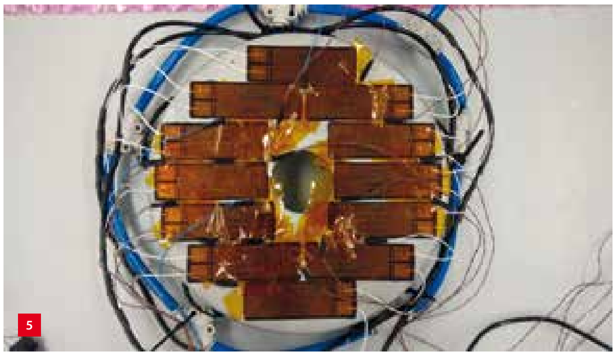
Prototype tests

To prove the potential of the AM structures and as an initial verification of the simulations, tests have been carried out on the prototypes given in Figure 2. Heaters and sensors were attached to the top surface (Figure 5). A step response of the PT100 temperature sensors is measured by applying a constant power to the heaters, with the water at nominal flow (7 l/min). The results are shown in Figure 6. To date, uniformity (derived from readings of multiple sensors distributed over the top surface) has not been analysed.

The first-order time constant was determined for each sensor location. It turned out that a good fit with the measured data could be achieved by using a single time constant. The average of the measured time constants is given in Table 2, together with the average amplitude of the step response. It can be seen that the time constants are well within the ranges predicted with the 1D modelling, proving the potential of AM to improve thermal conditioning. Furthermore, the channel design performs slightly better in time constant and amplitude. However, this is at the expense of a higher pressure drop.
It can be concluded that the AM structures performed as expected, hence enabling tighter control of the wafer

Table 2 *Summary of the time constants.*

	Prototype: pillar design		Prototype: channel design	
	Time constant [s]	Amplitude [K]	Time constant [s]	Amplitude [K]
Average (outliers exempt)	1.51	0.21	1.06	0.14



temperature. A full-size wafer table design based upon the 3D simulations should then include integrated water, air and vacuum tubing, as well as a suitable wafer contact layer.

What's next

It can be concluded from the above that using Additive Manufacturing technology yields significant added value for thermal conditioning applications that require fast thermal behaviour with good thermal uniformity. Hence, it will be beneficial to elaborate the generated concepts into real products.

However, before the SLM process can find high-tech application, such as in semiconductor equipment, a number of challenges still lie ahead that require further development:

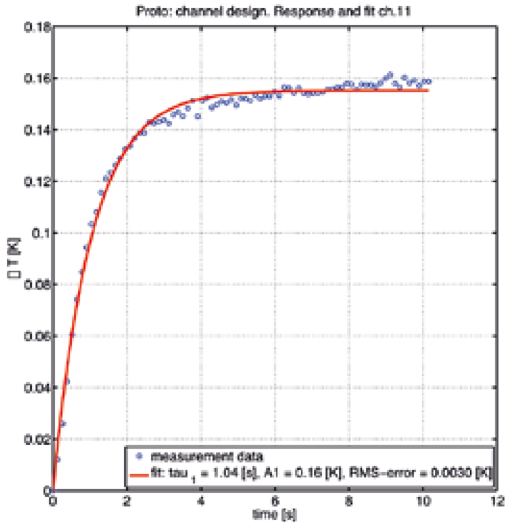
- cleanliness of cooling channels;
- material qualification & quality control;
- fully integrated manufacturing chain with robust interfaces;
- printing alloys with higher thermal conductivity;
- component size.

In addition, the design of an optimised structure is a far bigger bottleneck, looking at the vast amount of design freedom that is enabled by the manufacturing technology. Manufacturing issues can be solved by a limited number of focussed research groups, whereas for the industry to make maximum profit of AM, all the designers in the field have to be aware of the possibilities of AM.

As a result, the presented designs are still limited in the way the 3D design space is utilised. This is also caused by the fact that the designs are based upon existing products, and still carry a good resemblance to the design of the original product. The contribution by TNO, Gregor van Baars et al. (page 9 ff.), outlines a more advanced approach to the concept of thermal control, based on the same industry requirements that were the basis for the current study.

5 *Overview of one of the 200 mm prototypes instrumented with heater patches and PT100 sensors. Both were glued directly to the (rough) top surface of the thermal table.*

6 *Typical measured time response (circles) of a single measurement channel (location on the table) plotted together with a fitted 1D exponential model as shown in Figure 1.*
(a) Channel design.
(b) Pillar design.



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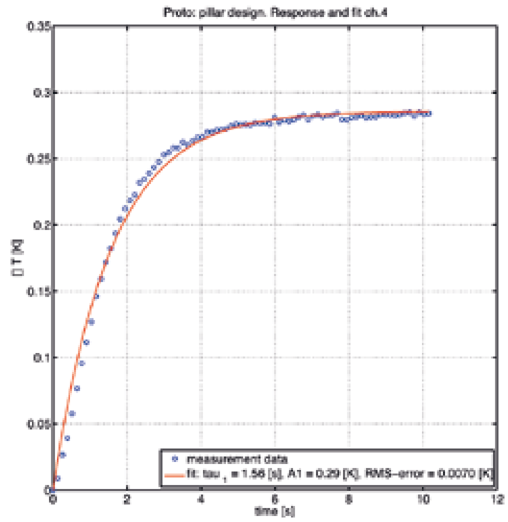

6b

To conclude, AM allows better thermal control by enabling lower thermal capacities and resistances, optimised convective transfer, and uniform flow distribution. Hence, this study clearly shows how the additional design freedom that AM provides can help to solve the very strict requirements of new thermal control structures, whilst enabling a reliable and economic product. ■

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UPCOMING **EVENTS**

3-5 March 2015, Veldhoven (NL)

RapidPro 2015

The annual event for the total additive manufacturing, rapid prototyping and rapid tooling chain, divided into RapidPro Industrial and RapidPro Home Professional. See also the News section.

WWW.RAPIDPRO.NL

17-18 March 2015, Huddersfield (UK)

Lamdamap 2015

Event focused on laser metrology, machine tool, CMM and robotic performance.

WWW.LAMDAMAP.COM

25-26 March 2015, Den Bosch (NL)

High-Tech Systems 2015

The third edition of this event is aimed at the high-tech systems industry in all European areas with significant high-tech roadmaps. It entails advanced system engineering and architecture, precision engineering, mechatronics, high-tech components system design as well as advanced original equipment manufacturing (OEM). The conference programme focusses on high-end system development for markets where smart engineering and technology make a difference.

WWW.HIGHTECHSYSTEMS.EU

22-23 April 2015, Veldhoven (NL)

Materials 2015, engineering & technology

Trade fair, with exhibition and lecture programme, targeted at product developers, constructors and engineers. The focus is on properties - applications - solutions.

WWW.MATERIALS.NL

22-23 April 2015, 's-Hertogenbosch (NL)

Mocon 2015

Dutch trade show covering industrial motion control and drive technologies. The latest innovations in design, construction, maintenance and use of components and systems will be displayed.

WWW.EASYFAIRS.COM/MOCON-NL

1-5 June 2015, Leuven (BE)

Euspen's 15th International Conference & Exhibition

This event will once again showcase the best international advances in precision engineering fields such as additive manufacturing, medical products, micro-biology, nano & micro manufacturing, metrology, mechatronic systems & control, renewable energy technologies and ultra-precision machines. Topics:

- Important/Novel Advances in Precision Engineering & Nano Technologies
- Nano & Micro Metrology
- Ultra Precision Manufacturing & Assembly Processes
- Renewable Energy Technologies
- Ultra Precision Machines & Control

Euspen Conference venue, the University Hall in Leuven.

WWW.EUSPEN.EU

3-4 June 2015, Veldhoven (NL)

Vision, Robotics & Mechatronics 2015 / Photonics 2015

Combination of two events organised by Mikrocentrum, featuring the RoboNED conference and the PhotonicsNL conference as parallel events.

WWW.VISION-ROBOTICS.NL
WWW.ROBONED.NL
WWW.PHOTONICS-EVENT.NL

22-26 June 2015, Eindhoven (NL)

International Summer school Opto-Mechatronics 2015

Five days of intensive training, organised by DSPE and The High Tech Institute.

WWW.SUMMER-SCHOOL.NL

PRECISION BY ADDING OR CHIPPING?

To print or not to print 3D, that is the question! An event such as the Precision Fair, this year on 12 and 13 November once again in Veldhoven, the Netherlands, provides an excellent opportunity to investigate the eagerness of manufacturers to adopt 3D printing as a promising precision technology. Because, if 3D printing – or, rather, Additive Manufacturing – were to develop into a faster, cheaper and more accurate technology, conventional milling, grinding and turning machines might be thrown onto the scrapheap. An exaggerated and unrealistic scenario or a grain of truth?

FRANS ZUURVEEN

AUTHOR'S NOTE

Frans Zuurveen is a freelance text writer who lives in Vlissingen, the Netherlands.

1 *Impression of the 2014 Precision Fair. (Photo: Jan Pasman)*

2 *A cooling flange produced by MTSA Technopower, with tolerances of only 5 μm.*

Just as in preceding years, the Precision Fair was characterised by numerous stands of companies that produce high-precision products (Figure 2). And, of course, many companies demonstrated their high-precision measuring machines. Just as many others exhibited their precision 2D or 3D positioning tables (Figure 3).

But unique to this year's Precision Fair was the exhibiting of complicated products (see Figure 4) realised by Additive Manufacturing (AM). ZME specialises in high-precision machining and recently acquired an 8-axis Willemin Macodel 508 MT universal machining centre. But, ZME recognises the advantages of 3D printing and therefore cooperates with Amitek, a specialist in AM. In fact, many of the products shown in Figure 4 cannot be manufactured by chipping because of complicated internal cavities, such as cooling channels.

3 *A Weiss 2.5D modular portal system with accuracy better than 3 µm at 500 mm. The z-movement is derived from two y-slides by converting their position difference into a vertical movement through a 45° slide. (Photo: Weiss)*

4 *Products, shown at the stand of ZME, made by AM with Amitek 3D prototyping machines.*

5 *A stainless steel air heat exchanger additively-manufactured by LayerWise.*

Interviewing specialists

It is quite interesting to listen to specialists' answers to the question of what future they imagine for AM. Robbert Smolders, of MTSA Technopower, predicts that within five years 3D printing technology will destructively impact conventional chipping machining. Eric Masseur, business unit manager at Bouman High-Tec Machining, states that solid manufacturing will stay interesting for the fast production of prototypes, because expensive tools are not necessary. But in his opinion it will continue to be a niche-market technology.

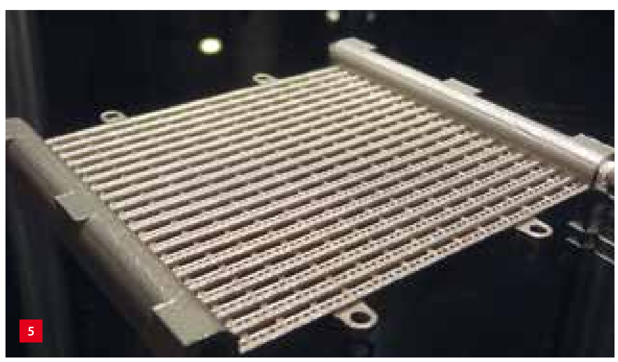
Raph Alink, account manager at Belgian LayerWise, recently acquired by USA-based 3D Systems, is very positive about the future of AM, because LayerWise can be considered as a pioneer in 3D printing of metal products, of course. Alink says that one of the obstacles on the way to higher accuracies is the minimal dimension of the particles to be printed. These particles, delivered to LayerWise by third parties, are tiny spheres of 30 to 50 µm diameter. They are produced by a plasma-based atomising process. Their dimension determines the 'resolution' of the manufacturing process and thus the accuracy. Alink also explains that the metals to be 3D printed should be weldable, so that the products can acquire a considerable filling grade by letting the particles melt together. Therefore, manufacturing parts from pure copper is very difficult or nearly impossible. Stainless steel alloys like 316L are the materials mostly applied by LayerWise (Figure 5).

Jürgen Barz, of Swiss-origin Schmelzmetall, confirms Alink's statement. His firm, specialising in the development and production of copper alloys, is able to print such alloys by applying lasers, but pure copper printing is very difficult and provides filling grades lower than 80%. Schmelzmetall produces extremely hard 3D printed nozzles and other components from copper-beryllium-nickel-cobalt alloys.

Giel Ulijn, sales engineer at Formatec Ceramics, explains that his company, specialising in manufacturing ceramic products using a sophisticated die-casting process, has developed an AM process for ceramics. Ceramic particles in a light-sensitive plastic are deposited layer upon layer and UV-lighted according to a z-position-dependent pattern. The UV radiation hardens the lighted parts in each layer, forming a 'green' product. This is subsequently heated in order to debind the plastic and to sinter the ceramic particles. In this way a complete ceramic product, aluminium or zirconium oxide-based, comes into being. Formatec has founded a new company, Admatec Europe, for the production of printing machines, as well as these ceramic products (Figure 6). Admatec already uses five of these machines, which are in-house developments.

3D printing R&D

Several firms report on their cooperation regarding research and development of AM technology. And, universities and other educational institutes invest in experimental 3D printing laboratories. In Eindhoven, the Netherlands, several manufacturing companies cooperate in Addlab, a 3D printing pilot factory for metal parts, housed in a former Philips building. The participating firms



6 *Ceramic products additively-manufactured by Admatec Europe. (Photo: Admatec)*

7 *Patrick Waller demonstrating Erowa clamping tools.*

8 *Diamond-based grinding wheels, exhibited by Technodiamant.*

include KMWE, NTS-Group, Frencken, De Valk, MTA, Kaak Group and Philips Innovation Services. KMWE is already active in this field by manufacturing the PixDro industrial 2D printer.

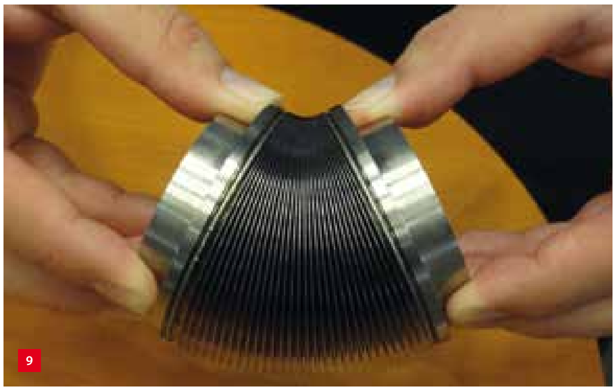
Likewise in Eindhoven, TNO is in collaboration with the Taiwanese non-profit organisation ITRI, in the Penrose Shared Research Programme for the development of next-generation AM machines. A third R&D 3D printing activity in Eindhoven is ObjeXlab (see page 53 ff.). ObjeXlab resulted from cooperation between Fontys University of Applied Sciences and the manufacturing industry.

More precision on show

Of course, many more interesting items were on show at the Precision Fair. For example, Switzerland-based Erowa demonstrated a selection of workpiece clamping tools with accuracies better than 2 µm (Figure 7). Philips Ceramics Uden exhibited a range of precision products made from PCA, polycrystalline alumina (Al_2O_3). These more or less transparent products are produced with accuracies better than 10 µm and are able to withstand temperatures up to 1,800 °C. They are being applied in professional lighting systems (see the article in the previous Mikroniek issue).

Technodiamant presented a range of diamond-based products: grinding wheels, monocrystalline bits for turning tools, and many other cutting and grinding applications (Figure 8). Tools with PCBN (polycrystalline cubic boron nitride) also belong to their delivery package. SBN Nederland, a subsidiary of SBN Wälzlager, displayed a complete range of roller bearings. Challenging to them is the production of subminiature bearings, including a ball bearing with 2.5 mm external diameter and 0.6 mm internal diameter. Another challenging task is the manufacture of stainless steel bellows. BOA Nederland produces these flexible elements, including bellows with individually-welded rings that are extremely difficult to make (Figure 9).

The last example of interesting precision-technological achievements is a web transport mechanism with porous air bearings (Figure 10), designed and manufactured by IBS Precison Engineering. This company – renowned for its submicron-range, even nano-range, measuring instruments – designed this device for R2R (roll-to-roll) foil processes. When producing flexible electronics for example, the avoidance of web contact is critical in reducing foil damage and contamination (see also the article on flexible electronics on page 48 ff.). With non-rotating porous rolls a very stiff air cushion of approx. 100 µm thickness was realised.



9 *A stainless steel bellow with individually-welded rings, produced by BOA Nederland.*
10 *A web transport mechanism with porous air bearings, designed and manufactured by IBS.*

To conclude

This Precision Fair yet again demonstrated the impressive accuracies 'good old' cutting technology is able to achieve. On the one hand, side ball bearings for a nigh on invisible shaft measuring 0.6 mm, and on the other hand, linear guiding systems with submicron measurement scales and equal straightness deviations. But, do we have to persist in making such precision components out of massive metal blocks by laboriously cutting chips? Or are we increasingly applying tiny metal particles in Additive Manufacturing technology?

Of course, the scrapheap referred to in the introduction almost certainly will not include our highly-expensive milling and grinding machines in the near future. More likely, the coming years will see both technologies existing side by side, each with their own merits. ■

Concluding message from the organisation

The 14th Precision Fair organised by Mikrocentrum in the Koningshof in Veldhoven on 12 and 13 November 2014 attracted a record number of 306 exhibitors and some 3,660 visitors (10% less than in the record-breaking year 2013). There was a remarkable growth in the number of exhibitors from abroad (in total 55), mainly from Germany, Belgium and the UK. Over 13% of visitors came from abroad, which is also more than last year.
A crowd-puller was the OEM plaza (Figure 11) where ASML, Roth & Rau and SoLayTec showcased their products together with partners from their precision engineering supply chain.

11 *Impression of the ASML stand at the OEM plaza. (Photo: Jan Pasman)*

The conference programme included 16 keynote speakers and 42 exhibitor presentations. Aside from the keynote tracks presented by CERN (European Organization for Nuclear Research) and ESRF (European Synchrotron Radiation Facility), mini conferences were held by DSPE (on the occasion of their 60th anniversary, see page 34) and Euspen (European Society for Precision Engineering and Nanotechnology). As usual, two awards were presented, see page 46.
Presentations can be downloaded from the website, www.precisiebeurs.nl/programma (or .../programme and .../programm, on the English and German sites respectively).

The next Precision Fair will be held on 18 and 19 November 2015.

WWW.PRECISIEBEURS.NL

YOUNG, ENTHUSIASTIC PRECISION ENGINEERING DESIGNERS

Mid November, in Veldhoven, the Netherlands, at the fourteenth edition of the Precision Fair, the Ir. A. Davidson Award and the Wim van der Hoek Award were presented. The awards went to Rens Henselmans, systems architect with NTS-Group in Eindhoven, and Marc Damen, mechanical engineer at Driem Dough Sheeting Technology, respectively. Henselmans received the prize for his achievements in the field of precision engineering and systems design as well as his great enthusiasm for the profession, Damen for his clever design and elegant construction of a robotic arm. Both awards are sponsored by DSPE.

Toon Hermans, managing director of Demcon Eindhoven, presented the Ir. A. Davidson Award on behalf of the DSPE board on the afternoon of Wednesday, 12 November. The prize aims to encourage young talent and is intended for a young precision engineer who has worked for some years in a company or institute and who has a demonstrable performance record that has been recognised internally and externally. Candidates must also use their enthusiasm to have a positive effect on young colleagues.

Ir. A. Davidson

The biennial prize, which was set up in 2005, is named after the authority in the field of precision mechanics at Philips in the 1950s and 60s. The prize comes with a trophy made by the Leiden Instrument Makers School (LiS), representing the handbook in precision mechanics with which Davidson laid the foundation for the constructors community of Philips.

2014 Ir. A. Davidson Award winner Rens Henselmans (left) receiving the award certificate from DSPE board member Toon Hermans. (Photo: Jan Pasman)

Systems architect

Rens Henselmans studied Mechanical Engineering at Eindhoven University of Technology (TU/e), earning his doctorate in 2009 under Professor Maarten Steinbuch, based on his design of the NANOMEFOS (Non-contact Measurement Machine for Freeform Optics). He worked for TNO in Delft as a senior systems engineer for 4 ½ years, where, among other things, he helped design and build the Laser Launch Telescope, part of the Very Large Telescope at ESO (European Southern Observatory). He also contributed a support for a segment of the European Extremely Large Telescope. In the spring of 2013 he joined NTS-Group in Eindhoven as a systems architect, where he has since helped on the design and construction of a complex module for an MRI-guided radiotherapy system.

Love of the profession

No fewer than eight candidates were nominated for the 2014 Ir. A. Davidson Award, a testament to the abundance of precision engineering talent in the Netherlands. The jury, however, selected Henselmans as the clear-cut winner, describing him as a young, enthusiastic precision engineering designer/architect. He has an impressive list of publications to his name, as well as a handful of product designs.

He believes the link between design and construction is vital, because it is in the latter that the designer is confronted with the consequences of their decisions. He is also notable for his passion for precision technology and systems architecture, and his professional commitment, as expressed through his willingness to share knowledge in reviews, bilateral contact and teaching courses.

Wim van der Hoek

The Wim van der Hoek Award (also known as the Constructors Award) was introduced in 2006 to mark the 80th birthday of the doyen of design engineering principles Wim van der Hoek. The Constructors Award is presented every year to the person with the best graduation project in the field of design in mechanical engineering at one of the three Dutch universities of technology. This award includes a certificate, a trophy made by LiS and a sum of money (sponsored by the 3TU Federation).

The 2014 Wim van der Hoek Award went to Marc Damen, who studied Mechanical Engineering at TU/e. He received the prize, in the presence of the award's namesake, from the chair of the jury and DSPE board member Jos Gunsing, Professor in Robotics and Mechatronics at Avans University of Applied Sciences in Breda, the Netherlands, and technology innovator at MaromeTech in Nijmegen, the Netherlands.

Marc Damen (left) receiving the 2014 Wim van der Hoek Award from the chair of the jury and DSPE board member Jos Gunsing.

Solid design process

Damen carried out his thesis project, "Design of a Robotic Arm for the Skinning of Pig Legs", at Marel Meat Processing in Oss. While at Marel, he worked on the automation of slaughter lines using dedicated robots. His work there was part of the DeboFlex project, sponsored in part by subsidies from the provinces of Limburg and North Brabant, the SRE Eindhoven Regional Partnership and the Dutch Ministry of Economic Affairs.

According to the jury, Damen distinguished himself in his thesis project work with a solid design process, which was "DDP worthy". "DDP" stands for "Des Duivels Prentenboek" (Dutch for "The devil's picture book"), a collection of notes and drawings originally collected as course material by Professor Van der Hoek and containing images of well-thought-out, statically defined structures. Damen investigated numerous design aspects of robotic arms in extreme detail and performed an accuracy analysis. This resulted in an elegant, thin-walled, tubular construction able to perform many functions in a limited amount of space – no simple task. Damen now works in Den Bosch, the Netherlands, at Driem Dough Sheeting Technology, an affiliate of Benier, a subsidiary of the Kaak Group. ■

INFORMATION
WWW.DSPE.NL/EVENTS/AWARDS

SMART AND FLEXIBLE

"Applying technologies for functional prototypes in the field of hybrid and wearable electronic applications for partners and customers." This mission statement of the Holst Centre in Eindhoven, the Netherlands, doesn't indicate a precision technology aspect. But, upon examining details of this research institute's activities real precision technology can be discovered. For example, the screen printing of successive layers of electronic circuitry with details of 30 μm and an overlay accuracy of 100 μm. Quite an achievement for such a traditional process from the book printing and textile worlds.

FRANS ZUURVEEN

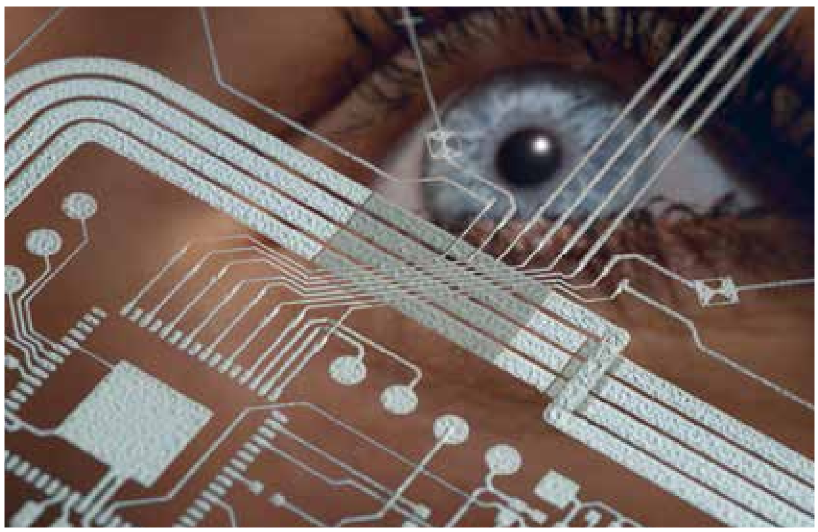
AUTHOR'S NOTE

Frans Zuurveen is a freelance text writer who lives in Vlissingen, the Netherlands. He acknowledges the input by Marc Koetse and Pit Teunissen, both researchers at the Holst Centre.

The Holst Centre was founded in 2006 by the Belgian IMEC – Interuniversity Micro-Electronics Centre in Leuven – and the Dutch TNO (Netherlands Organisation for Applied Scientific Research). Partners include Philips Electronics, DuPont, NXP and SPGPrint. The staff consists of about 170 researchers, of whom 70 resident from universities and industry. Their research aims at the development of flexible electronics and wireless transducer systems. The main aspects of flexible electronics are printing, assembly and encapsulation. Topics are OLED lighting, organic solar cells, rollable displays and flexible smart devices.

Flexible smart devices

For the deposition of electronic circuits on foil (see Figure 1) the Holst Centre applies three technologies: screen printing, inkjet printing and lithography. Each technology has its specific advantages and disadvantages. Screen printing works faster than inkjet printing but inkjet printing achieves higher resolutions. The best resolution is attainable with lithography, originating from the IC industry, but its high accuracy isn't always justified because the dimensional stability of foil is smaller than the stability of silicon. Moreover, lithography is a time-consuming manufacturing process when not automated. In general, *additive* screen printing is the cheapest process, whereas *subtractive* lithography is the most expensive one. Figure 2 shows one of the first flexible smart devices: an organic memory circuit.



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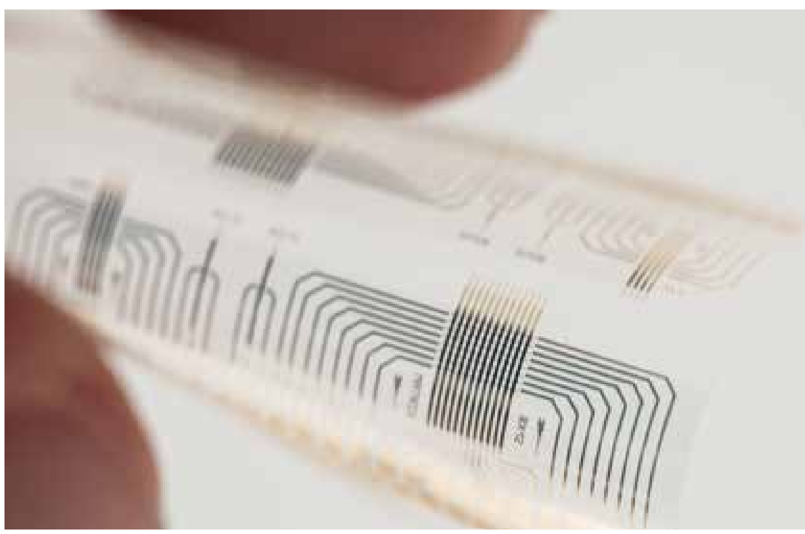

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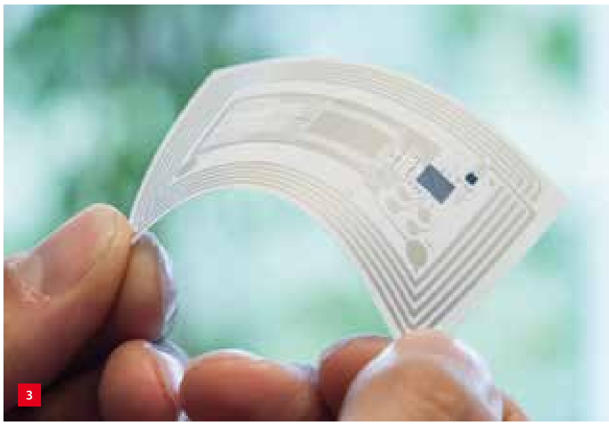
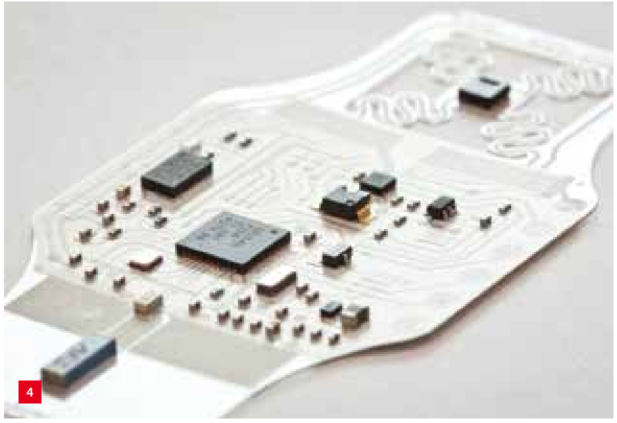
1 *An example of electronic circuitry on foil.*
2 *One of the first flexible smart devices: an organic memory circuit.*





3 *A flexible circuit with flip-chipped components.*

4 *SMD components on the flexible foil, connected to the circuitry by conductive glue.*

Combining printing with discrete components

Copper- or silver-based pastes can be applied when printing electronic circuitry on foil. The specific conductivity of silver circuits is higher but pastes with silver particles are more expensive, whereas copper conductors are susceptible to oxidation. After the deposition of pastes with micron or even nano particles, the pastes undergo a drying and sintering operation to merge the particles via atomic diffusion.

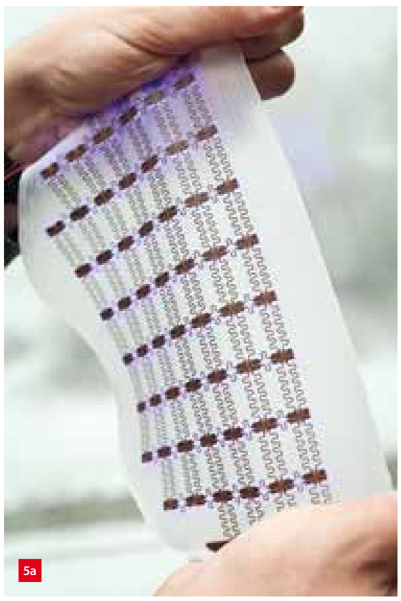
The trick of designing cheap and reliable flexible electronics is combining the deposition technology with discrete components, which can be positioned *onto* the foil or embedded *into* the foil. With the latter, unpackaged 'naked' chips are applied using so-called flip-chip assembly technology (see Figure 3). Figure 4 shows the application of SMD components (Surface Mounting Devices) on the foil.

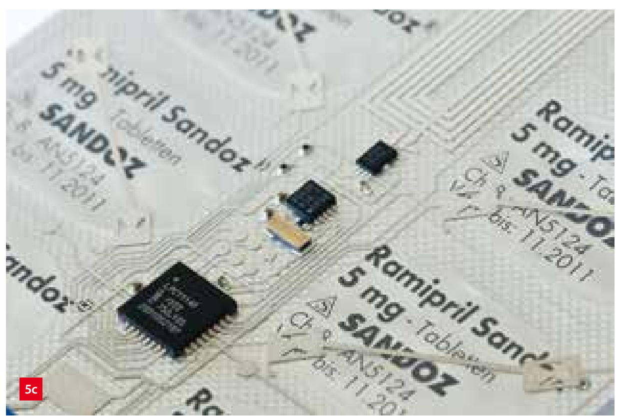
Connecting discrete components to the printed circuitry by conventional soldering is impossible because the used cost-effective substrates cannot withstand the temperature of molten solder. That's why conductive glue has to be applied.

Flexible electronics designed by the Holst Centre very often belong to the field of medical and healthcare applications. Examples are a sensor that monitors skin perspiration, and a device that monitors heart beat frequency, skin temperature and humidity when positioned on a breast. Figure 5a depicts straps that emit blue light for healing subcutaneous diseases. Figure 5b shows the former design of a smart blister packaging device with a separate control unit on PCB. It monitors which pill has been taken out of the blister at what time. This data is saved in the micro-controller and can be transmitted to a telephone or other device. Figure 5c shows the Holst Centre smart blister design for Qolpac with the control unit integrated in it. This application will be discussed in more detail below.

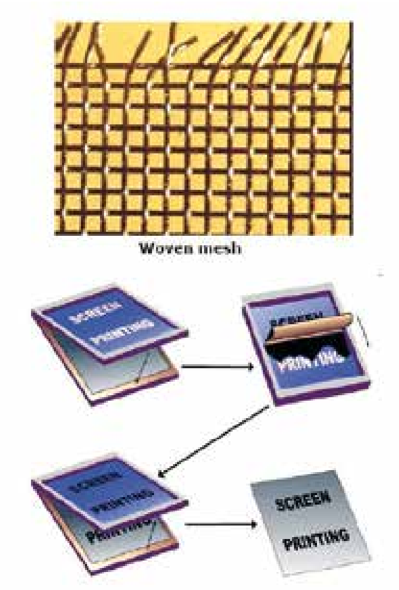
Smart blister packaging

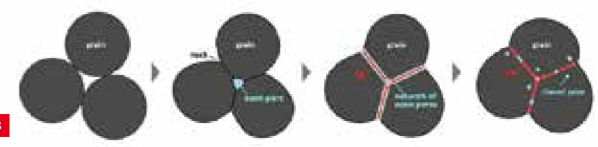
The control unit on foil consists of five building blocks: a thin-film battery provides power; a resistance ladder senses the place of the pill that has been taken out; a logic building block houses chips for measuring and registration; a radio





5 *Some flexible-foil applications.*
(a) Straps that emit blue light for subcutaneous therapy.
(b) Former design of smart blister packaging for medicines with control unit on PCB.
(c) Holst Centre design with control unit in blister.





6 The Holst Centre experimental screen printing production line with a SPGPrint R2R rotary screen printer on the left. The operator handles a rotary screen.

7 Schematic depiction of the screen printing process.

8 Schematic depiction of the sintering process, providing a filling grade of nearly 100%.

block contains chips for wireless communication and data storage; and an antenna transmits data to an external receiver.

The building blocks described above require the deposition of five successive layers on the substrate, for which PET foil (polyethylene terephthalate) has been selected. Screen printing with a DEK Horizon 03i machine is the preferred deposition technology. This is a so-called S2S (sheet-to-sheet) machine, in which PET sheets are fed by hand or robot. For higher throughputs an R2R (roll-to-roll) machine (see Figure 6) is a better proposition because such machines are easier to couple in series for the deposition of successive layers: continuous versus batch processing.

The deposition of the first two layers – circuit and antenna – in particular requires a minimal feature size of 100 μm and equally sized overlay accuracy: quite a challenge for screen printing technology. For the printed resistors layer, the ohmic deviation should be lower than 5%.

Screen printing technology

The principle behind screen printing comprises the positioning of a patterned mesh – the screen – above the substrate, subsequently applying paste on the mesh and finally pushing paste through the mesh with a so-called squeegee, which at the same time removes excess paste. Figure 7 explains this process: reproducing a direct image of the screen pattern on the foil.

The smallest feature size that can be reproduced under laboratory conditions amounts to 30 μm. The mesh may consist of a stainless steel woven fabric or an electro-formed nickel sheet with tiny holes (SPGPrint PlanoMesh). For the creation of a pattern on the screen the lithographic Si-wafer technology from the integrated circuits industry has been adopted: deposition of a thin light-sensitive lacquer, locally lighting the lacquer by optically projecting the required pattern and finally removing the lighted lacquer (or the unlighted lacquer) in accordance with a chemical development process.

Paste with silver particles of micron size is used for the conductive layers. Alternatively, nano-sized silver particles in a less cheap but more accurate process are applicable. For the dielectric layers non-metallic pastes are used, of course. The resistors are made by applying pastes with carbon particles.

The final step in the screen printing process is sintering (see Figure 8), in which the particles merge through atomic diffusion and solvents are damped out. The smart blister device is thermally sintered at a temperature of 130 °C. Alternative processes are photonic and electrical sintering.

Results

For the final smart blister circuitry on foil more than five layers were applied because extra isolating layers proved necessary as silver grains could cause short-circuits by protruding through one single isolating layer. Furthermore, an extra silver layer improved conductivity of the antenna for exact resistance tuning.

Figure 9a shows printed 100 μm wide lines on top of two layers of silver and four layers of dielectric. Figure 9b gives a height profile of bridging connectors across silver and

INFORMATION
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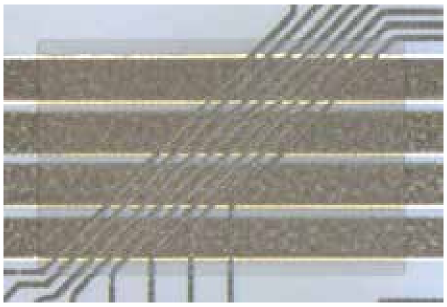

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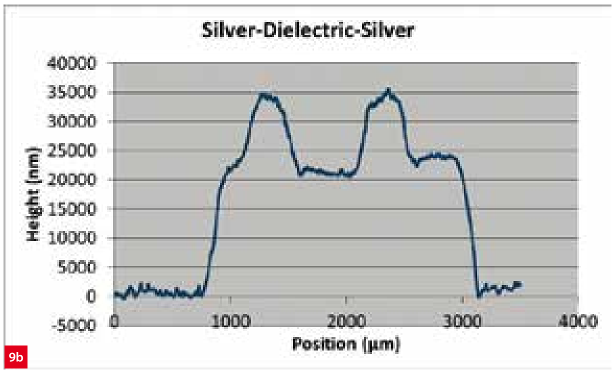


9b

9 *Results.*
(a) Printed 100 µm wide lines on top of two layers of silver and four layers of dielectric.
(b) A sharply defined height profile of bridging connectors across silver and dielectric layers.

dielectric layers. This profile proves the precision of the screen printing process: sharply defined high-resolution silver lines on a multi-layer stack. For the antenna a resistance of 15 to 16 Ω has been reached with PlanoMesh screens, whereas less than 40 Ω was specified.

Outlook

A few hundred prototypes of the smart blister packaging device have been manufactured successfully. The ongoing research will serve to technically and economically improve the smart blister manufacturing process.

For cheap high-volume smart-foil products many more applications look very promising. For example, a large-area pressure sensing foil detects the presence and removal of objects on and from a shelf: quite interesting for supermarkets. Skin patches which detect and transmit temperature, humidity, movement and pH will help to reduce public health costs. Smart flexible electronics will be integrated in clothing to improve comfort and wellness of the wearers. Almost certainly intelligent minds will invent many more applications that up to now only existed in dreams. ■

CPE COURSE CALENDAR

COURSE (content partner)	CPE points	Provider	Starting date (location, if not Eindhoven)
BASIC			
Mechatronic System Design - part 1 (MA)	5	HTI	9 February 2015
Mechatronic System Design - part 2 (MA)	5	HTI	20 April 2015
Construction Principles	3	MC	16 January 2015 (Enschede) 8 April 2015 19 May 2015 (Utrecht)
System Architecting (Sioux)	5	HTI	9 May 2015
Design Principles Basic (SSvA)	5	HTI	to be planned (January 2015)
Motion Control Tuning (MA)	6	HTI	8 April 2015
DEEPENING			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	24 November 2015
Actuation and Power Electronics (MA)	3	HTI	16 March 2015
Thermal Effects in Mechatronic Systems (MA)	3	HTI	29 June 2015
Summer school Opto-Mechatronics (DSPE/MA)	5	HTI	22 June 2015
Dynamics and Modelling (MA)	3	HTI	7 December 2015
Summer School Manufacturability	5	LiS	17 August 2015
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	3 November 2015
Applied Optics	6.5	MC	5 March 2015
Machine Vision for Mechatronic Systems (MA)	2	HTI	19 March 2015
Electronics for Non-Electronic Engineers (T2Prof)	10	HTI	13 January 2015
Modern Optics for Optical Designers (T2Prof)	10	HTI	23 January 2015
Tribology	4	MC	21 April 2015 3 November 2015 (Utrecht)
Introduction in Ultra High and Ultra Clean Vacuum (SSvA)	4	HTI	to be planned
Experimental Techniques in Mechatronics (MA)	3	HTI	1 April 2015
Design for Ultra High and Ultra Clean Vacuum (SSvA)	3	HTI	to be planned
Advanced Motion Control (MA)	5	HTI	5 October 2015
Iterative Learning Control (MA)	2	HTI	to be planned
Advanced Mechatronic System Design (MA)	6	HTI	3 July 2015
Finite Element Method	5	ENG	to be planned

DSPE Certification Program

Precision engineers with a Bachelor's or Master's degree and with 2-10 years of work experience can earn certification points by following selected courses. Once participants have earned a total of 45 points (one point per course day) within a period of five years, they will be certified. The CPE certificate (Certified Precision Engineer) is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills. The certificate holder's details will be entered into the international Register of Certified Precision Engineers.

WWW.DSPE.NL/EDUCATION/LIST-OF-CERTIFIED-COURSES

Course providers

- Engenia (ENG)
  WWW.ENGENIA.NL
- The High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LISACADEMY.NL

Content Partners

- Dutch Society for Precision Engineering (DSPE)
  WWW.DSPE.NL
- Mechatronics Academy (MA)
  WWW.MECHATRONICS-ACADEMY.NL
- Settels Savenije van Amelsvoort (SSvA)
  WWW.STTLS.NL
- Sioux
  WWW.SIOUX.EU
- Technical Training for Professionals (T2Prof)
  WWW.T2PROF.NL

IN SEARCH OF OPTIMAL COMPONENT DESIGN

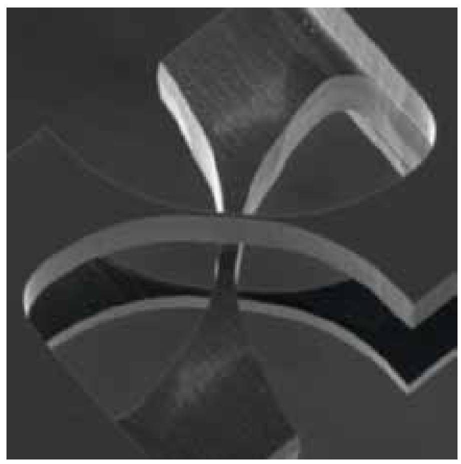
To identify components currently made by conventional machining technology that are suitable for redesign within Additive Manufacturing (AM) technology, it is essential to have a good understanding of the distinctive properties AM technology has to offer. This article provides a brief introduction, with a particular focus on metal printing. An overview is then given of the questions to be asked for screening the current (conventionally machined) product/component portfolio regarding their AM potential. Finally, an example underlines the importance of modifying component design to enable optimal AM.

SJEF VAN GASTEL

Introduction

What is nowadays commonly called 'Additive Manufacturing' (AM), started as 'Rapid Prototyping' in the mid-Eighties. The first commercially available 3D printer was based on the stereo lithography principle, where an (X, Y)-controlled UV light beam hardened out a layer of liquid plastic on a software-controlled (Z) build platform. The value of this novel technology was soon observed within the design and fashion industry for the purpose of rapid prototyping (3D printing).

Since then a lot has changed and currently a manifold of 3D printing technologies exists, each having specific characteristics to serve a share of market demand. All technologies have two things in common.
Firstly, building up a component by means of AM technology is done layer by layer (after addition of a new layer of the native component, the build platform is lowered by a layer thickness to enable building up the next layer).
Secondly, the interface language between the CAD system and the 3D printer is based on the STL (Surface Tessellation Language) interface format. The STL files describe only the surface geometry of a three-dimensional object without any representation of colour, texture or other common CAD model attributes. An STL file describes a raw, unstructured triangulated surface by the unit normal and vertices (ordered by the right-hand rule) of the triangles using a three-dimensional Cartesian coordinate system.



Since the introduction of low-cost FDM (Fused Deposition Modelling, see Figure 1) printers (€ 300-2,500) some years ago, 3D printing has become extremely popular and has entered the consumer market. In an FDM printer a plastic wire (filament) is fed into a heated extruder where the solid plastic is weakened and pressed through a nozzle. This nozzle is moved in the (X,Y) surface by means of a software-controlled gantry. The movement path of the nozzle equals the slice outline of the layer to be built. Below this nozzle there is a build platform which is lowered each time a layer of the object has been built.

AUTHOR'S NOTE

Sjef van Gastel is Director of Innovative Production Technologies at Fontys Hogeschool Engineering, part of Fontys University of Applied Sciences in Eindhoven, the Netherlands. He also is Technologies & Patents Manager at Assembléon, in Veldhoven, the Netherlands.

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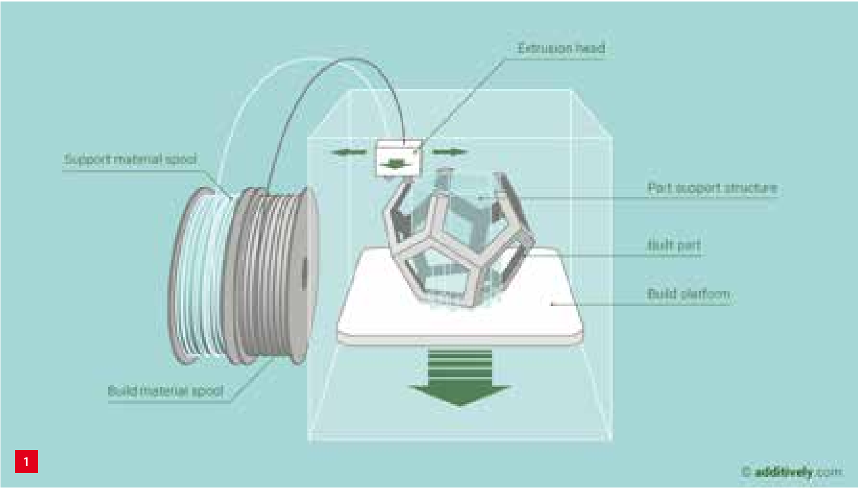


1 *Fused Deposition Modelling (FDM) printing principle.*

Most AM technology in use nowadays is related to consumer applications (3D printing of plastic objects). However AM technology also offers great benefits for industrial applications (plastic, metal and ceramic objects). Some (pioneering) companies have already noticed these benefits and have invested in 3D printing equipment.

Metal printing

The most commonly used technology for printing of metal parts is SLS (Selective Laser Sintering) or SLM (Selective Laser Melting, see Figure 2). SLS and SLM are related technologies, where a metal or plastic/ceramic powder is distributed equally in a thin layer over a build platform (powder bed), by means of a roller or a squeegee. Typical layer thickness is around 25-100 µm. An (X,Y)-controlled laser beam melts (or sinters) the powder particles in the build layer together. After building a slice of the component, the platform will lower over one layer thickness and a new layer of powder will be applied over the previous one.

Here the powder bed will be heated to reduce too large temperature differences between the particles that should be joined together and the superfluous particles. Also, the atmosphere inside the machine should be low in oxygen content to reduce unwanted oxidation. This can be attained by applying a nitrogen or argon atmosphere or by means of evacuation. After the component has been built, the superfluous powder should be removed (after cooling the component down to room temperature).

In the case of the SLS process the part density will typically be around 95-98%, and particles have only been partially attached to each other, resulting in a brittle structure. To obtain a better, stronger higher-density object, sintering at elevated temperatures will be needed. In the SLM process (metal-only) density will be around 100% and sintering is not necessary.

Comparing AM to conventional machining

As stated earlier, most machine factories and machine shops are not aware yet of the benefits of AM technology. In conventional machining of components all processes are executed sequentially and material is removed from the starting material until the desired object (final component) is attained. The biggest benefit of conventional machining is that component quality (tolerances, surface roughness) is (still) superior to the quality of an AM component. However, there are also many disadvantages, such as: work preparation covering all sequential fabrication steps, limitations in component shaping (for example: curved holes are not possible), many different tools being required (costs, tool wear), many different machines being required (lathes, milling, grinding, welding, drilling, etc.), and most of the starting material isn't used for the final component but is removed in the form of chips.

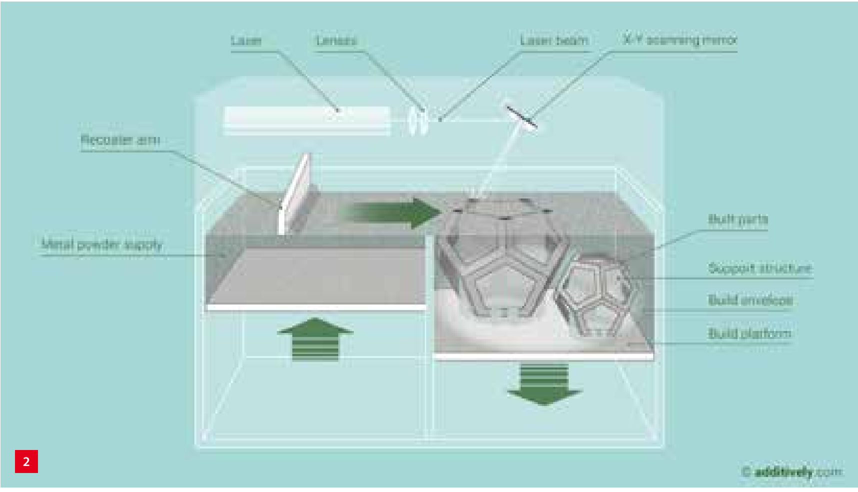
AM technology, on the other hand, is a single manufacturing process where all shapes of the final component are realised in a (single) manufacturing stage. However, in most cases (partial) machining of the AM component will still be needed to achieve the desired tolerances and surface finish.

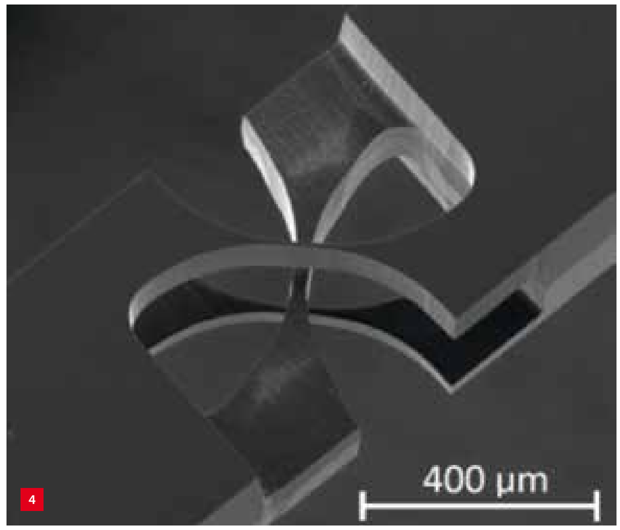
ObjeXlab

Nowadays, many initiatives are taken to introduce 3D printing technology for educational purposes (FabLabs, public libraries, schools). Because of its inspiring feedback between the design of an object and the physical object, 3D printing has become an important factor in stimulating students to opt for a technical education.

At Fontys University of Applied Sciences in Eindhoven an initiative was taken in 2012 to set up a laboratory for AM, called 'ObjeXlab'. ObjeXlab aims for a public-private cooperation to explore AM opportunities by means of applied research projects focussed on the Dutch Brainport area. ObjeXlab is part of the Centre of Expertise High Tech Systems & Materials at Fontys.

Projects are manned by both industry participants (engineers, researchers) and educational participants (students, teachers). The outcome of these collaboration projects will be beneficial both for industry (student talent scouting, project results, facility sharing) and for education (education of students, training of staff in emerging technologies, knowledge for curriculum).





2 *Selective Laser Melting (SLM) printing principle.*
3 *3D printed metal component with internal lattice structure.*
4 *Example of an integrated miniature 3D printed component. [1]*

Exploring opportunities for AM technology

To identify components (currently made by conventional machining technology) for redesign within AM technology, it is essential to have a good understanding of the distinctive properties AM technology has to offer. It makes no sense to copy conventional components exactly by means of AM. This will lead, in most cases, to more expensive components of inferior quality. So, what are the distinctive properties of AM?

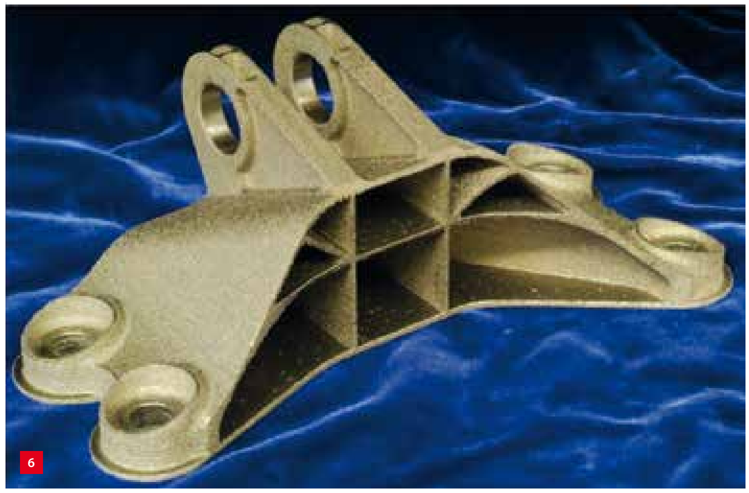
First of all, AM is extremely suitable for unique, one-of-a-kind, components. Consider here, for instance, personalised items such as personal gifts, medical implants (jaw implants, skull implants, knee joints) and medical aids (hearing aids, ear shells, orthotics, dentures).
Secondly, AM allows more freedom in shaping component surfaces, such as external curvature and curved holes. These curved holes, for example, can improve heat transfer in integrated heat exchangers.
Thirdly, it is possible to make components with variable mass density, using lattices (see Figure 3). These lattices enable mass reduction and stiffness optimisation in machine design.
Fourthly, it will be possible to combine functionality of multiple individual components into one integrated component, enabling both cost reduction and improved functionality. A new EU-funded project ('Femtoprint') is exploring the limitations of 3D printing, for example, regarding integrated miniature 3D printed components (see Figure 4).

Finally, one can benefit from specific properties of 3D printed components, such as the 'orange peel' of SLM components for optical mounts to reduce internal light reflections or the porosity of SLS components to apply in vacuum grippers.

'AM killer applications' workshop

To help identify the opportunities for AM within a company's product portfolio, the ObjeXlab (see the text box) has developed the 'AM killer applications' workshop. In this workshop the ability of AM to achieve competitive advantages via product attributes that would be impossible using conventional manufacturing technology will be investigated. The following questions need to be answered to identify these opportunities.

- What are the main points of distinction of a company's products compared to its competitors:
  - How is this distinction realised?
  - What are the typical product attributes that determine this distinction?
- Which (components of a) product(s) determine(s) this?
- Are there typical attributes of AM (shorter time-to-market, customisation, design freedom, mass reduction, integration of functions) that could strengthen the competitive advantage?
- If so, what (sub) components are eligible?



5 *Original jet engine loading bracket (milled).*
6 *The winning design (3D printed using SLM technology).*

- Can the potential benefits of the identified components be quantified? (e.g. cost reduction, lead time reduction, performance)
- How would one rank the identified opportunities, when an assessment is made of efforts (risks) versus the potential reward?
- What are the most promising application(s) for AM?

GE design challenge

To illustrate the effect of optimising a machine component for AM technology, GE organised a design challenge for engineering students in June 2013, the GE jet engine bracket challenge [2]. Loading brackets onto jet engines plays a very critical role: they must support the weight of the engine during handling without breaking or warping. These brackets may be used only periodically, but they stay on the engine at all times, including during flight. The original bracket that GE challenged participants to redesign (see Figure 5) via 3D printing methods, weighed 2033 grams. The winner was able to reduce its weight by nearly 84%, to just 327 grams (see Figure 6).

GE Aviation 3D printed the ten shortlisted designs at its AM plant in Cincinnati, Ohio. GE workers made the brackets from a titanium alloy on an SLM machine, which uses a laser beam to fuse layers of metal powder into the final shape. The team then sent the finished brackets to GE Global Research (GRC) in Niskayuna, New York, for destruction testing. GRC engineers strapped each bracket onto an MTS servo-hydraulic testing machine and exposed it to axial loads ranging from 35.6 to 42.2 kN. Only one of the brackets failed and the rest advanced to a torsion test, where they were exposed to torque of 565 Nm. This GE jet engine bracket challenge is an excellent illustration that emphasises the importance of modification of component design to enable optimal Additive Manufacturing.

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[2] www.ge.com/about-us/openinnovation

OBJEXLAB WORKSHOP

An optimal design, combined with AM, will strengthen a company's competitive edge. Interested parties are invited to contact the ObjeXlab, which will be happy to organise an in-company 'AM killer applications' workshop.

WWW.OBJEXLAB.COM

THE IMPACT OF PRINTING

The printing process plays an important role in digital manufacturing. When developing a new digital manufacturing application, the chances are high that one or more phases of the printing process will prove challenging. Insight into the printing process is necessary to overcome these challenges and develop a robust printing process and application. Simulating the phases of the printing process will provide the necessary insight at an early stage of the development process. An overview is presented of a set of simulation models covering the different phases of the printing process.

ERIK DANNENBERG AND JAKKO NIEUWENKAMP

AUTHORS' NOTE

Erik Dannenberg is an expert simulation & modelling and Jakko Nieuwenkamp a senior expert modelling & simulation at Reden, based in Hengelo (Ov). This work was partially supported by the Dutch PrintValley project.

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Introduction

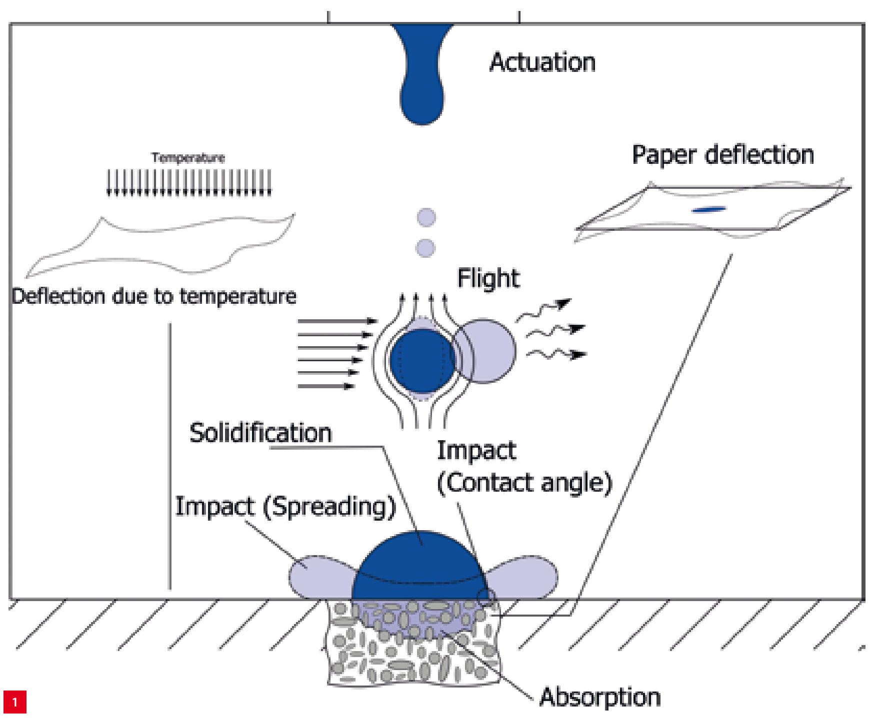
Making new products is all about the building blocks and assembly process. The building blocks define the potential of the product whilst the assembly process defines utilisation of the potential. This is no different when looking at a printer. The building blocks, the droplets, create immense potential due to the fact that they are small and can in theory be of any material, e.g. ink, polymers, tissue and molten metals. The accuracy of positioning the droplets in space and time (assembly) and how one can control negative side effects determines a large part of the product quality.

In order to fully utilise the potential of the printing process, more understanding and better prediction of droplet behaviour, during flight and upon impact, is needed. The behaviour of the substrate due to droplet depositioning (for example, local temperature changes and deformation due to absorption) is of interest too, since this influences the precision of the printing process.

Modelling is a good way of gaining insight into the phenomena which drive the different stages of the printing process. The capability to predict the behaviour of the droplet and substrate is of high value.
Although the focus in this article will be on drop-on-demand piezo inkjet printing (PIJ), using water-based ink, these models can underpin future research into the printing of polymer, molten metal and tissue, and other materials.

The different phases of printing

In the printing process four phases can be distinguished: droplet actuation, droplet flight, droplet impact and substrate behaviour upon impact (see Figure 1).

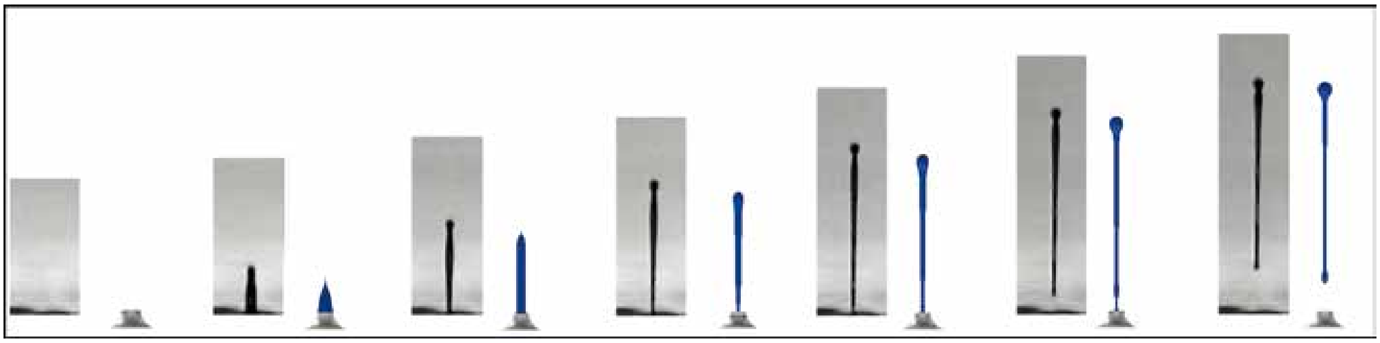


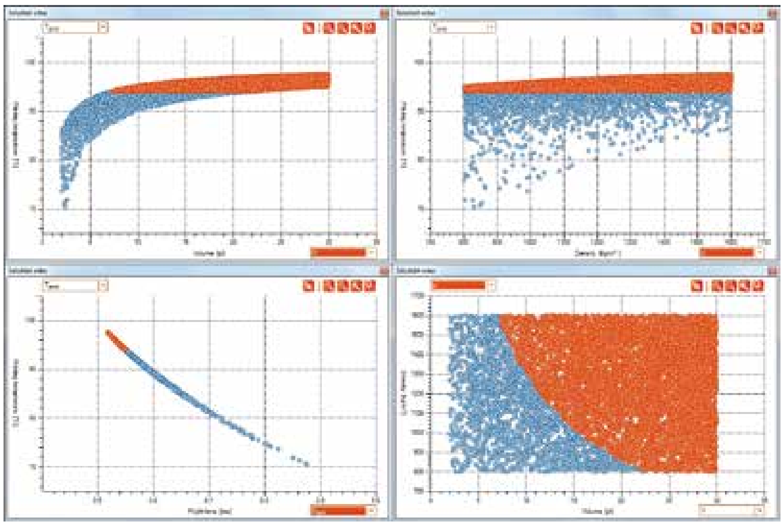
1 *The phases in the printing process.*

In all four phases, different phenomena occur. In the next sections, the different phases are discussed. An overview will be given of the methods used to gain insight into the phenomena, resulting in design rules.

The actuation phase

In the actuation phase, a closer look is taken at droplet formation. In PIJ, droplet generation is driven by a pressure wave in the nozzle chamber. The liquid in this case is a water-based ink, with density ρ = 1,000 kg/m^3 and dynamic





2 *Droplet actuation. Experimental work of Wijshoff [2] and the current simulation results, side by side, left and right, respectively. To the lower left the pressure pulse for actuation is shown.*

3 *Solutions found by MrReves for different droplet parameters. The red solutions are the solutions with impact temperatures above 94 °C.*
Upper left: volume versus impact temperature.
Upper right: density versus impact temperature.
Bottom left: impact temperature versus flight time.
Bottom right: volume versus density.

viscosity μ = 10·10^{-3} Pa·s. The air is taken into account with density ρ = 1.2 kg/m^3 and dynamic viscosity μ = 18·10^{-6} Pa·s. The droplet actuation is modelled using the commercial finite-element model (FEM) package Comsol Multiphysics [1], in which use is made of the implemented level set function and the Navier-Stokes equations.

In Wijshoff [2], the droplet actuation mechanism using a pressure pulse, is studied experimentally by photographing the droplet during the actuation phase. The same conditions as used by Wijshoff for the experimental droplet actuation are used here. The nozzle diameter is 32 µm, from which the length scales can be calculated. As can be seen in Figure 2, the simulation concurs with the experimental work of Wijshoff [2]. (Wijshoff also found good agreement between experiment and simulation, using Flow3D).

Using this model, the droplet formation using different pressure pulses can be investigated: the formation of satellite droplets due to the actuation mechanism, as well as the influence of the actuation mechanism on the final droplet speed. Also, the formation of one droplet from several smaller droplets can be researched.

The droplet flight

During the flight of the droplet between nozzle and substrate, the droplet undergoes temperature loss and drag (deflection and/or deceleration). For this phase, analytical equations with regard to the impact velocity, time to impact and temperature loss have been derived. Note that the input for this phase, such as droplet speed, is the output of the previous phase. In this phase, the droplet is assumed to be spherical.

These equations have been implemented as design rules into the software tool MrReves [3]. Using this software tool, the equations can be solved (fully coupled) for any set of parameters that the user provides. Also, a domain can be specified, and the effect of parameters within this domain can be shown by MrReves.

As an example, in Figure 3 different parameters are plotted against each other for the following jetting parameters: a printhead velocity (parallel to the substrate) of 200 mm/s, at a distance of 2 mm above the substrate, and the printhead (initial drop) temperature is 100 °C. The drops will leave the nozzle at a speed of 4 m/s, the surrounding air has a temperature of 20 °C (specific heat capacity of the ink 4,180 J/kg/K, thermal conductivity 0.6 W/(mK)).
The volume and density vary between 2 and 30 picoliter, and 800 and 1,600 kg/m^3 respectively.

MrReves generated solutions until 2,000 valid solutions were found for the given parameters. The results can be visualised in a two-dimensional plane, in which the user can choose the different variables. These different parameters are plotted in Figure 3. In the solutions found by MrReves, subsolutions with an impact temperature (T_{print}) of at least 94 °C (as a reference) are selected. These solutions are highlighted in red.

In the first plot (left top) the T_{print} as a function of the droplet volume is plotted. One can see that not all volumes can acquire the necessary T_{print}. There is a first regime which shows that none of the droplets will make it with a T_{print} of 94 °C. A second regime shows that some of the droplets will fulfil the impact temperature; some of them won't. When the volume is big enough, all the droplets with such a volume, no matter which other parameters from the chosen domain, will reach the substrate with $T_{print} \geq 94$ °C.

In the top right plot, the impact temperature as a function of the density is shown. The influence of the density is clearly less in the chosen domain than that of the volume. For all densities there seems to be a solution such that a droplet will impact with $T_{print} \geq 94$ °C onto the surface.

At the left bottom side, the impact time as a function of the flight time is plotted. It is clear that the flight time should be as low as possible to obtain as high an impact temperature as possible. As all solutions that fulfil the $T_{print} \geq 94$ °C are only at the side where the lowest flight times are, this shows that the flight time is a dominant factor within the given domain.

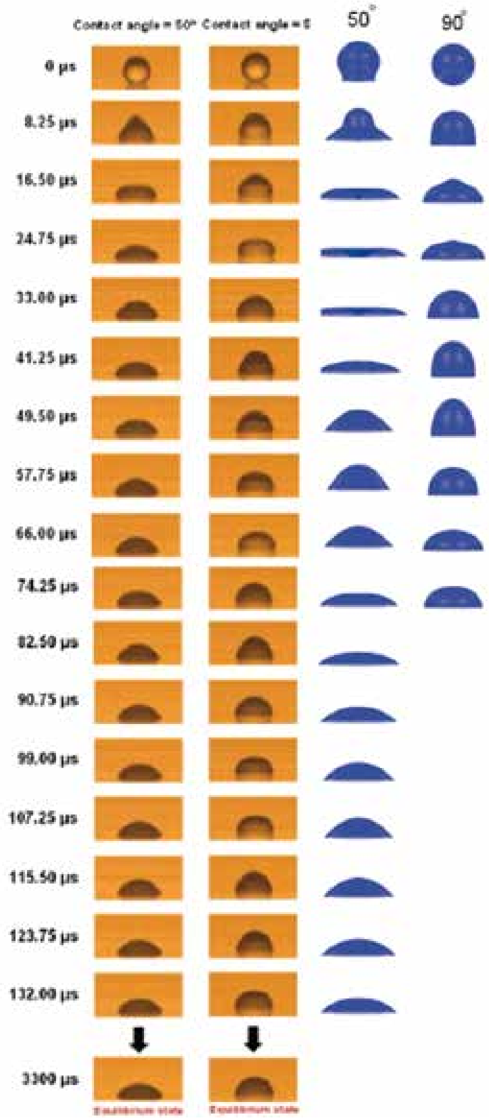
In the last figure, bottom right, the density versus the volume of the droplet is plotted. As the flight time dominates the impact temperature, one can consider the selected group (red) as representing a specific (short) flight time. The flight time seems a clear function of the volume and density. However, it's not just the mass ($\rho \cdot V$) that describes this phase, as the droplets with a lower density must still have a higher mass to keep the same flight time. This is due to the increase in volume and the drag coefficient which changes due to the frontal area of the droplet.

The use of MrReves on the solutions generated by analytical equations (or design rules) makes it easy to find new relations for different regimes between printing parameters. Design rules and/or analytical equations are coupled and solved by MrReves.

The droplet impact

The impact phase is the time between first impact and equilibrium (or, for bouncing droplets, between first impact and detachment from the surface). The impact phase depends on the Weber and Reynolds numbers which determine whether or not the droplets splash (see, for example, the work of Bussmann [4]). The contact angle between liquid and substrate can play an important role in the droplet dynamics and final state of the droplet.

The FEM model used to investigate jetting is also used to look at impact. This time, a water-based ink droplet with a size of 46 µm is investigated. The Reynolds and Weber



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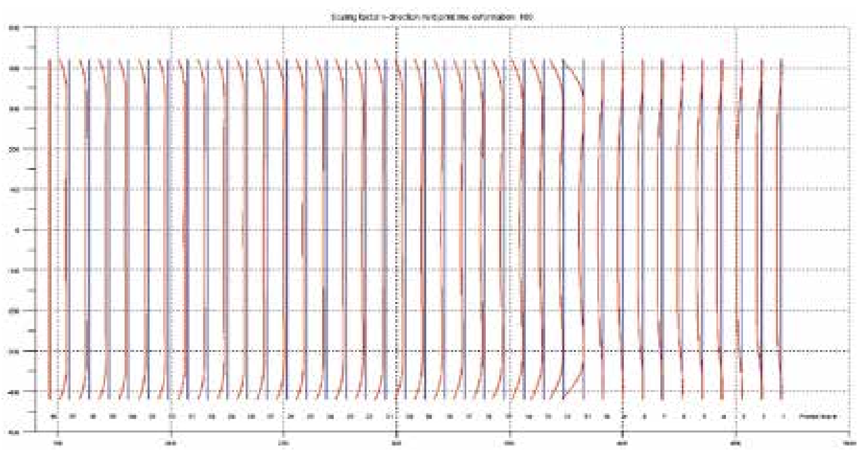
4 *Impact of a water droplet with a diameter of 46 µm on a substrate with a contact angle of 50° and one with a contact angle of 90°. On the left, the experimental data [5] and on the right, the Comsol Multiphysics simulations.*

5 *Lines printed during paper transport along a heated area (see Figure 6), in the deformed stage (blue) and the same line after the deformation has gone (red). This shows the error in droplet placement due to the in-plane deformation of the paper due to a change in temperature.*



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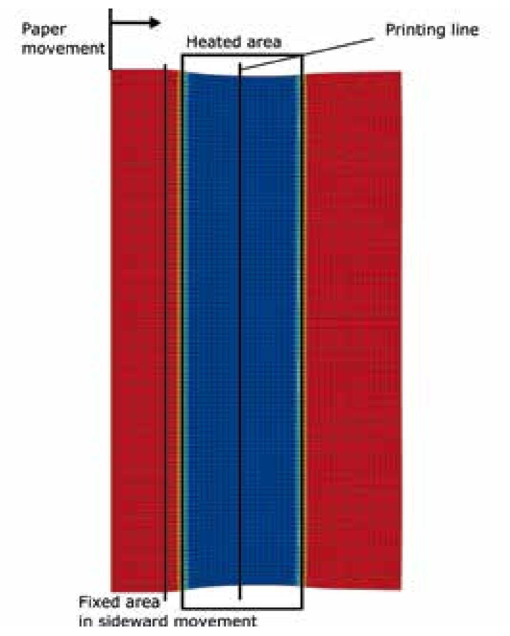

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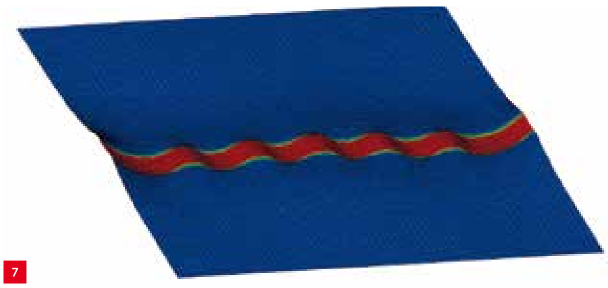

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numbers are chosen such that no splashing should occur. The material properties are the same as used in the jetting phase and the droplet velocity is approximately 1.44 m/s. The exact properties can be found in Son et al. [5]; they took images of the droplet impacting on a smooth substrate. Their work will be used as validation of the FEM model.

The contact angle is varied, and the droplet spreading due to this variation is investigated. In Figure 4, the impact behaviour of a water-based droplet on a smooth substrate with contact angles of 50° and 90° is shown. The simulations show concurrence with the experimental work by Son et al. [5]. Future work on impact will be to include non-Newtonian flow and high Weber number impact (splashing).

Influence toward the substrate

Not only the actuation, flight and impact determine the droplet placement and final geometry, but the substrate position does so too. Substrate deformation during the printing process will cause misplacement of the droplets on the substrate.

In this example, the deformation and wrinkling of paper due to absorption of water-based ink and a temperature gradient is examined. These simulations are built within the FEM package Abaqus [6].
First, the influence of in-plane deformation due to temperature gradients is examined. The paper substrate is moved underneath a printhead, which will heat a small area of the substrate. Due to the temperature increase the substrate will deform (see Figure 5). When printing lines, these lines are straight in the deformed situation, but will change when the paper is out of the heated area, which results in curved lines (Figure 6).
A second effect is the out-of-plane wrinkling due to ink load on the paper. This causes local expansion of the paper, resulting in wrinkles (Figure 7). These deformations result in wrong depositioning of the droplets on the substrate.

Conclusions

A set of simulation models have been developed for the different phases of the piezo inkjet printing process. These simulation models can be used to predict droplet behaviour during actuation, flight and impact, as well as the behaviour of the substrate due to the printing process. The influence of the different parameters in the printing process can be highlighted easily with these simulation models. A next step could be to extract the knowledge from the simulation models and use it to supplement the MrReves knowledge base. This gives an efficient and fast method for predicting the droplet behaviour from actuation to end-of-impact in specific cases (for example, a specific machine).

Also, the models could be extended to incorporate non-Newtonian fluids, to enable research toward the behaviour of polymer and tissue. The models could be extended to investigate the impact on three-dimensional geometries, such as appear in rapid prototyping. The impact model could be extended by including evaporation, solidification and absorption of the droplet during impact.
The substrate behaviour models could also be extended to 3D geometries and incorporate the behaviour of different materials. This will enable predictions of deformations for 3D tissue and polymer models. ■

6 *Temperature increase (blue) of the paper whilst transported from left to right. The printhead is located in the middle, above the temperature increase zone. (Deformation magnified 100x.)*

7 *Wrinkling in a sheet of paper due to wetting in the middle of the paper (wetted area approximately 20 mm wide).*

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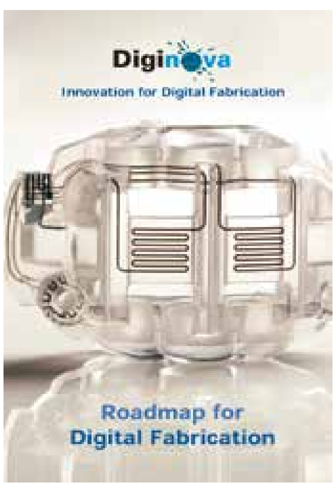
MANUFACTURING THE FUTURE: DIGINOVA

Earlier this year, the European Diginova consortium published the Roadmap for Digital Fabrication. Digital Fabrication can be defined as a new kind of industry that uses computer-controlled tools and processes to transform digital designs and materials directly into useful products.

The European Diginova project was started to establish the current status across material domains and application domains in Europe in order to identify the most promising technology and business propositions for Digital Fabrication. The project consortium, consisting of four large companies, seven SMEs and nine research institutes identified and connected main stakeholders through the establishment of innovative networks centred around concrete business cases to determine the added value and feasible routes to commercialisation.

Business drivers
- Independence of economies of scale
- Product customisation, personalisation and customer involvement
- Increasing design freedom
- Supply chain consolidation and decentralisation
- Reduced raw material use and waste
- Reduction of hazardous materials use and waste
- Reduction in lead times

Promising applications
- Digital graphical printing
- Digital textiles
- Functional end-use parts and products
- Additively manufactured objects with embedded printed intelligence
- OLED lighting and displays
- Smart windows
- Printed sensors
- Personalised diagnostics & drug delivery
- Medical microfactories



INFORMATION
WWW.DIGINOVA-EU.ORG

Key technology challenges
- Process implementation and economics
- Core process technology
- Design systems
- Supporting processes
- Supply chain support
- Education, legal and political agenda
- Improvement of material properties
- Material recyclability
- Biomaterials

Future
To address the technology challenges, the roadmap authors make recommendations for future research, ranging from the development of approaches to improve the reliability and repeatability of the Digital Fabrication processes, to the establishment of methodologies for the recycling of end-use products manufactured via Digital Fabrication. Embedded in larger European research and innovation programmes, the Diginova roadmap should provide links to 'Factories of the Future' initiatives and offer growth opportunities for sustainable manufacturing in Europe. ■

Vision for Digital Fabrication

Within the next 10-20 years, Digital Fabrication will increasingly transform the nature of global manufacturing, with an increasing influence on many aspects of our everyday lives. Manufacturing will evolve towards a global distribution of digital design and specification files that will form the basis of local production.

The economical advantage of large-scale production will decrease, which makes smaller series production increasingly competitive and customised products affordable to an increasing number of consumers. The combined characteristics and possibilities of Digital Fabrication will generate new business models and new markets for new types of products and services.

Transformation to Digital Fabrication will contribute to the decrease of resource consumption and resource-intensive production, targeting low-carbon and zero-waste manufacturing. This paradigm shift in manufacturing opens up great opportunities for entirely new ways of production and material development in Europe.

Dutch 3D-Print Magazine launched

In October, the first issue of the Dutch language 3D-Print Magazine was published by Made-in-Europe.nu and 54U Media, a publisher in the metal industry. The magazine is devoted to Additive Manufacturing (AM) in the industrial world and is part of the Made-In-Europe portfolio, which includes newsletters, online magazines and a website.
The first issue contains a wide variety of highly informative articles. For example, an extensive overview is presented of 3D printing technologies, featuring working principle, materials (metals, plastics or ceramics), workspace dimensions, (dis)advantages, applications and machine suppliers. Comparisons are also made with conventional fabrication technologies, such as milling and injection moulding.

A procedure for colouring 3D printed components is even discussed.

A new phenomenon is the rise of hybrid concepts, combining additive and subtractive processes. Several 'traditional' CNC machine builders have introduced hybrid machines, each with their own individual concept. Another interesting example of additive-subtractive cross-over presented by 3D-Print Magazine is the case of the German tool manufacturer Mapal that uses 3D printing to produce drills (subtractive tools) fitted with complex internal cooling channels.

Naturally, the magazine reviews the growth potential of AM (opportunity vs. hype) and its role as a 'game changer' within industry. For example, some of the so-called super alloys that cannot be milled may be suitable for 3D printing. Special attention is paid to product design. 3D printing offers a lot of design freedom, but it will not be straightforward to make optimal use of this potential, taking into account aspects such as topology optimisation, heat dissipation, supporting structures and post-processing.

Mention is made of the Additive World Design Challenge which Eindhoven-based start-up Additive Industries launched during the Dutch Design Week in October. Engineers are challenged to redesign an existing industrial design or product for AM. During the RapidPro event early in March 2015, two winners will be announced (within the 'industrial professional' and 'student' categories).

If the new 3D-Print Magazine makes one thing clear, it is that the industrial world is the real winner with 3D printing. This promising technology infuses new life into Western industry.

WWW.MADE-IN-EUROPE.NU

TU/e HTSC kick-off symposium

In order to meet today's societal challenges, there is a strong demand for a breakthrough in technological and social innovation. The High Tech Systems Center (HTSC) of Eindhoven University of Technology (TU/e) is the university's response to the increasing demand from industry for fundamental research and development in the area of high-tech equipment and instrumentation. At the Center, academia meets industry to address critical challenges facing the sector now and in the future.

On 8 January 2015, a kick-off symposium will be organised. After the vision of HTSC is revealed, three thought leaders (from Honeywell, VDL ETG and Maastricht University) will present their experiences and visions on how HTSC can help in resolving societal and industrial challenges.

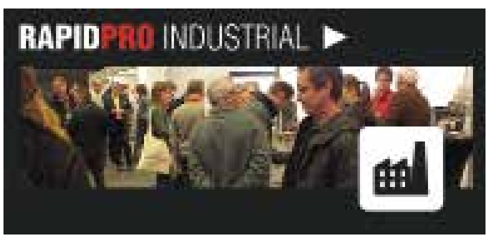
WWW.TUE.NL/HTSC

3 Days of 3D printing

The 5th edition of RapidPro will take place on 3, 4 and 5 March 2015 at the NH Conference Centre Koningshof in Veldhoven, the Netherlands. This edition is the first that spans three days, which marks the rapid development of the event that started back in 2011 as a one-day event. For the second year running there is a division between Industrial and Home Professional. Both have a specialised lecture programme and workshops for home professionals shall also be held.

Exhibitors at RapidPro Industrial

- Suppliers of 3D printers and scanning and measuring equipment for B2B applications.
- Suppliers of materials for the industrial market.
- Software suppliers.
- Service providers for making high-quality prototypes and (small series of) products, using Additive Manufacturing, CNC milling, casting, vacuum forming or thermal forming.
- Service providers: scanning, measuring, surface treatment, finishing processes.
- Product developers.
- Knowledge institutions and research centres.



Exhibitors at RapidPro Home Professional

- Suppliers of 3D printers, scanners, materials and services for home professionals.
- Artists, designers and design agencies.

WWW.RAPIDPRO.NL

Sioux and CCM join forces to become a leading system house

In October, Sioux and CCM announced they have combined their complementary strengths to become the largest independent system house in the Benelux. CCM is a player in the field of mechatronics systems and Sioux is active in the domain of embedded systems. Together, they become an innovative technology partner with over 400 multi-disciplinary engineers. CCM will be a subsidiary of the Sioux Group.

Together, Sioux and CCM can offer the entire range to their customers, from technology consultancy to total product development, and production and life cycle management. By joining forces they can accommodate the development of complete high-tech products and systems in which software is an increasingly important component. Both CCM and Sioux claim to be breeding grounds for innovative solutions.

Examples of products (co)developed by Sioux and CCM, respectively: the Phenom tabletop Scanning Electron Microscope (top) and the Generic Substrate Carrier. (Photos: Sioux)

By combining disciplines of both companies optimal integration of mechanics, optics, physics, dynamics, electronics, mathematics and software is achieved during the product creation process. Core competencies are precision technology, (motion) control engineering, vacuum technology and hybrid drives, as well as machine control, image processing, user interaction, remote services and mobile apps.

WWW.SIOUX.EU

WWW.CCM.NL

NEWS

High-accuracy, thermally stable galvano scanner

Aerotech has launched a new galvano scanner. The highly repeatable and thermally stable feedback sensors used on the AGV-HPO scanner systems can be calibrated down to single-digit, micron-level accuracy over the field of view. With the extremely low thermal gain drift performance of the position transducers, complex, high-density laser machining applications will maintain consistent micron-level feature placement accuracy over the lifetime of the process, Aerotech claims.

The AGV-HPO utilizes all of Aerotech's advanced motion and PSO (Position Synchronized Output) capabilities that have been developed for traditional servo-based laser processing applications. Contouring functions such as Acceleration Limiting can be used to automatically reduce speeds in tight corners or small radii to minimize overshoot. The laser can be triggered based on the position feedback of the mirrors with PSO to ensure consistent spot overlap as the scanner changes speed.

The location of the AGV-HPO mirrors can be captured and analysed in real time. With direct access to the positions of the scanner, the user no longer has to program delay parameters to compensate for lag and tracking errors in the servo system. The process can be optimised prior to marking the part, saving time and reducing material waste. The state of the laser can also be controlled based on in-position and velocity criteria, further reducing programming complexity.

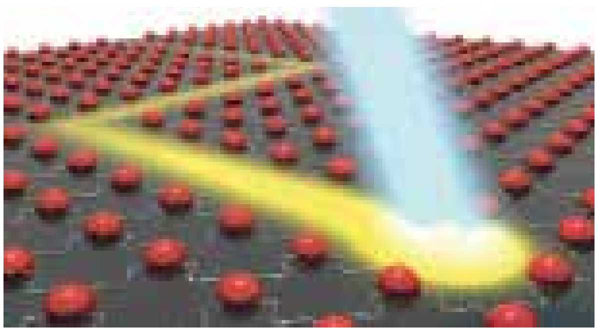
Aerotech's Infinite Field of View (IFOVTM) function seamlessly combines servo and scanner motion to extend the marking capability of the scanner across the entire travel of the servo stages, eliminating stitching errors that can occur in a more traditional move-expose-repeat process.

WWW.AEROTECH.COM

New ARCNL lab

Mid november, the new lab of the Advanced Research Center for Nanolithography (ARCNL) was officially opened by Dutch State Secretary for Education, Culture and Science, Sander Dekker, and ASML President and Chief Technology Officer, Martin van den Brink.

ARCNL focuses on the fundamental physics involved in current and future key technologies in nanolithography, primarily for the semiconductor industry. ARCNL's program is intimately connected with the interests of semiconductor equipment manufacturer ASML. A significant part of the initial programme is devoted to the physics that is central in the generation of high intensities of extreme ultraviolet light and its use in nanolithography. In the course of time, ARCNL's programme will evolve to keep the centre at the frontier of research in the area of nanolithography.



■ *Nanolithography by using novel supramolecular structures.*

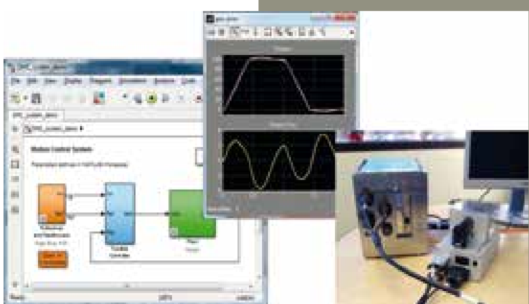
ARCNL is a public-private partnership between the Dutch Foundation for Fundamental Research on Matter (FOM), the University of Amsterdam (UvA), the VU University Amsterdam (VU) and ASML. ARCNL is managed by FOM under the auspices of the Netherlands Organisation for Scientific Research (NWO) and is located at the Amsterdam Science Park.

WWW.ARCNL.NL

MathWorks – software for innovative engineering

MathWorks is a leading developer and supplier of software for technical computing and Model-Based Design. The software is used by engineers, scientists, mathematicians, and researchers all over the world.

MathWorks provides software for high-tech engineering in a growing number of industries and markets, ranging from automotive, aerospace and electronics to industrial automation, medical devices and materials handling.



The two core products are MATLAB®, used for performing mathematical calculations, analysing and visualising (big) data, and writing new software applications; and Simulink®, used for modelling and simulating complex dynamic systems.

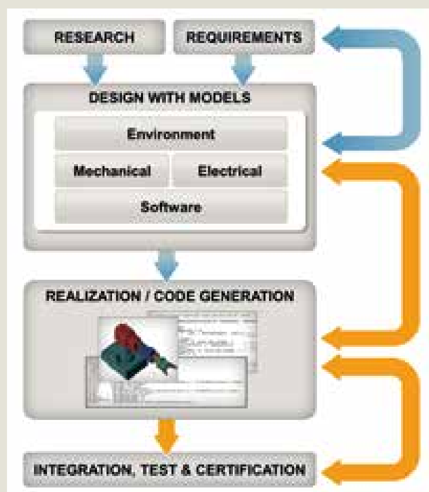
Together with over 75 additional tools for specialised tasks such as processing images and signals and simulating 3D mechanical systems, MathWorks serves more than one million engineers at innovative technology companies, government research labs, financial institutions, and more than 5,000 universities. Employing more than 3,000 people, MathWorks (founded in 1984) is headquartered in the USA and has offices and representatives throughout the world. The Benelux office is located in Eindhoven, providing local training, consultancy and technical support.

A powerful and extensive off-the-shelf environment for model-based engineering enables engineers to quickly go from innovative idea to high-quality product. Simscape™ provides an object-oriented modelling environment for multi-domain physical systems. SimMechanics™ builds on this to allow easy CAD-based modelling of precision engineering mechanics for rigid-body 3D kinematics and dynamics analysis. Simulink and Stateflow® can be used to design control algorithms to interact with these physical systems.

This approach enables engineers to simulate, analyse, optimise, and test full system behaviour before building any prototypes. Additional products provide capabilities for requirements linking, automatic design, test generation, code generation, fixed-point translation, formal verification, and high-integrity certification within one environment. Companies using software for innovative engineering report reduction of development time by 50% or more, while simultaneously improving product quality. ■

Model-Based Design

Model-Based Design simplifies the development of mechatronic systems by providing a common environment for design and communication across different engineering disciplines. It extends the computer-aided engineering (CAE) world with an additional perspective on system-level design. Just as computer-aided design (CAD) provides a geometric or static description of equipment, Model-Based Design incorporates the dynamics and performance requirements needed to properly describe the system. This approach is software-driven, so engineers can fluidly investigate competing designs and explore new concepts without the overhead of extensive hardware investment. In addition, Model-Based Design automates code generation.



Model-Based Design workflow.

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