



Steffen Rübling, TRUMPF (I.), and Dr. Dennis Haasler, Fraunhofer ILT, with the world's first industrial 1-kW USP laser, located at the Fraunhofer Cluster of Excellence Advanced Photon Sources CAPS in Aachen.

Lasers – a key technology of the present and future

High-power laser systems are indispensable in industry and research. Their interaction with digital methods and tools is increasing their enormous potential even further.

Janine van Ackeren

Laser and photonics technologies are central to addressing many of today's major societal challenges. High-power and high-energy lasers, for example, enable the controlled ignition of fusion plasmas and thus form the technological foundation of laser-driven fusion – a potential source of clean, CO₂-free energy. Laser-based additive manufacturing processes such as laser material deposition and laser powder bed fusion allow complex components to be repaired or produced with exceptional precision, up to and including industrial series production, for instance in aerospace applications. Equally forward-looking is the interaction between laser technology and artificial intelligence (AI). AI enables complex laser-material interactions to be analyzed in real

time, processes to be adapted dynamically, and quality and efficiency to be improved continuously. In this way, laser systems evolve from isolated tools into learning, networked production systems.

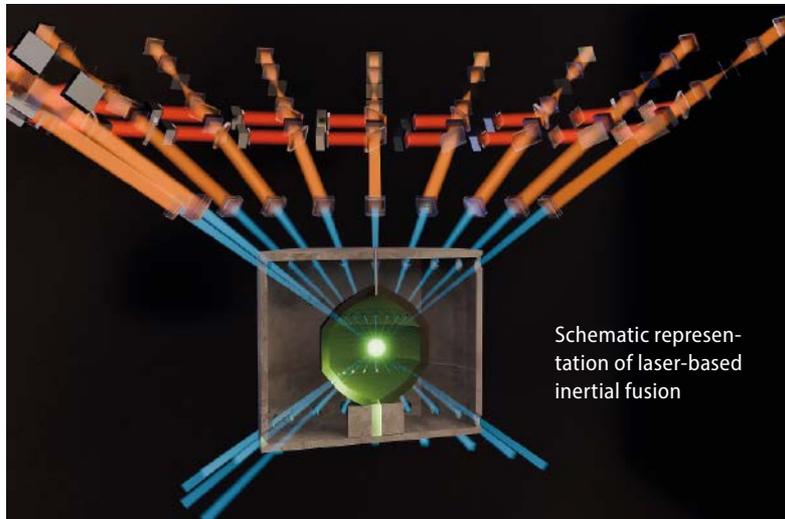
Opportunities and prospects for fusion research

An unimaginable 15 billion degrees prevail inside the sun: This is because the nuclear fusion that takes place there fuses hydrogen nuclei, more precisely deuterium and tritium, into lighter helium nuclei – the excess mass is released in form of energy. Every second, the sun converts around 600 million tons of hydrogen into 596 million tons of helium, releasing energy equivalent to a mass of four million tons.

Following the example of the sun, research aims to harness fusion energy for the Earth and make it available around the clock. After all, it promises humanity a virtually inexhaustible, CO₂-neutral energy source: One gram of fusion fuel can generate as much energy as the combustion of eleven tons of hard coal. Unlike in conventional nuclear reactors, chain reactions leading to meltdowns are impossible. Researchers at the Lawrence Livermore National Laboratory (LLNL) at the National Ignition Facility (NIF) achieved a long-awaited breakthrough in fusion research on December 5, 2022: Using high-energy lasers, they were able to ignite a fusion plasma and heat and compress a fuel pellet made of deuterium and tritium. The fusion

released 154 percent of the energy that the laser pulse coupled into the fuel pellet – achieving a net energy gain for the first time.

Despite this success, the road to commercial use is still long. Among other things, the energy cycle must also be closed in power plants – in other words, the power plant must deliver more energy than it consumes, from the laser light to fusion to the conversion of fusion energy into electricity. “This is the first fundamental point we are working on at Focused Energy,” says Markus Roth, co-founder and chief science officer of Focused Energy GmbH and professor of laser and plasma physics at TU Darmstadt. “The second point is closing the fuel cycle, for example by extracting tritium from the reactor wall.” The first fusion power plant to achieve this will be a demonstration plant measuring two



Schematic representation of laser-based inertial fusion

Fraunhofer ILT, Aachen, Germany / Sarah Klein

to two and a half soccer fields in size, which Focused Energy is currently building. “In ten years, we want to have our first large-scale test facility up and running and demonstrate all the necessary technological maturity levels,” emphasizes Roth. Ten times per second, a ball

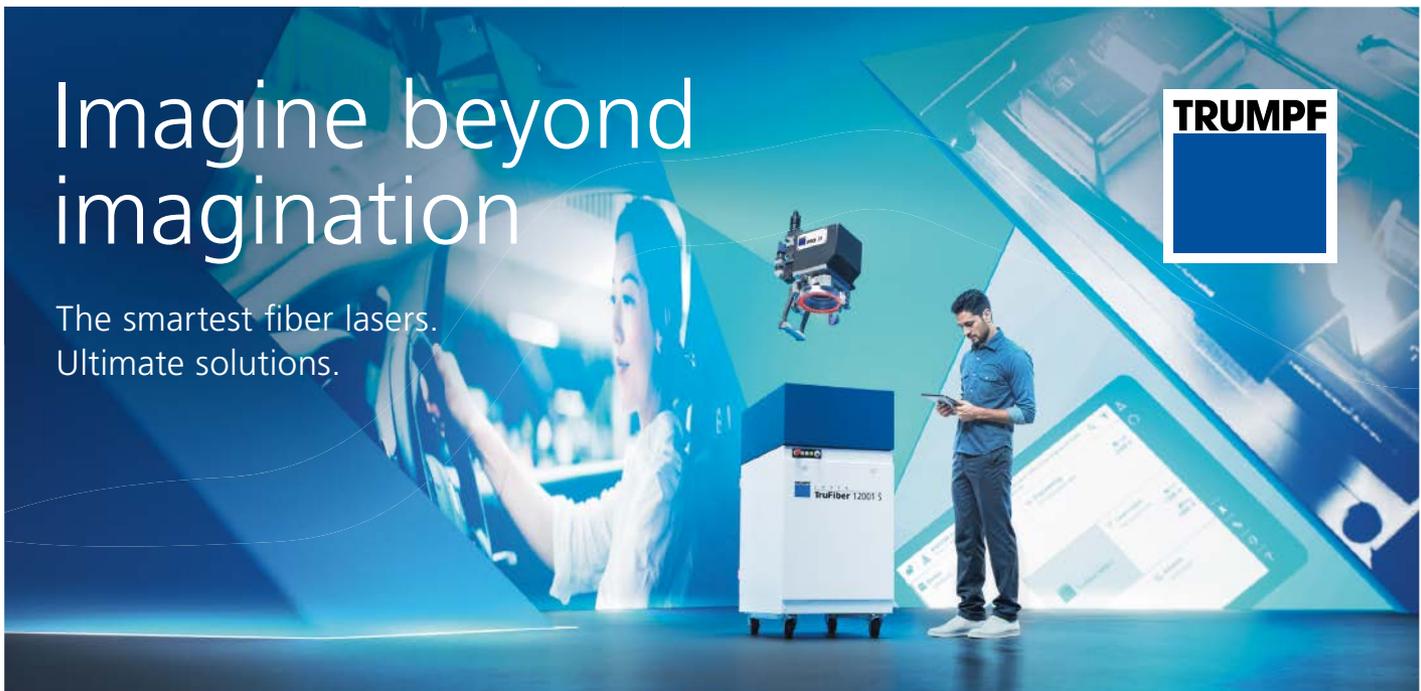
of a deuterium-tritium gas mixture will be fired into the reactor and reliably hit by the laser beam. For this purpose, 1100 laser systems will be installed, with a total laser energy of 1.7 megajoules.

Comprising the Fraunhofer Institutes ILT and IOF, the Laser

Imagine beyond imagination

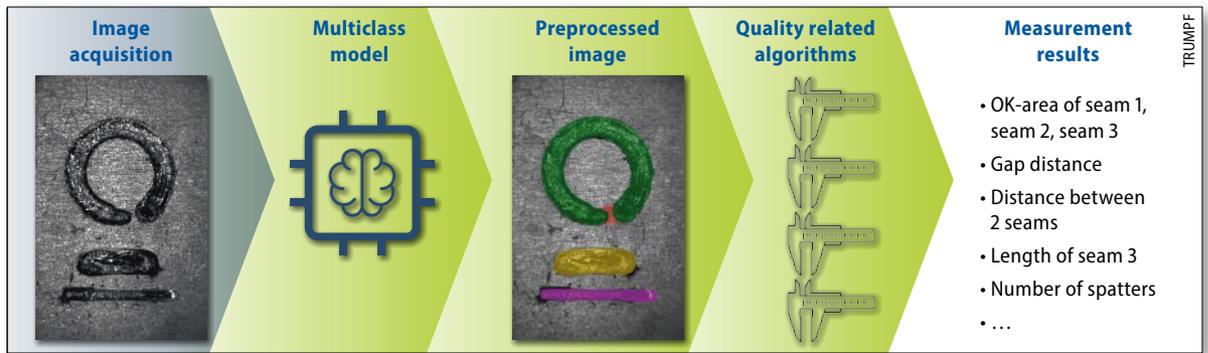
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Application panel VisionLine-Inspect

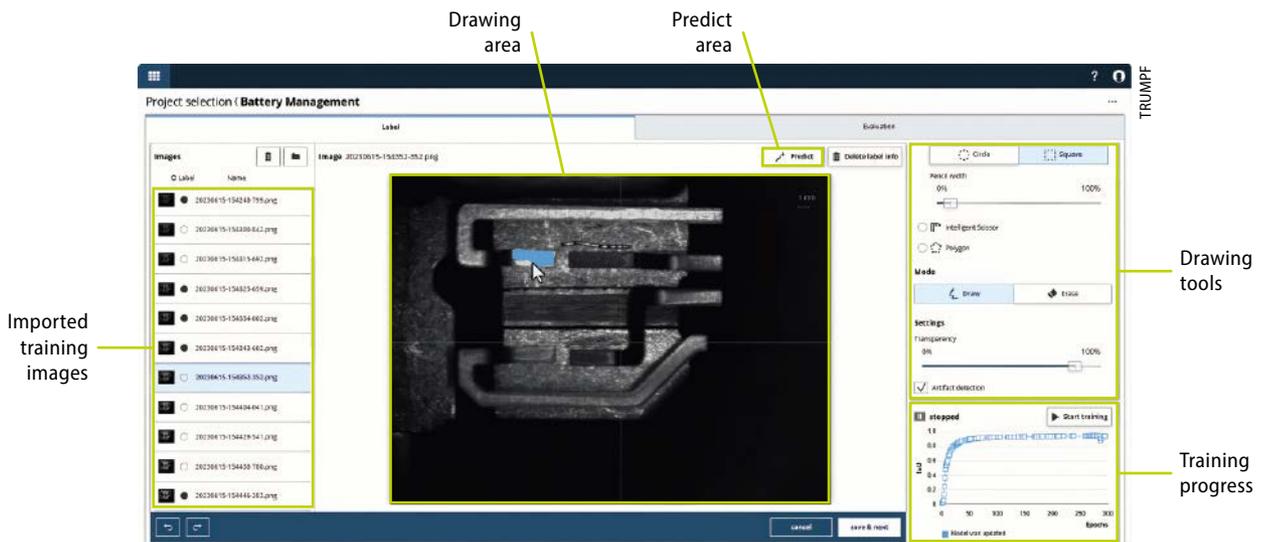
Zentrum Hannover (LZH), startups such as Focused Energy GmbH and Marvel Fusion GmbH, as well as medium-sized companies and corporations, a consortium is dedicated to fusion research. In the PriFUSIO joint project, which is funded by the German Federal Ministry of Research, Technology and Space with 18 million euros, it is developing powerful, reliable, and cost-effective laser sources and optics and is working on automated fuel supply and efficient use of the waste heat generated. “What is needed are highly efficient optics and heavy-duty optical coatings that can withstand several billion shots, i.e., about ten to twenty years,” says Hans-Dieter Hoffmann, head of the Lasers and Optical Systems depart-

ment at Fraunhofer ILT. The lasers operate with kilojoule pulse energy and a pulse frequency of around ten hertz, i.e., an average power in the 10 000-watts class – after all, they have to compress the millimeter-sized fuel pellets and ignite the fusion at temperatures of more than 100 million degrees Celsius.

Although these high power and frequency values can generally be achieved, they have not yet been possible simultaneously. The project aims to change this: while the companies formulate the requirements for the high-power lasers, Fraunhofer ILT and IOF, together with the Laser Zentrum Hannover (LZH), derive the specific research and development needs necessary to implement

these specifications. The IOF is developing heavy-duty coatings and optical gratings, while LZH is testing the resilience of the optics – they have already tested around a thousand optics in the project. “At the Fraunhofer ILT, we use a simulation code to simulate all relevant parameters of the high-power laser with increasing accuracy,” explains Hoffmann. The simulations are currently being validated with experimental results from TRUMPF and, in the case of laser glasses, with results from Livermore that are accurate to many decimals.

“However, the challenges for nuclear fusion lie less in the technical issues and more in the necessary restructuring of the German industrial landscape,” Roth is certain. “If



Application panel EasyModel-AI

laser fusion is to make a sustainable contribution to the energy supply of Germany, Europe, or the world, laser systems must be built like cars: away from single-unit production and toward thousands of laser systems per day. Germany is still way ahead, especially in the optics and laser industry, and is in a position to play a leading role in this field. However, China has invested two billion in a single start-up company in the field of laser fusion in 2025 – so there is an urgent need to act.”

Greater added value through AI control of laser processes

Production processes are becoming increasingly complex. This increasing complexity can be clearly seen in the battery pack for e-mobility, for example: While a car door has only seventy weld seams, a battery pack has up to a thousand cells joined together with a thousand weld seams. Closely linked to this are the costs incurred by a potential defect: A production error in a car door costs less than a hundred euros, but several thousand euros have already been invested in the production of batteries at the time of the welding process. Quality control is therefore becoming increasingly important – as are AI methods designed to optimize processes on the basis of data. “AI and machine learning algorithms are very well suited to the challenges that need to be solved in engineering and photonics,” confirms Prof. Carlo Holly, head of Data Science and Measurement Technology at Fraunhofer ILT. “Artificial intelligence has long since left stage 2.0 behind; it is now operating far beyond that.” Dr. Volker Rominger, head of Machine Learning & Simulation for Laser Applications at TRUMPF Laser- und Systemtechnik GmbH, shares this opinion. “AI delivers significant added value, especially in laser-based manufactu-



Fraunhofer ILT, Aachen / Volker Lannert

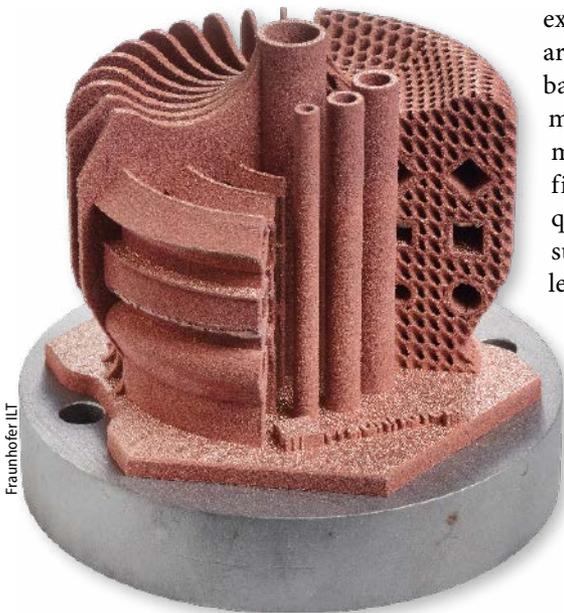
In the EU project ReSoURCE, used refractory materials are identified using LIBS measurements and reused in a CO₂-saving manner.

ring,” he says. “After all, customers are faced with the challenge of manufacturing components of reliable quality at the lowest possible cost at a high degree of reliability.”

There are plenty of success stories at both TRUMPF and Fraunhofer ILT. Take component recognition, for example – after all, a component must first be positioned correctly on the machine for laser material processing. “We have been offering component recognition using classic algorithms for over a decade. Artificial intelligence now helps us increase the accuracy of the results,” Rominger says. His company uses a hybrid approach, in which the original image is first binarized by semantic segmentation and the component position for example, in the case of hairpins – is then determined using classic algorithms. The image-based approach also allows us to evaluate the quality of the manufactured components very well. “Multiclass models in conjunction with classic machine vision algorithms make it possible to reliably generate measured values in SI units for quality control of weld seams,” says Rominger. AI-supported quality assurance is already available as a product at TRUMPF.

Laser-induced breakdown spectroscopy, or LIBS for short, also benefits greatly from artificial intelligence. This laser spectroscopic method can be used to determine the element-specific composition of a sample via plasma. When refractory materials, rare earths, and high-quality alloys pass by on a conveyor belt in recycling processes, rapid classification is necessary for sorting by type. “In the EU-funded ReSoURCE project, we are therefore combining the LIBS process with a 3D sensor, a spectral camera, and AI evaluation,” explains Holly. Based on the test results, the system knows what material a part is made of – a robot quickly grabs it from the conveyor belt and sorts the piece of material into specific boxes for recycling. The AI aspect of this is: With all the differently shaped parts, where do you place the measuring points in order to classify them as accurately as possible?

In addition, AI is an important tool in parameter optimization for coordinating various target and input variables such as laser power, feed rate, or material properties – for example, in laser material deposition, extreme high-speed laser material deposition (EHLA), or



Small quantities and the high complexity of lightweight, high-performance components are already among the strengths of additive manufacturing.

ultrashort-pulse laser processing. How can optimal process parameters be found so that the layer thickness, porosity, and component strength of the manufactured product are suitable? Whereas parameters were previously set manually in a time-consuming and laborious process, researchers are now closing this loop with algorithms. “We are incorporating sensor technology and enabling the system to act independently. The AI conducts

experiments, the results of which are fed back into models. In the background, a so-called surrogate model is being built: a replacement model that enables the system to find optimal parameters very quickly,” explains Holly. Using the surrogate model, researchers can learn from the living object, so to speak, and instantly adjust the parameters for new tasks – in the end, the condensed process knowledge is contained in the model. “Machine learning opens up new possibilities for intelligent parameter optimization and inline control,” says Holly.

As far as TRUMPF’s customers are concerned, an important factor of AI is transparency. “The results must be comprehensible to users, and the application must be easy to use and function almost without any prior knowledge of AI,” says Rominger. A high-quality user interface and a zero-code methodology for training and executing AI models are essential for this. In other words: do-it-yourself AI.

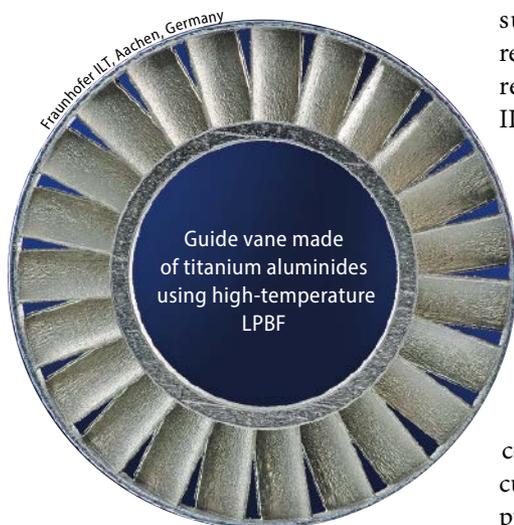
Additive manufacturing in aerospace

Aerospace companies face major challenges: Among other things, they need to drastically shorten development cycles, develop more sustainable technologies, and reduce costs at the same time. They receive support from Fraunhofer ILT, where additive manufacturing (AM) processes such as laser material deposition and laser powder bed fusion are developed, optimized, and adapted to the specific requirements of the aviation industry. These are processes that can significantly improve the ecological footprint and reduce the production costs of components. “One of our customers in the aerospace sector is pursuing two directions in additive

manufacturing: on the one hand, repair, and on the other, the series production of new parts using additive manufacturing for OEMs,” says Dr. Thomas Schopphoven, head of the Laser Material Deposition department at Fraunhofer ILT.

As far as repairs are concerned, the company is working closely with Fraunhofer ILT on a current project. “At the moment there is a lack of suitable technologies for repairing landing gear components: corroded, worn areas must be repaired in such a way that the repaired component achieves the same material parameters as a newly produced one,” explains Schopphoven. For this reason, Fraunhofer ILT and the industrial customer are continuing to develop laser material deposition so that the company can overcome this hurdle. The endeavor is extremely worthwhile, as these are large components that can cost tens of thousands of euros.

In laser material deposition, a laser beam locally melts the base material and simultaneously feeds in a filler material in powder or wire form to allow the damaged areas to grow back into their original shape. “We are investigating and optimizing various steps along the process chain of preprocessing, repair process, and postprocessing,” says Schopphoven. “Of particular interest is postprocessing and finishing during production, which enables properties that cannot be achieved through sequential processing.” For example, compressive residual stresses can be introduced, thereby avoiding otherwise problematic tensile residual stresses. These cause premature fractures in the material and make it difficult to return forged components to service after repair. “I am extremely confident that together we will be able to meet the requirements for strength and residual stresses and get repaired components certified,” says Schopphoven.



Additive manufacturing can now be used not only for repairs, but also for economical and resource-efficient production. One example is the metallic 3D printing process developed at Fraunhofer ILT – laser powder bed fusion (LPBF), also known as laser beam melting – which forms the basis for today's prototype construction and the production of customized components in the aerospace industry. "This process has several advantages. On the one hand, it can be used to create complex geometries that are not so easy to produce using conventional machining processes, and to achieve weight advantages," explains Dr. Tim Lantzsch, head of Fraunhofer ILT's Laser Powder Bed Fusion department. Another advantage is speed: while forging components can take months, if not years, to procure the appropriate dies and bring the first forged parts into series production, AM quickly produces components that are geometrically accurate.

Nevertheless, many different subsequent process steps are necessary to make a 3D-printed component suitable for series production: starting with a hot isostatic pressing process, in which the component is freed from internal porosity under pressure and temperature, through mechanical postprocessing to chemical treatment with hydrofluoric acid, especially for titanium alloys. "Our customer is already printing smaller components for the A350 from a titanium alloy," explains Lantzsch. These processes are also partly the result of a collaboration with us.

At the beginning of 2025, researchers at Fraunhofer ILT, where the basic patent for today's PBF-LB/M process was developed and registered around thirty years ago, completed a major project in the field of aviation research: New aluminum materials were devel-

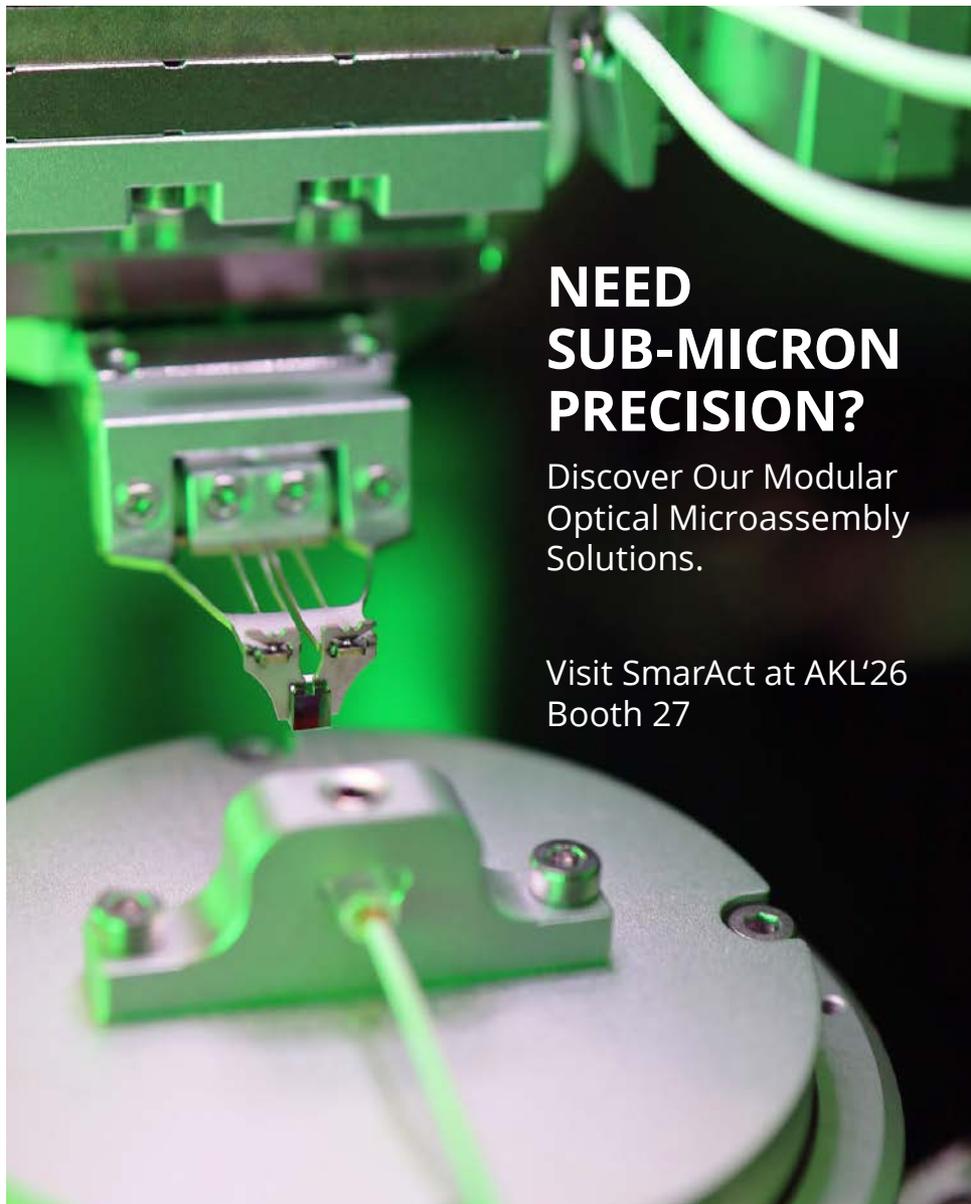
oped for laser powder bed fusion that can be processed particularly productively and require only short heat treatment cycles for post-processing. "Now we want to use test components to prove that the new material is suitable for aviation applications and that the components can be used in series production," says Lantzsch. Here, too, quality control is crucial. "Streamlining the certification and quality assurance of aerospace components has been a concern for many companies for years," says

Lantzsch. "The holy grail is in-situ monitoring, which would ultimately eliminate the need to put every component through CT testing."

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