A HOT **KICK-OFF**

In the development of precision systems and machines, thermal effects can play a critical role. As accuracy, productivity and optimisation demands increase, the challenge to further improve performance from the perspective of improved thermal control is of growing importance to markets, ranging from inkjet printing to automotive to lithography systems. On 25 February 2016, the kick-off of a consortium concerned with advanced thermal control was held at the High Tech Campus Eindhoven, the Netherlands.

IBS Precision Engineering and ASML were the main advocates of forming an industrial consortium of leading companies from the Dutch high-tech sector to address the topic of thermal control. The members of the consortium are ASML, FEI, IBS, Philips, VDL and Segula. The consortium aims to advance the theoretical and applied approaches to design, simulation, measurement and compensation techniques essential for the development of precision modules/systems subject to internal or external thermal loads.

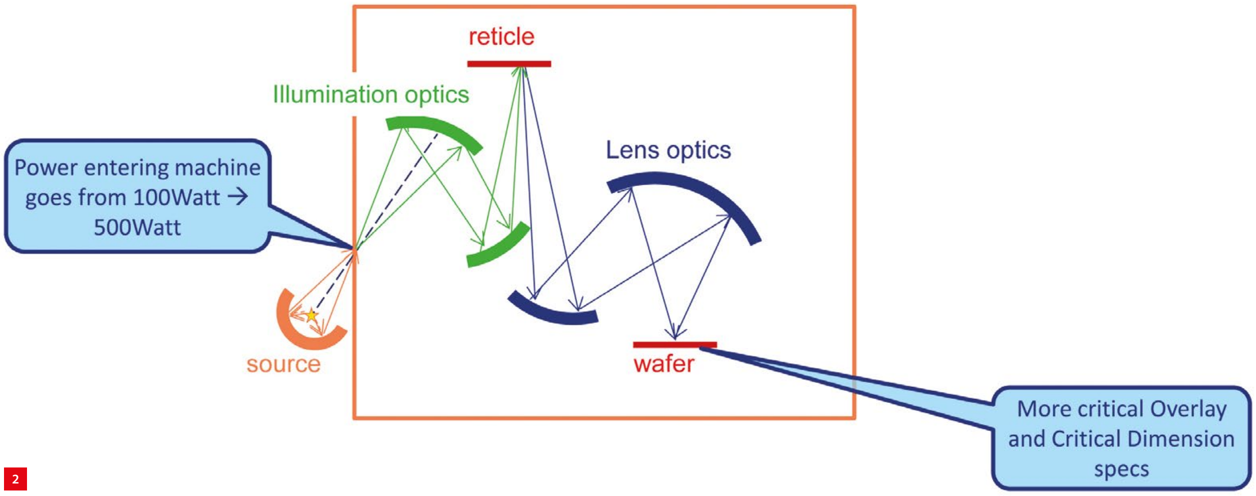
The kick-off of the Advanced Thermal Control Consortium (ATCC) in the Conference Center at the High Tech Campus Eindhoven (Figure 1) attracted a decent crowd. This confirmed that 'thermal effects in high-precision systems' is a hot topic. The temperature rose in the crowded conference room during the meeting, which featured a short introduction on behalf of the initiators and presentations from the academic and industrial partners as well as pitches from non-consortium partners.

Research scope

The consortium will fund Ph.D. projects, in collaboration with both Eindhoven University of Technology and Delft University of Technology, covering:

- Design rules and optimisation tools that enable the module designer to effectively account for transient thermomechanical performance and optimisation for systems under feedback control.
- Advanced methods for experimental modelling (i.e. identification) and feedback control for thermal problems.
- Model reduction including next-generation techniques for complex systems.
- Multivariable feedback control for thermal applications and controller design methods.
- Systematic and effective tools for observer design.
- Thermal management of optical systems.

1 *The ATCC kick-off took place in the Conference Center in The Strip, at the High Tech Campus Eindhoven.*



2 Thermal challenges in ASML's new EUV lithography machines.

In her introduction, Theresa Spaan-Burke, IBS innovation director, recollected how first explorations started in 2012, with interest from high-tech companies, but no available government funding. The consortium will work with a spirit of open innovation, finding the right balance between IP protection and sharing. The aim is to develop a satellite network body of international expertise and interest in the field. The consortium will provide this body with full insight on developments within the generic research of the consortium and a forum for sharing industry perspectives and academic developments.

Academic partners

The first speaker at the kick-off representing the academic partners of the consortium was Fred van Keulen, professor of Structural Optimization and Mechanics (SOM) in the Department of Precision and Microsystems Engineering at Delft University of Technology. He talked about thermal topology optimisation for precision applications. Topology optimisation can be used for improving the performance of systems. The extensive design freedom offered by this method may result in complex geometries that can only be realised with additive manufacturing (AM) techniques. When thermal performance is included in the optimisation, AM-only cooling channels can be integrated into the design of a precision system.

Maarten Steinbuch, professor of Control Systems Technology in the Department of Mechanical Engineering at Eindhoven University of Technology (TU/e), started off by offering his congratulations to the ATCC initiators. His contribution included an overview of applications with thermal control issues covered by his research group, ranging from density control in a plasma fusion reactor to waste heat recovery from diesel engines and motion control in scanners and printers. He concluded that the integration of modelling and control is key when dealing with thermal issues, combining data-based and model-based approaches. Steinbuch stressed that thermal control cannot be copied from dynamic control as there is a difference in mathematical formulation (partial vs ordinary differential equations) and in time scale ('thermo' is slower, except on the nanoscale).

Technology trends lead to an abundant availability of (cheap) sensing, computation and communication. This encourages the use of discrete (finite-element) models for real-time monitoring and optimisation of systems. However, to keep the computational effort in hand, such models have to be reduced. Siep Weiland, professor of Control Systems in the Department of Electrical Engineering at TU/e, discussed the need for control-relevant model reduction, preserving the physical relevance of the model, for thermal control. As an example, he presented the case of thermal control in an AM process.

Industrial partners

As co-initiator of the consortium, ASML was the first industrial partner to deliver a presentation. Wim Symens, in charge of Mechatronics & Control Technology Development at ASML Research, gave an overview of the challenges facing advanced thermal control at ASML. He showed that the evolution in lithography machine design leads to a larger impact of thermal loads on deformations. This can be ascribed to the increase of light source power that enters the machine, the more stringent overlay and focus requirements (Moore's law) and the increase of machine dimensions (Figure 2). "The importance of the Joules to nanometers impact will increase for ASML."

Symens also stated that thermomechanics is not equal to structural mechanics/dynamics, but that there are opportunities to build on the vast experience that has already been built up with motion control in the latter area.

Jeroen de Boeij, mechatronics architect at FEI, discussed the same issues for electron microscopy systems and applications. He presented a general design approach for systems working under cryogenic conditions (< 100 K). This includes preventing heat from the environment reaching the sample, providing a good thermal connection from the sample to a Dewar, keeping heat loads as constant as possible, and realising a vacuum around the sample to avoid convection.

The next speaker was Henny Spaan, CEO of IBS, the company that specialises in metrology machines and metrology solutions for machine tools. Spaan showed how dealing with thermal behaviour in the design of a metrology machine involved not only the use of a metrology frame, but also the exclusion of thermal sources, the careful selection of 'thermo-insensitive' materials, such as SiC and Zerodur, and passive thermal shielding. In machine tools, thermal drift is a big issue. IBS partners up with organisations such as Fraunhofer to research advanced thermal models of machine tools.

Rob van Gils, thermal technologist at Philips Innovation Services, gave an overview of the challenges facing Philips when addressing thermal effects in mechatronic systems: model reduction, system identification and advanced thermal control design. Patrick Smulders, director of System Architecture at Segula Technologies, highlighted the Segula approach of thermal control in thermal & flow systems: model-based design which involves modelling on different system levels, designing with different types of models, and verification with measurements.

Non-consortium organisations

The kick-off was concluded with pitches made by interested non-consortium partners. Jan Bienstman talked about thermal management research at Flanders Make, the Flanders strategic research centre for the manufacturing industry. He stressed that thermal effects limit the performance of systems, vehicles, etc., and showed examples of advanced thermal control in 3D-printing processes and in the cooling of power electronics and integrated drivetrains.

Jens Flügge from the Department of Dimensional Nanometrology at the German National Metrology Institute (PTB) discussed the need for thermal control in order to obtain homogenous temperature fields in measurement machines, such as for the calibration of length artefacts. Ruud Börger demonstrated the accurate thermal modelling capabilities of COMSOL simulation software. Matěj Sulitka from the Research Center of Manufacturing Technology at the Czech Technical University in Prague (Czech Republic) talked about advanced techniques for modelling and compensation of thermal errors, and their industrial implementation in machine tools.

Maurice Limpens from TNO discussed the combination of dedicated analysis and manufacturing techniques for performance optimisation of precision systems. He showed the use of (patented) micro-fin structures for liquid evaporation-based cooling, which is capable of removing significant heat fluxes while using very small (water) flows. Another example was adaptive surface cooling/heating of individual 'pixels' in a (wafer) table using complex 3D-printed structures (Figure 3).

These pitches illustrated the wide range of thermal control issues. Anticipating a demand for thermal control engineers, Jan-Jaap Koning of TU/e introduced a two-year PDEng programme on the subject of thermal control (PDEng is a Professional Doctorate in Engineering).

On the road

The Advanced Thermal Control Consortium (ATCC) kick-off ended with a reception offering participants the opportunity to cool down, meet consortium members and consider registration as a partner. The ATCC offers workshops, reports, preferred supplier status regarding the research, and access to roadmapping activities. Thermal control has hit the road! ■

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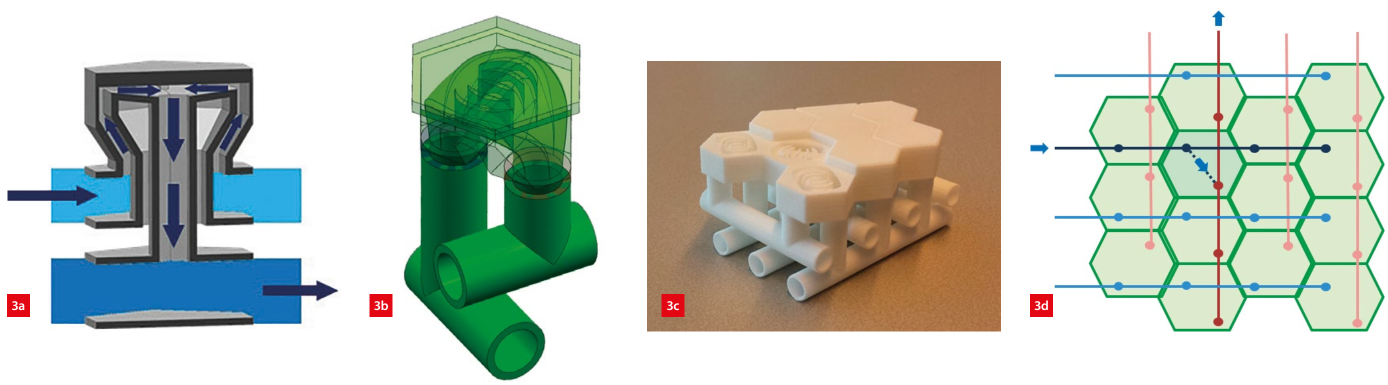

3 *Thermal pixel development (reprinted from Mikroniek 2014, no. 6).*
(a) Basic idea starting point.
(b) One of the design concepts.
(c) Printed sample with multiple thermal pixels.
(d) Possible supply and return channels to feed each thermal pixel with cooling flow.