LASER COMMUNITY.

Of people and photons

Hydrogen is coming

How laser technology is driving a new boom.

#32

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LASER COMMUNITY. *#32*

ISSUE May 2021 **PUBLISHER** TRUMPF GmbH + Co. KG, Johann-Maus-Straße 2, 71254 Ditzingen, Germany; www.trumpf.com
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DISTRIBUTION Phone +49 7156 303-31559, athanassios.kaliudis@trumpf.com, www.trumpf.com/en_INT/company/press/magazine
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DESIGN AND PRODUCTION Die Magaziniker GmbH, Stuttgart, Germany; Gernot Walter (AD), Martin Reinhardt **TRANSLATION** Wieners+Wieners GmbH, Ahrensburg, Germany **REPRODUCTION** Reprotechnik Herzog, Stuttgart, Germany **PRINTED BY** W. Kohlhammer Druckerei GmbH + Co. KG, Stuttgart, Germany

Illustration: Timo Müller; Cover: Adobe Stock / Konstantin Yuganov

Gernot Walter

Challenge accepted!

Back when I was a young laser researcher experimenting with a transverse flow CO_2 laser at the German Aerospace Center (DLR) in the mid 1980s, I would often see Europe's first-ever hydrogen-powered car being taken for a spin. It was a red BMW that Professor Carl-Jochen Winter and his team had successfully converted. It was clear to most people that the hydrogen pioneer's car would still need a few decades to establish itself. Even today, there is still some way to go, but the signs all point in the same direction: research, industry and politicians all regard hydrogen as the linchpin of our future energy supply.

This is good news for TRUMPF and for laser technology, because fuel cells are at the heart of the hydrogen economy. These cells extract energy from the chemical reaction of hydrogen and oxygen. The technical requirements on fuel cells are so demanding that there is no alternative to the laser. Hundreds of wafer-thin stainless-steel plates have to be welded together in such a way that they can withstand all knocks, reliably conduct electricity and remain completely gas-tight. These stainless-steel plates may only be a few micrometers thick, but they have to provide 100 percent safety! Even the slightest pore in a cell could have fatal consequences, such as in a hydrogen-powered vehicle. Scanner-based welding lasers, coupled with sensitive sensors, are able to meet these requirements in terms of precision, speed and safety in a cost-effective manner when it comes to gas-tight welds.

Admittedly, there is a world of difference between these lasers and "my" CO_2 laser from my DLR days. But innovations in the field of laser technology often build on knowledge that has already stood the test of time. And gas-tight welding is no exception: our first encounter with this requirement was in the welding of pacemakers. We were then able to harness this experience when the first automotive customers wanted our support in the gas-tight welding of components for lithium-ion batteries, the aim being the rapid development of suitable industry solutions for electric vehicles. And with the fuel cell, things are taking another step forward. The demands made by hydrogen pioneers on laser technology are challenging both developers and engineers alike. But these demands are also spurring them on to new heights, allowing them to weld even faster and with even greater precision.

Do I believe in hydrogen as a fuel technology? Absolutely! It won't be next year and it won't be a silver bullet. But it definitely has a role to play within a healthy mix of different technologies for different types of vehicle.

DR.-ING. CHRISTIAN SCHMITZ
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Member of the Managing Board of TRUMPF GmbH + Co. KG
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Twice the fun

Saving the planet for our children using smart and energy-efficient injection molds. What could be better than action figures? After having their photo taken, two of our authors' kids played with the exciting new additions to their toy collections. **Page 6**.

Five professors

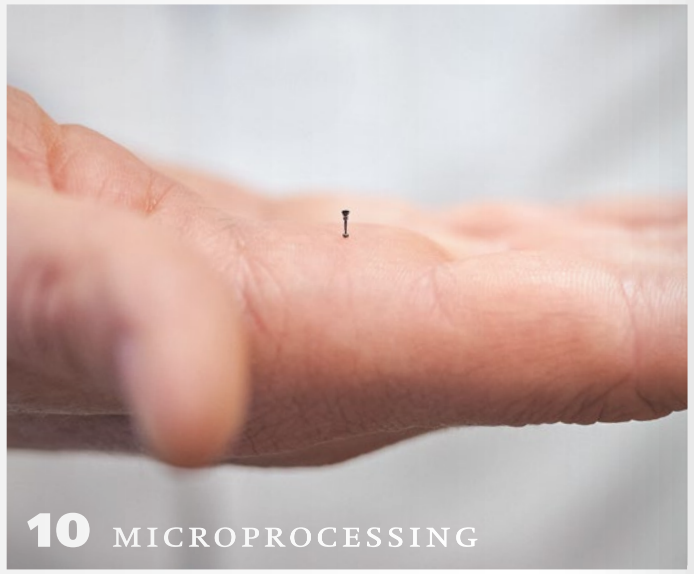
Hold on, a quantum is in multiple places at once!? Then the same should be possible for a quantum physicist! Inspired by this idea, we immediately decided to take this preliminary photo in the next room. Tobias Gerber then brought the idea to life, with top physicist Jörg Wrachtrup taking on **page 26**.

Simply beautiful

Oh, to shine like a supermodel! A dream come true for one €6.99 bottle of whiskey from a discount supermarket. Art Director Gernot Walter worked his magic with light, lens and mouse turning this ugly duckling into a beautiful swan. As you can see on **page 31**.

Martin Reinhardt, Gernot Walter

LASER COMMUNITY.



Stefan Hobmaier, Timo Müller

Andreas Reeg, Tobias Gerber, TRUMPF

POWER

Thanks to a new tool design, mass-produced items such as injection-molded figures can now be made in a much more energy-efficient way.

THE DREAM OF GREEN TOOLS

Internal conduits, produced using laser metal deposition welding, cool the tool in exactly the right places.

The laser equips copper and steel tools with cooling conduits, thus improving their environmental footprint.

Whether in car body production or mechanical engineering, press hardening and injection molding are highly popular manufacturing methods—but they have a dismal environmental footprint. After all, they generate huge amounts of heat, and waste tons of energy and coolant. But help is at hand—in the form of cooling conduits within the press-hardening and injection-molding tools; these discharge heat by conducting it into the metal. The more efficiently they do so, the more energy is saved. As suppliers around the world produce millions of parts every year, even the smallest savings make a difference. The German Federal Government thinks so too, which is why it is supporting resource-saving ideas through its Climate Action Plan. In this area, TRUMPF is working in tandem with several partners as part of the "Identification of energy- and resource-efficient process chains for the production of thermomechanically stressed tools through a holistic assessment method" (reProTools) project, which is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi). The idea is that lasers form customized cooling channels instead of drilling them.

This is made possible by the additive laser metal deposition (LMD) process, which allows scope for design freedom. Unlike with drilling, there are no limits to the length of the conduit; in some cases, bends and radii are also possible. With LDM, the laser deposits layer after layer on the basic steel tool, thus forming the tool with an ideal arrangement of cooling conduits. It creates a melt pool on the surface of the tool: a nozzle sprays powder onto the tool, with this powder then fused by the laser. During the cooling process, the additive powder and the workpiece form a metallurgical bond. The basic idea is nothing new. The notion of using LMD to embed finished cooling conduits within press-hardening tools was circulating back in the early 2000s, but reProTools goes one step further.

After all, if you're already utilizing an additive process, why not form the channels in a second material that is exceptionally good at conducting heat? Copper is just the ticket. Until recently, this combination was not possible; infrared lasers struggle with copper, as it exhibits highly reflective properties on account of a wavelength of 1,030 nanometers. This gives rise to spatter and poor reproducibility. Industrial beam sources are now available with a green wavelength of 515 nanometers, making them exceptionally good at coupling into copper. In the reProTools project, a green disk laser produces tools with optimum cooling properties.

As such, the temperature of the tools can be controlled more quickly, the cooling system does less work and manufacturing is more efficient. This not only saves resources and boosts productivity, but is also good news for the climate and users' budgets. ■

Gernot Walter, TRUMPF

LORD OF THE LIGHT

GLORY

LED pioneer Shuji Nakamura has been awarded the 2021 Queen Elizabeth Prize.

2015 was a big year for *Laser Community*: freshly crowned Nobel laureate in Physics Shuji Nakamura wrote an essay for this magazine entitled *More Light*, in which he declared his love of light, celebrated its importance for human civilization, and set out his vision of an illuminated world. There could have been no worthier recipient.

The Japanese engineer spent the late 1980s locked in a seemingly endless series of trial-and-error experiments in his company's laboratory. His aim was to develop high-quality gallium nitride (GaN) crystals in order to be able to generate blue light using light-emitting diodes (LEDs). Red, yellow and green LED light already existed, but the blue light spectrum was stubbornly refusing to shine. But bright and exceptionally energy-efficient white LED light is only possible with the addition of blue. The world became a brighter place. "For one-and-a-half years, I spent every morning and every afternoon modifying reactors nonstop," explains Nakamura, who is now Professor of Materials and Electrical & Computer Engineering at the University of California, Santa Barbara. Nakamura's perseverance paid off: he developed the first blue GaN LED, followed by the first green indium gallium nitride light-emitting diode, a white LED, and eventually a blue laser.

His inventions paved the way for the ongoing success story of energy-saving LED lighting and pioneering display technologies. Now, Shuji Nakamura has also been recognized with the prestigious Queen Elizabeth Prize for Engineering, along with four fellow pioneers of LED research: Isamu Akasaki, Nick Holonyak, M. George Craford and Russel Dupuis. In the words of the judges, this year's winners are "[...] recognized not only for the global impact of LED and solid-state lighting but also for the tremendous contribution the technology has made, and will continue to make, to reducing energy consumption and addressing climate change."

In 2015, Nakamura wrote the following in this magazine: "I am delighted that light bulbs and fluorescent lamps are slowly but surely being consigned to the world's technology museums and that solid-state lighting is handling the job of illuminating the world. I regard affordable light as a driver, indeed a benchmark, for civilization. Can you imagine human civilization without light?"

No, we cannot. ■

Shuji Nakamura's perseverance paid off: today, his energy-efficient LEDs illuminate our rooms and screens.

Matt Perko / USCB

“We print your bones”

Heraeus Amloy prints radius plates in amorphous metal on the TRUMPF TruPrint 2000. Customized implants from 3D printers will revolutionize medical technology. **Valeska Melde**, Head of Marketing and Sales at Heraeus Amloy’s, is sure of it.

Andreas Reeg / Fotogloria; editing: Die Magaziniker

The dream: implants that fit precisely between or within existing bone structures and that can take on exactly the same strain as the real bones that they are replacing. Heraeus Amloy wants to make this dream come true.

Ms. Melde, what is currently stopping us from producing precision implants using 3D printing?
Among other things, the requisite mechanical properties. Bones are extremely lightweight, exceptionally hard and highly flexible. Today’s materials merely offer a compromise between these attributes. Metallic materials, for instance, are too stiff, whereas polymers are too soft. 3D printing, however, could make it possible to produce customized implants.

And that would be desirable?
Yes. As things stand, surgeons often have to improvise in order to adapt series-produced implants to patients’ bodies. They bend them into their final form by hand and fix them in place using screws. That’s why we want to help.

And how?
By printing precision implants from a unique material: amorphous metal.

Sounds pretty fancy. What’s amorphous metal?
In normal molten metal, the atoms buzz around wildly. When the temperature falls, they slow down and arrange themselves in the most energetically favorable form, i.e. the crystal structure. If, however, the molten metal cools down at 200 kelvins per second, the atoms are unable to arrange themselves in position and are instead frozen in their molten state. The shapeless confusion of the atoms is retained in the solid metal. Here at AMLOY, we develop alloys that enable this process. Incidentally, the same phenomenon can be observed in glass, which is why amorphous metals are also referred to as “metallic glass.”

And how does this help in terms of implants?
Since amorphous metals do not have any crystal structures, they behave very differently to “normal” metals. For example, they are extremely robust, highly flexible and exceptionally resistant to wear and tear. Just like bones, the implants are therefore able to withstand considerable stresses and strains. And not just in the form of knocks and other impacts. Think about all the biting and chewing that jawbones have to contend with—or the fact that ribs have to endure some eight million breathing motions a year.

And 3D printing can handle amorphous metals?
With aplomb! In collaboration with TRUMPF, we have enhanced the process so that we can work with an exceptionally fine focus and extremely small volumes of molten metal. As such, the heat is quickly conducted away. In turn, this facilitates the critical cooling rate of 200 kelvins per second; an individually customized implant emerges from the powder bed and solidifies with an amorphous structure.

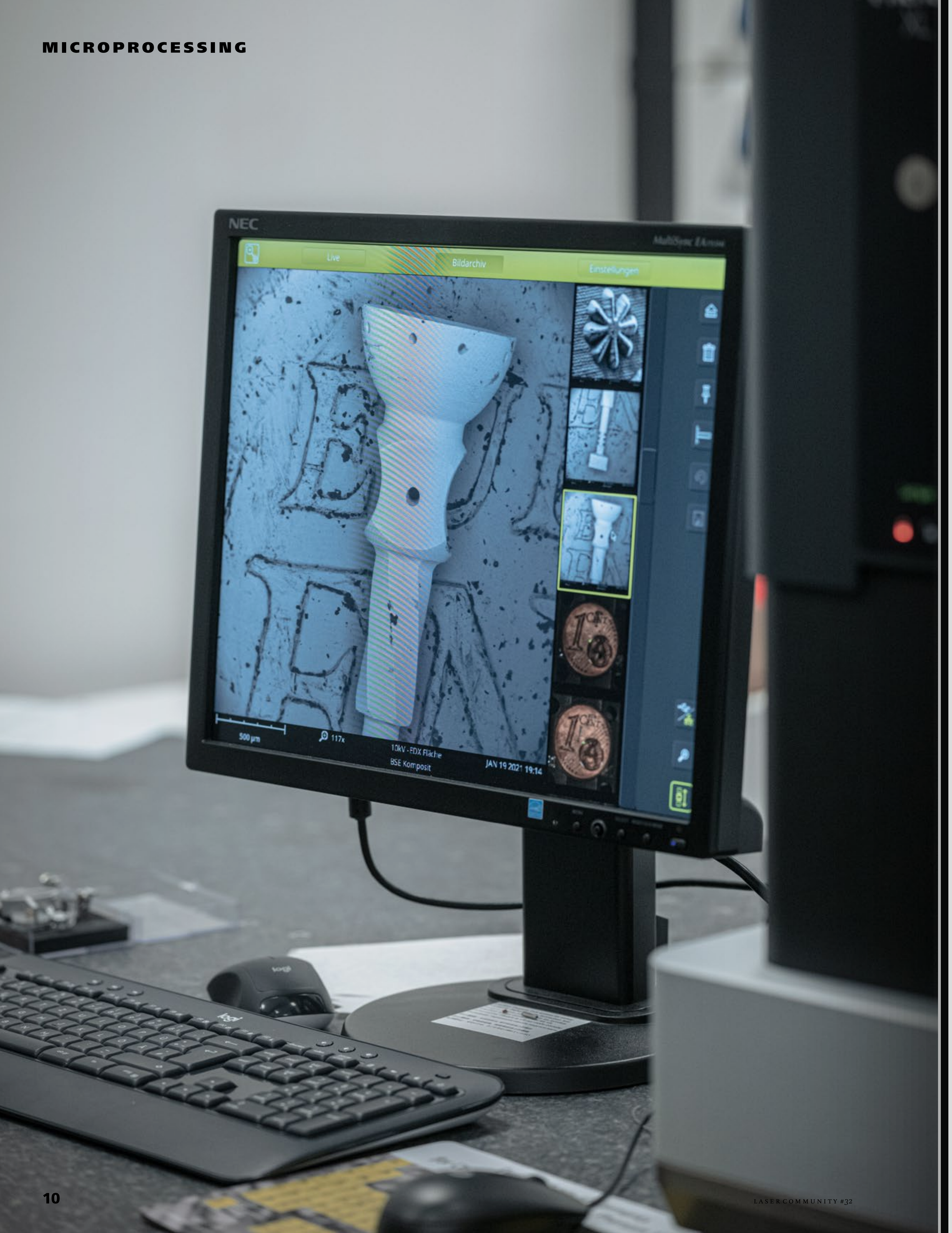
So two in one.
Even more, in fact! The 3D printing of amorphous metals offers yet another decisive advantage: we are much more flexible when it comes to the alloys. We already have zirconium-based alloys. At the same time, we are also working on an amorphous, titanium-based alloy. We are optimizing this and all our other alloys for 3D printing. They are particularly sought after in the medical technology sector, as AMLOY amorphous alloys feature an elastic modulus similar to that of human bones, which is a huge advantage in terms of the healing process and the resilience of the previously weakened body part. Our alloys are corrosion-resistant and biocompatible.

When will I be able to have the first printed implants fitted?
This is something that we are currently testing in tandem with partners such as TRUMPF as part of the Clinical Additive Manufacturing for Medical Applications (CAMed) project at the University of Graz. The results are promising, and we are already able to manufacture implants that can then be tested and approved by our clients. So the idea of us printing your bones is already reality. ■

The company: Heraeus Amloy develops and sells amorphous alloys and uses them to make components for its clients. Zirconium-based alloys are already available, with titanium-based versions set to follow.

The products: Amorphous components are also gaining ground in fields other than mechanical engineering and medical technology: an amorphous, 3D-printed bridge and volume/tone controls already adorn the first electric guitar, whereas NASA plans to equip its space robots with drill bits made from these specialty metals.

The material: Amorphous metals are produced by flash-freezing molten metals. The atoms solidify in a random arrangement and do not form crystal structures.



FINE ART

Left: magnified dramatically on the screen; right: the actual component in the machine. Mechanical turning isn't much use when dealing with such tiny precision parts.

Stefan Hobmaier / Fotogloria

GFH invents laser turning.

D

“Damn, he’s right,” says GFH CEO, Florian Lendner, to himself. One of his customers from the medical technology sector has just told him that he will only see the laser as the perfect tool once he can use it for turning. This gets Lendner thinking; turning has, up to now, been the only machining process for which there is no practical laser-based alternative. But Lendner wants to change that.

During turning, the workpiece rotates—and a chisel moves across its outline, cutting away material. The force exerted upon the component is known as “cutting force.” And this is what Lendner is interested in. GFH machines are not used to manufacture finger-sized valves or thick pistons. GFH builds microprocessing machines—and cutting forces have no place in the world of microprocessing. His customers want to produce tiny medical forceps that are just a few micrometers thick, stylish mini watch hands, or exceptionally fine electronic modules. If he were to start applying brutal cutting force, there would be a constant risk of rejects due to deformation. GFH machines therefore use lasers in place of mechanical machining tools for processes such as drilling, milling and surface finishing. But lasers aren’t suitable for turning. This gives rise to the age-old problem of mechanical tools in the microprocessing sector: “When the turning chisels become ever finer, they wear out very quickly, meaning that tools have to be constantly replaced,” explains Lendner. “What’s more, even the tiniest turning chisels eventually reach their physical limits.”

Therefore, Lendner and his team do exactly what they have been doing for the past 20 years: they think about how they can replace a mechanical tool with ultrashort pulse lasers (USPs). They have already achieved this feat in terms of texturing, cutting and drilling at micro level. But that’s not all: GFH brings together all three USP laser machining processes in a combined machine, meaning that the workpiece doesn’t even need to be re-clamped. Lendner is proud, but then a customer from the medical technology sector comes along and suddenly also wants laser turning.

A SECOND WIND “The USP laser is a universal tool. Its light doesn’t touch the workpiece or heat it up. At micrometer precision, it removes precisely the material that we want to remove. So there shouldn’t be any reason why laser pulses can’t also be used for turning,” remarks Lendner.

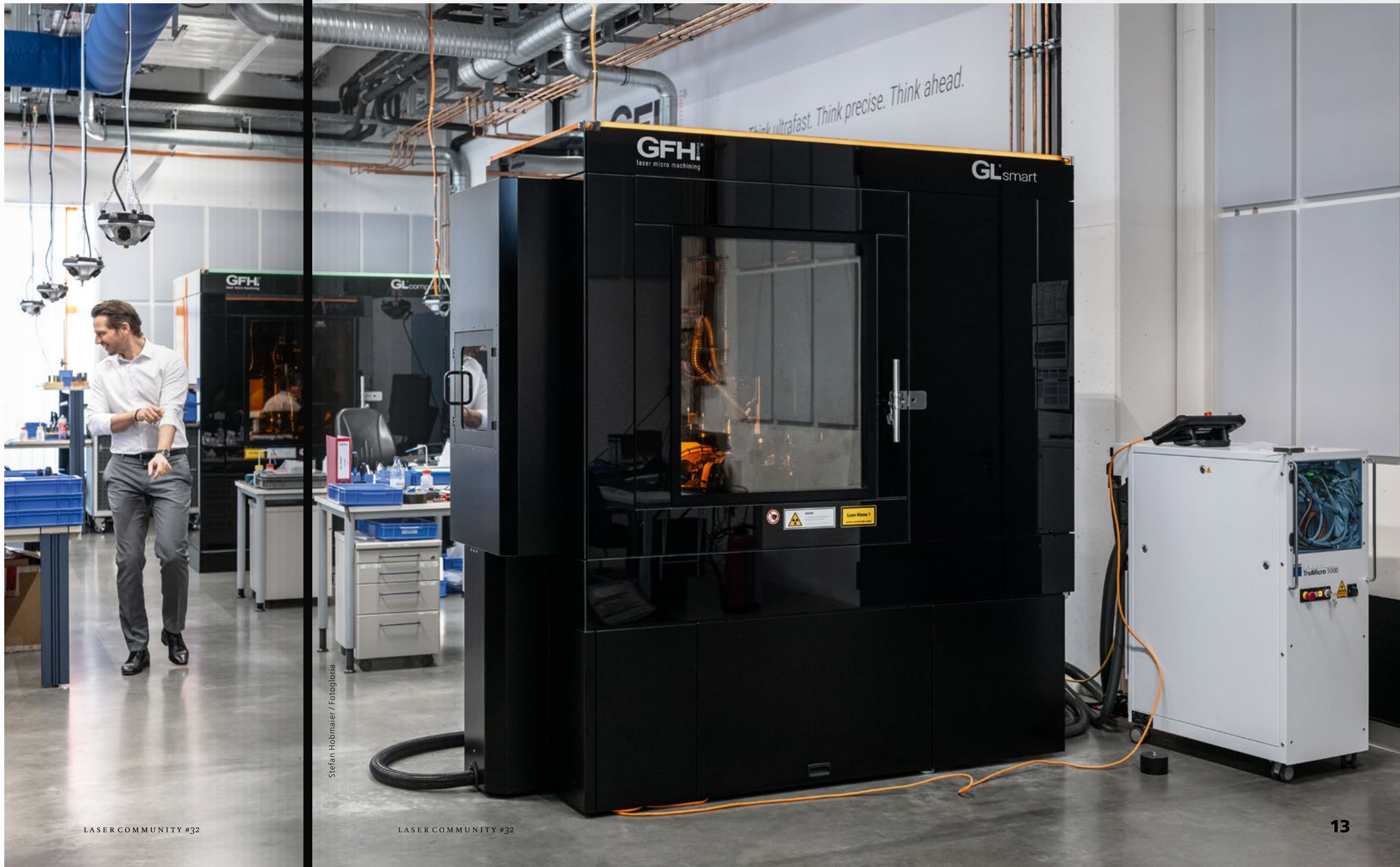
But the reality proved to be harder than envisaged. Even the initial attempts performed on sample parts required the entire expertise and combined frustration tolerance of his team. Lendner: “I reached the point where I wondered whether all the hard work was even worth it. We therefore published the initial results in order to see whether anyone was even interested in laser turning.” The response was huge—and went well beyond the field of medical technology. “We saw that the demand was there and that we could really make a splash!” This energized the GFH team, who were given a second wind.

IT TAKES TWO TO TURN! They needed this energy, as they still had many years of development ahead of them. The main problem was the processing speed. “When you have a rotating part, the laser only ever processes a narrow strip of the surface, i.e. the strip that is currently turned toward the optical element. Therefore, the key factor is how quickly the machine can rotate new, unprocessed sections of the surface into the light.” Thanks to a high-precision air-bearing rotation axis, the workpiece can reach up to 3,500 rotations per minute. Although this looks incredibly fast to the naked eye, it feels like tortuous slow motion to a laser that pulses at a rate of picoseconds. The laser can cut a line, drink one or two cups of coffee, read a book, take a lunch break, watch the director’s cut of the *Star Wars* trilogy and then see whether it’s needed again. “At this rate, material abrasion is quite simply too slow to be cost-effective.”

But the team then had a light-bulb moment: although all kinds of physical constraints apply to a rotating piece of metal, there are no such constraints on incorporeal light. With this in mind, the developers then started rotating the laser beam at lightning speed. When the beam is applied to the rotating workpiece, the processing speed is increased dramatically by means of contrarotation.

THE DECISIVE IDEA BEHIND THE MACHINE: LET THE LASER ROTATE, TOO!

The GL.smart combines four USP laser machining processes at micro level: cutting, drilling, texturing and turning. The workpiece can pass through the system without ever having to be re-clamped. The patented trepanning optical element seamlessly works through each processing stage until the workpiece is finished.



Stefan Hobmaier / Fotogloria

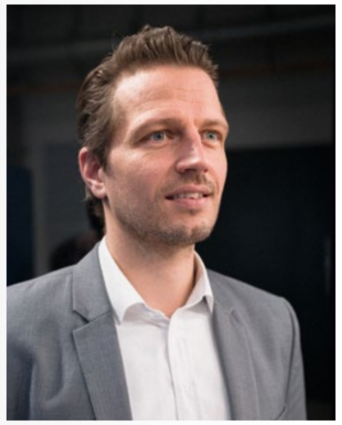
This fresh idea brings with it a third wind. The GFH engineers now utilize a trepanning optic that they had actually developed for a different project. At the heart of the trepanning optical unit are rotating cylindrical lenses, enclosed in an extremely finely balanced precision spindle. This unit allows the focus to circle the workpiece at up to 30,000 times a minute, firing off a lightning-fast salvo of ultrashort pulses. In the first step—rough machining—the light vaporizes as much material as possible, with considerable energy input. In the subsequent fine-machining stage ("finishing"), less energy is used and the final surface finish achieved. Mission "laser turning" has been accomplished.

YET ANOTHER TRIUMPH The trepanning optic has even more up its sleeve. If a beam can come into contact with the surface from a variety of angles and circle the workpiece, it is also more effective at cutting and drilling at micro level. "We can now precisely determine the wall angles of cuts and boreholes—and even produce holes that dilate downward," explains Lendner. "Try doing that with a mechanical drill!"

And the team's euphoria hits new heights when it becomes clear that they—as secretly hoped—are able to process sapphire glass, ceramic and diamonds in next to no time. These are materials that have always offered stiff resistance to any mechanical ablation process—and that have finished off one tool after another. Lendner puts it in more matter-of-fact terms: "This demonstrates a key advantage of laser technology compared to conventional manufacturing processes: no strain on the workpiece, no wear and tear on the tool. This is what makes the technology so cost-effective."

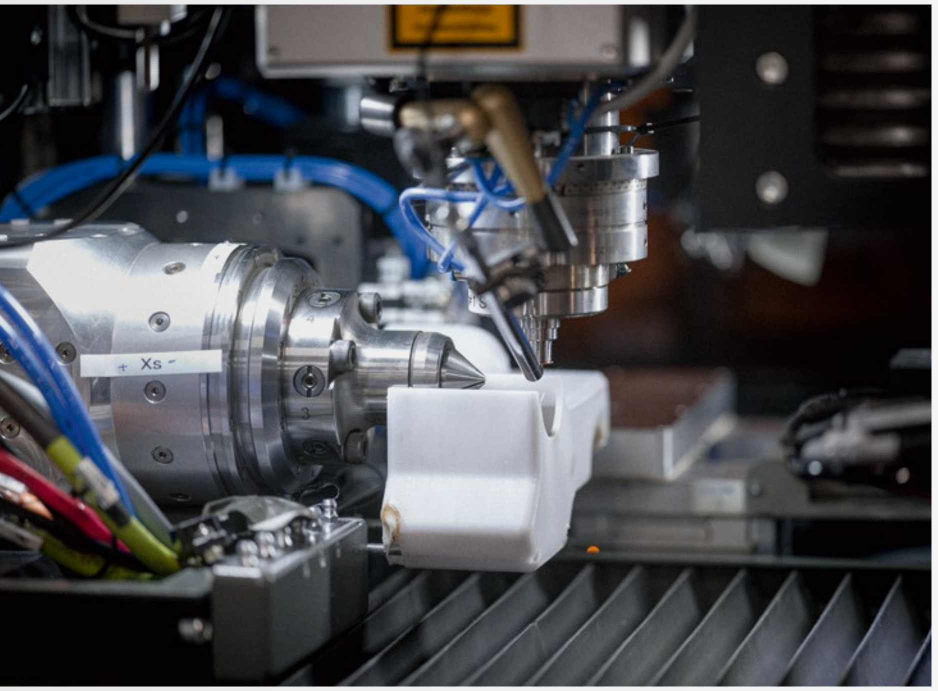
Since 2020, the GL.smart microprocessing machine has been in use at the sites of several customers, including in the medical technology sector (where the idea originated). It is the first laser system that combines all four machining processes at micro level: drilling, texturing, cutting—and now turning. "Well, you can't really refer to it as 'machining' when you use ultrashort pulse lasers, but rather 'vaporizing'—but everyone knows what you mean," says Lendner, with a beaming smile. ■

Contact: Florian Lendner, CEO, phone: +49 991 29092-113, florian.lendner@gfh-gmbh.de



"EVEN THE TINIEST TURNING CHISELS EVENTUALLY REACH A PHYSICAL LIMIT. LASER LIGHT IS THE ONLY WAY TO GO BEYOND THIS LIMIT."

Florian Lendner,
CEO of GFH



The principle of laser rotation: (to the left) the air-bearing rotational axis that holds the workpiece; the trepanning unit works from above. The workpiece rotates at a speed of 3,500 rotations per minute, where the focus circles are 30,000 times per minute.

Stefan Hobmaier / Fotogloria

Healing properties

Even medical practitioners regard the laser as a blessing. Exactly 60 years ago, a laser destroyed an eye tumor, thus healing a human being for the first time. Much has happened since then.

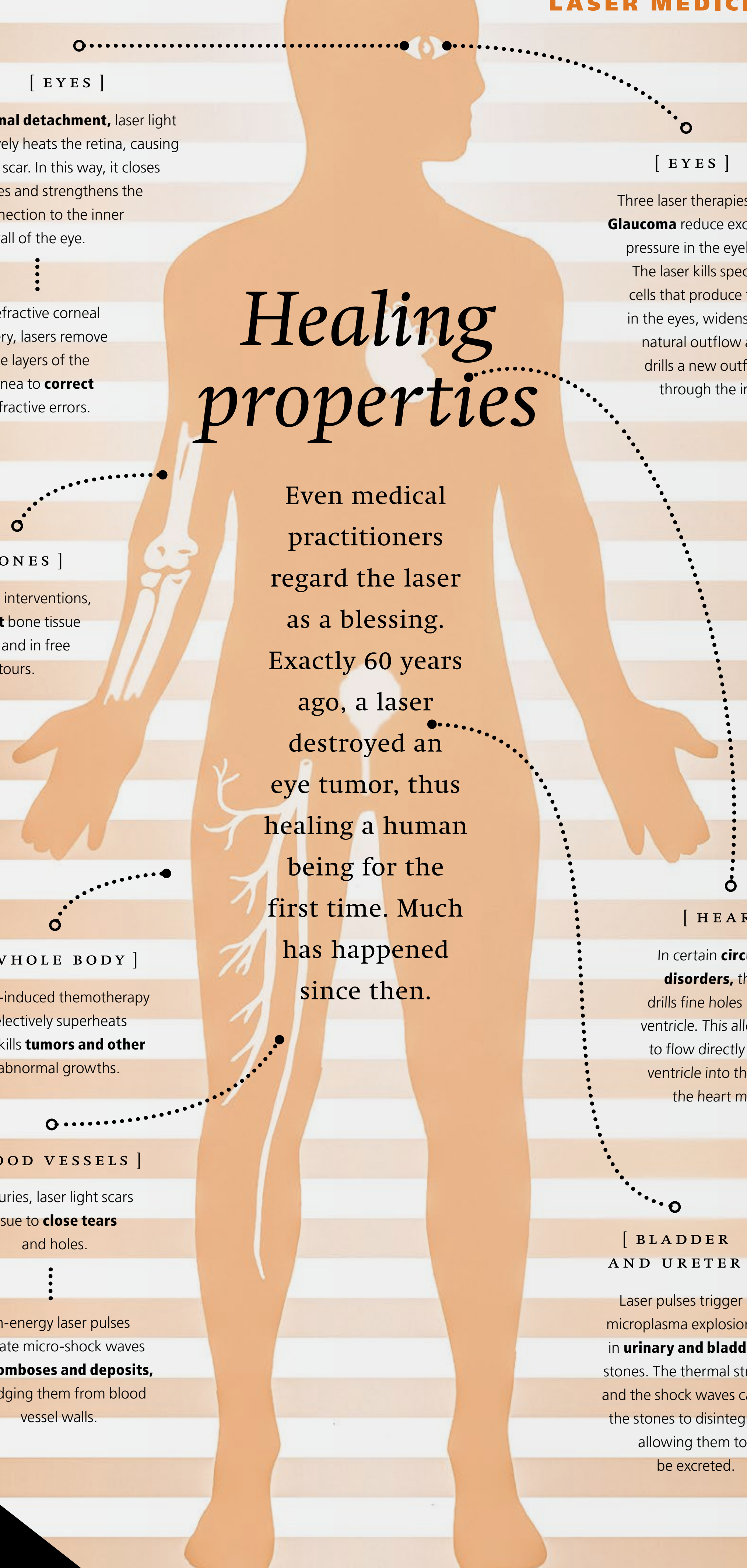
KEY MECHANISMS OF ACTION

Heating: The laser stimulates molecule vibration. The tissue undergoes controlled heating.

Erosion: The laser deploys so much energy that it destroys and vaporizes tissue directly.

Ablation: Laser pulses generate microscopic plasma explosions. Shock waves dislodge sections or layers of tissue.

Photodynamic therapy: An initially harmless substance is introduced into the body. Once the substance reaches the place of action, the laser light breaks down its molecules into aggressive agents.



[EYES]

In **retinal detachment,** laser light selectively heats the retina, causing it to scar. In this way, it closes holes and strengthens the connection to the inner wall of the eye.

In refractive corneal surgery, lasers remove fine layers of the cornea to **correct** refractive errors.

[EYES]

Three laser therapies for **Glaucoma** reduce excessive pressure in the eyeball. The laser kills specific cells that produce fluid in the eyes, widens their natural outflow and drills a new outflow through the iris.

[BONES]

In surgical interventions, **lasers cut** bone tissue precisely and in free contours.

[WHOLE BODY]

Laser-induced themotherapy selectively superheats and kills **tumors and other** abnormal growths.

[HEART]

In certain **circulatory disorders,** the laser drills fine holes in the left ventricle. This allows blood to flow directly from the ventricle into the veins of the heart muscle.

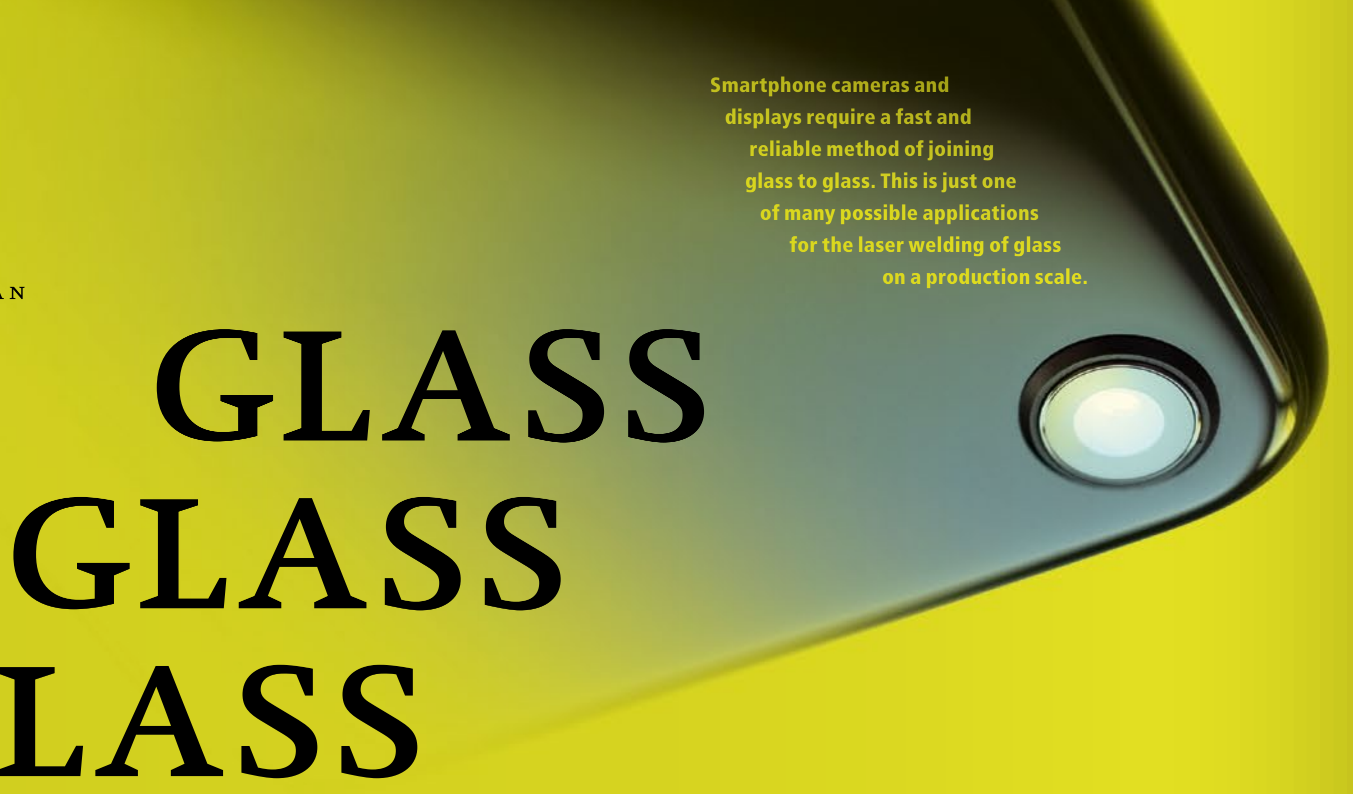
[BLOOD VESSELS]

In injuries, laser light scars tissue to **close tears** and holes.

High-energy laser pulses generate micro-shock waves in **thromboses and deposits,** dislodging them from blood vessel walls.

[BLADDER AND URETER]

Laser pulses trigger microplasma explosions in **urinary and bladder** stones. The thermal stress and the shock waves cause the stones to disintegrate, allowing them to be excreted.



Smartphone cameras and displays require a fast and reliable method of joining glass to glass. This is just one of many possible applications for the laser welding of glass on a production scale.

BY SEBASTIAN HECKER

GLASS GLASS GLASS

Fully automated quality control paves the way for the laser welding of glass on a production scale.

Production-scale bonding of transparent and semitransparent materials such as glass and sapphire is a common requirement in many industries, including the consumer electronics, automotive, architecture, photovoltaics, technical optics and medical device sectors. One way to bond glass to glass is by using ultrashort pulsed laser technology. This method has been production-ready for several years and delivers high-quality results, yet it has so far been confined to small-batch manufacturing. Nevertheless, it has the potential to be both fast and enormously productive.

Many industry sectors currently rely on gluing, a bonding process that is well suited to conventional mass production. Over time, manufacturers have progressively optimized their gluing techniques, yet they still encounter disadvantages and quality problems that are directly linked to the gluing process itself.

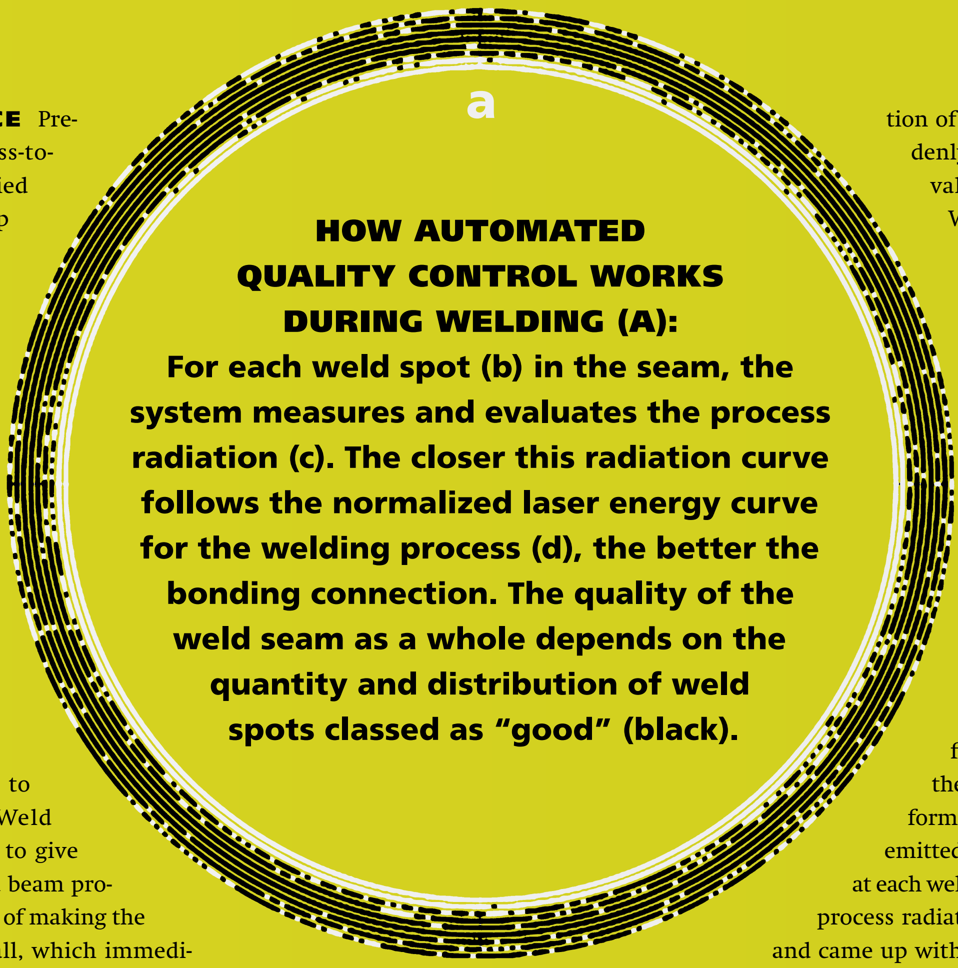
One of the fundamental problems of gluing is the basic fact that it requires glue! This adds another material that must be integrated into the manufacturing process. Machines or workers apply the glue and press together the parts to be joined, but the effect is not immediate, since the glue has to harden before the joint will be strong enough to hold. Laser welding eliminates the need for any additional materials and produces full-strength weld seams instantaneously. Adhesives also have other disadvantages; for example, the fact that their chemical and mechanical properties are different to those of the parts being joined. This can have significant consequences. Glue may release gases that could contaminate the assembly. It also ages and becomes brittle, potentially reducing a product's service life. What's more, glued joints are only effective at keeping out gas and liquid to a limited extent—and only for a relatively short period of time. In contrast, ultrashort laser pulses can create a durable bond between the parts to be joined without any of the problems outlined above. Moreover, laser welding can make assemblies more compact: thanks to its higher seam strength, it doesn't require as large a bonding surface as glue. Laser welding is also more flexible when it comes to the geometry of the joining surfaces, giving part designers more scope to find creative solutions.

SEBASTIAN HECKER was a doctoral student at TRUMPF Laser in Schramberg. In his doctoral thesis for the University of Stuttgart, which he completed in 2020, he devised a method to automatically monitor glass welding and also developed a system to apply this method in practice.

Yet despite these formidable advantages, laser glass welding has been difficult to apply in production due to two key shortcomings, namely the need for high-quality joining surfaces and the lack of an automated weld quality control system. Fortunately, we now have a solution for both these problems.

HOW IT WORKS Before presenting our solution, let me briefly describe the basic principles of how the method works. The key requirements is pulsed, infrared laser light with a high repetition rate and a pulse duration in the picosecond range or shorter. We start by placing one of the glass components on top of the other. We then fire the laser beam through the upper component so that it's focal point is inside the lower component. The laser pulses melt the material at the focal point, and droplets of this molten material spread upwards into the component above. The molten material solidifies to create an interlocking connection. We repeat this process several thousand times for each weld path. Within a matter of seconds, this combination of thousands of weld spots produces a durable bond.

TRUMPF, Gernot Walter



HOW AUTOMATED QUALITY CONTROL WORKS DURING WELDING (A):
For each weld spot (b) in the seam, the system measures and evaluates the process radiation (c). The closer this radiation curve follows the normalized laser energy curve for the welding process (d), the better the bonding connection. The quality of the weld seam as a whole depends on the quantity and distribution of weld spots classed as "good" (black).

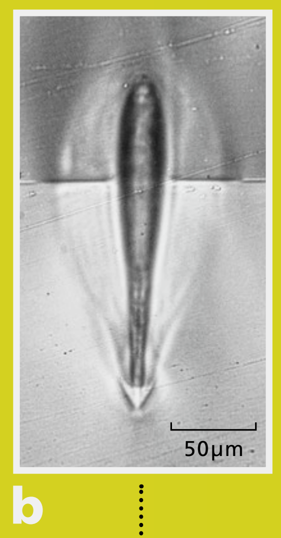
MORE TOLERANCE Previously, optimum glass-to-glass laser welding relied on keeping the gap between the parts to be joined in the region of one to four micrometers, but no higher. Exceed this gap size, and the molten material would spill out the sides of the gap and the bond would fail. But keeping within these limits on an industrial scale was a lot to ask! So we began looking for ways to increase the tolerances.

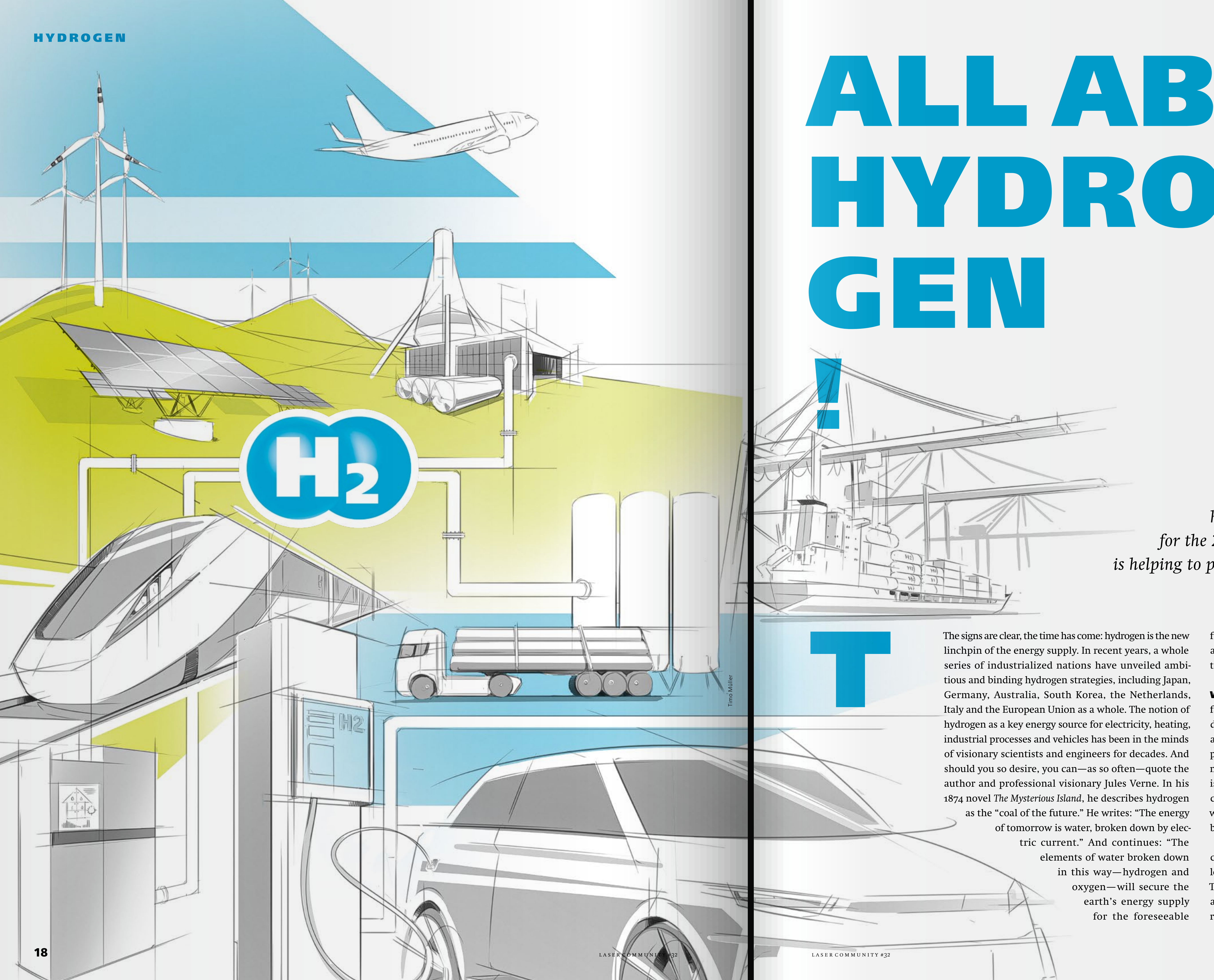
Our first step was to switch to the TOP Weld optics, which allow us to give the pulses an elongated beam profile. This has the benefit of making the weld seam larger overall, which immediately doubles the tolerance for the gap that you have to bridge. But it's the next step that really marks a key breakthrough in two respects. The key is to modulate the laser energy for each individual weld spot. In other words, we start by allowing the energy of the laser pulses for each weld spot to surge, and then immediately allow it to drop again. This boosts the gap-bridging tolerance by a further 30 percent, and increases the maximum bridgeable gap size by as much as 50 percent. These improvements provide the kind of tolerances that can realistically be met on a production scale.

AUTOMATED MONITORING The other benefit of energy modulation was that it finally opened the door to automated quality control. Previously, we could only inspect the seam after the process was complete, either using optical methods or by examining random cross-section samples under the microscope. This was a costly and unsatisfactory approach. But the introduction of energy modulation suddenly gave us a new, known value within the process. What we needed now was a second, measurable signal from the process, but it had to be one that varied in direct correlation with the process. Our thinking was that we could then compare these measurements to the energy modulation figures to determine whether each individual point on the seam had been successfully welded. We found the signal we needed in the form of the process radiation emitted by the molten material at each weld spot. We measured this process radiation using a photodiode and came up with various calculations to establish a correlation between the two signal curves, i.e. between the modulated energy figures that we already had and the measured intensity of the process radiation. The result gives us a reliable indication of the strength of the bond at each weld spot. We can actually predict the quality of each individual weld spot with an accuracy of 98.6 percent!

A weld seam usually consists of thousands of weld spots. By calculating the sum of all successful weld spots and analyzing their distribution along the entire weld, we can automatically calculate how successful the welding process has been overall. Automated quality control is a huge step forward on the path toward industrial production. It even opens up the possibility of rescuing pieces that would otherwise be scrapped, because defective welds can be corrected.

Laser welding with automatic monitoring is a mature, productive and reliable method—and it offers industry a viable alternative means of joining glass and other transparent materials. ■





Timo Müller

ALL ABOUT HYDROGEN!

T

Things are getting serious: hydrogen is the new energy source for the 21st century. And laser technology is helping to produce fuel cells, pipes and tanks.

The signs are clear, the time has come: hydrogen is the new linchpin of the energy supply. In recent years, a whole series of industrialized nations have unveiled ambitious and binding hydrogen strategies, including Japan, Germany, Australia, South Korea, the Netherlands, Italy and the European Union as a whole. The notion of hydrogen as a key energy source for electricity, heating, industrial processes and vehicles has been in the minds of visionary scientists and engineers for decades. And should you so desire, you can—as so often—quote the author and professional visionary Jules Verne. In his 1874 novel *The Mysterious Island*, he describes hydrogen as the "coal of the future." He writes: "The energy of tomorrow is water, broken down by electric current." And continues: "The elements of water broken down in this way—hydrogen and oxygen—will secure the earth's energy supply for the foreseeable future." Bearing in mind that he wrote these words almost 150 years ago, why is it now suddenly possible to bring this idea to life?

WHO GETS THE MONEY? In the past, one hard fact in particular stood in the way of the hydrogen dream: the use of other energy sources such as coal, oil and natural gas was, quite simply, cheaper and more profitable. However, the impacts of the climate crisis now make it clear to absolutely everyone that "cheap" is a relative term. It is hard to accurately forecast the cost and effort associated with dealing with global warming, which has already begun. There is, however, broad agreement that they will be huge.

But the new sense of urgency is more than just a climate policy imperative, as there are also extremely logical reasons for promoting the hydrogen economy. The benefits of using this simple gas as an energy source are impossible to overlook: water—the main raw material for hydrogen generation—is available in abundance.

What's more, established resources such as natural gas are, in certain circumstances, suited to the clean production of hydrogen (see the box on the hydrogen color code). H_2, i.e. hydrogen, is a zero-carbon fuel—so when it is burned, it only releases the useful energy and the "waste product" of new water. Hydrogen is absolutely ideal when it comes to storing and transporting electrical energy ("power to gas"). This will serve as a game-changer for green but erratic technologies such as wind and solar power. A further advantage lies in the fact that the use of hydrogen has proved its mettle for many years, such as in rocket engines and the fuel cells of cars, buses and trains. Chemical engineers have many years of practical experience with H_2: they have long been using it as a base material for myriad processes, such as the extraction of ammonia for fertilizers, methanol for various acids, and ethylene and propene for plastics. Even the transportation of hydrogen in pipelines measuring hundreds of kilometers has long been standard practice. New yet familiar territory, as it were.

So it's no wonder that more and more industrialized nations are willing to invest billions of euros in the development and construction of a future-proof hydrogen infrastructure.

FIRMS THAT USE LASER TECHNOLOGY CAN FULLY HARNESS THE HYDROGEN BOOM.

Who is set to be part of the hydrogen megaproject? All those companies that are already willing to embrace the emerging boom and who are equipped with the cutting-edge technology required to build all the electrolyzers, pipes, tanks and fuel cells that are set to come. In order to get involved, firms need foresight, a dash of entrepreneurial courage—and laser technology.

LASERS IN FUEL CELLS The centerpiece of any hydrogen economy is a galvanic cell that extracts energy from the reaction between hydrogen and oxygen: the fuel cell. Fuel cells are the very reason why a hydrogen economy can operate efficiently in the first place; the reaction between hydrogen and oxygen harbors an incredible amount of energy. But unlike with most other high-energy chemical reactions, the fuel cell offers a technological method of conducting them in a controlled manner. And the energy from these reactions can be converted into electricity relatively directly via combustion heat, turbines or similar technology. Fuel cells are not only energy converters, but they are flexible too. Fuel cells can power cars and ships, but also supply buildings and industrial facilities with electricity.

Plenty of experience has been gained with fuel cells, ever since they were built for the first time in 1838. However, all the fuel cells that have ever been produced will pale into insignificance compared with the huge numbers that will be built over the next ten years. Therefore, the search has begun for factories and processes that will soon manufacture high-efficiency cell after high-efficiency cell.

Depending on their area of application, fuel cells have different technical designs. Clearly, stationary fuel cells that supply buildings have completely different specifications in terms of efficiency, short-term energy provision and size than mobile fuel cells in cars and trucks. The type with the greatest potential for mobile applications is the low-temperature proton-exchange membrane fuel cell (or "low-temperature PEM cell" for short). PEM cells can easily withstand impacts during operation and—for their volume and weight—boast outstanding power density, which is exactly what is required to accelerate a vehicle.

The linchpin of a PEM cell is a stack comprising hundreds of bipolar plates, with two bipolar plates enclosing each membrane. In turn, a bipolar plate consists of two stainless-steel half-shells welded together; they are between 75 and 100 micrometers thick and feature thin channels on the surface. Hydrogen and oxygen flow toward each other from opposite ends of these channels before reacting on the textile membrane to generate water and energy.

The whole idea only works if the two wafer-thin half-shells—and the walls of each individual channel—are welded together extremely tightly. The slightest pore on a bipolar plate can cause the entire stack to fail. The cumulative welding seam on each stack can even run to a length of several kilometers. As things

ONLY LASERS WELD BIPOLAR PLATES FOR FUEL CELLS IN A COST-EFFECTIVE MANNER.

H_2

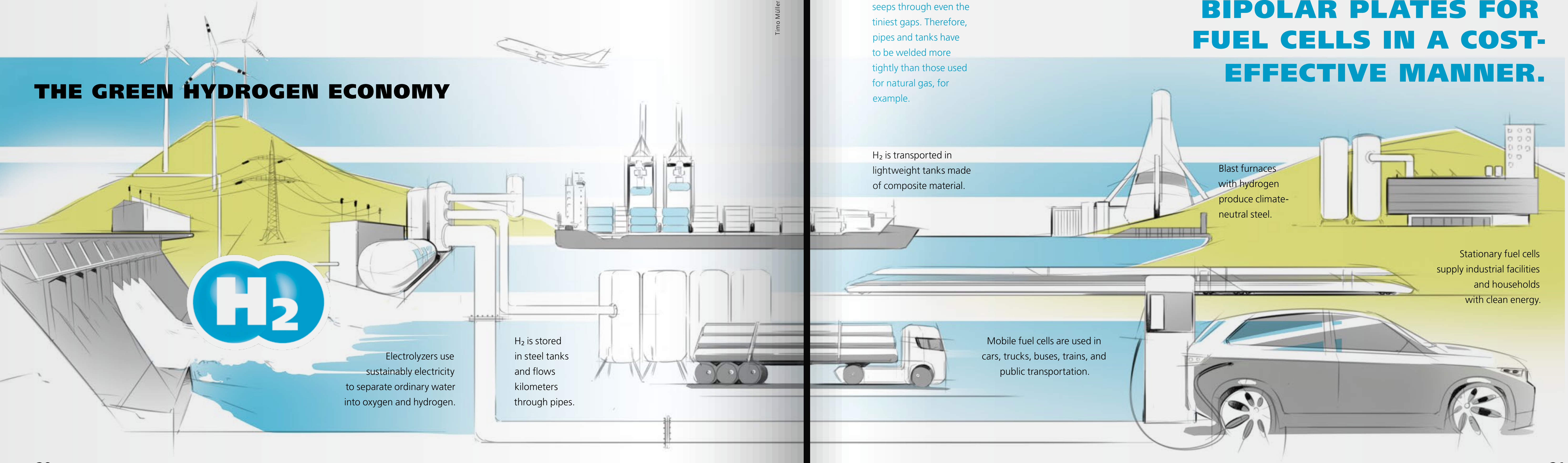
Atomic: Hydrogen is the smallest, simplest and most common element in the universe—and accounts for about 90 percent of all atoms. It consists of one proton and one electron.

Molecular: Hydrogen occurs almost exclusively as a molecule with two atoms (H_2). It is the smallest molecule of all.

Physical: Under normal conditions, hydrogen is a colorless and odorless gas. It is the most lightweight of all gases.

Chemical: Hydrogen is flammable and forms an explosive mixture when combined with air and other oxidizing gases.

Technical: Hydrogen seeps through even the tiniest gaps. Therefore, pipes and tanks have to be welded more tightly than those used for natural gas, for example.



THE GREEN HYDROGEN ECONOMY

Electrolyzers use sustainably electricity to separate ordinary water into oxygen and hydrogen.

H_2 is stored in steel tanks and flows kilometers through pipes.

H_2 is transported in lightweight tanks made of composite material.

Mobile fuel cells are used in cars, trucks, buses, trains, and public transportation.

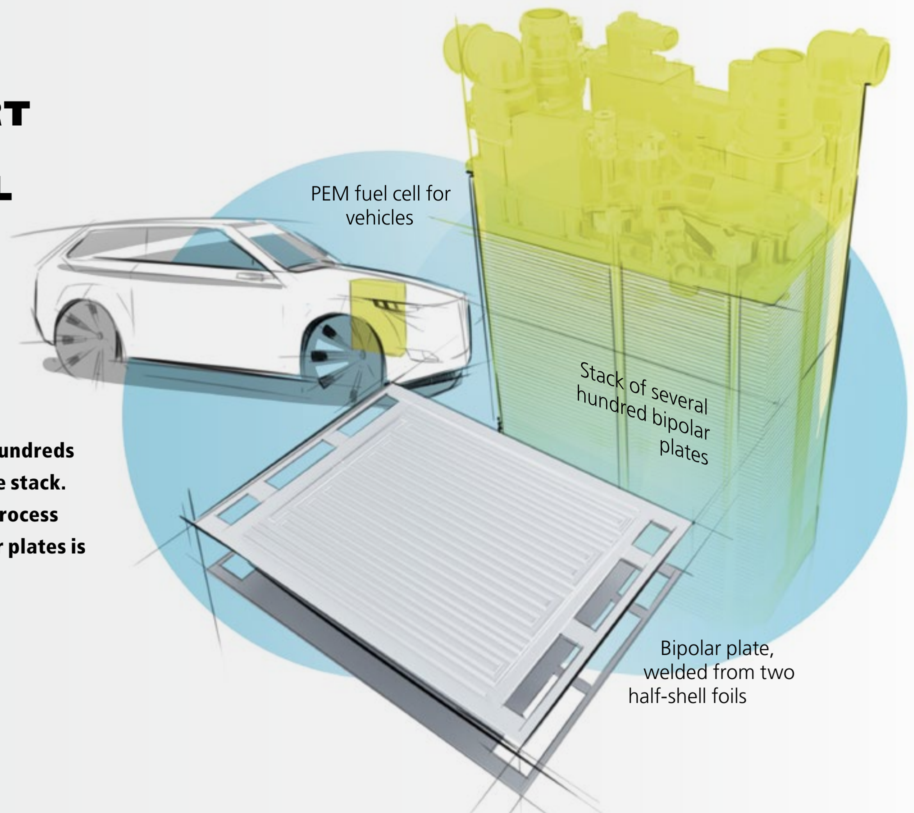
Blast furnaces with hydrogen produce climate-neutral steel.

Stationary fuel cells supply industrial facilities and households with clean energy.

Timo Müller

THE HEART OF THE FUEL CELL

The PEM fuel cell produces electricity for cars, trucks and other vehicles. Hydrogen and oxygen are converted into energy and water in hundreds of bipolar plates in the stack. The only economical process to join the thin bipolar plates is laser welding.



ONE THING IS CLEAR: MORE HYDROGEN MEANS MORE LASER TECHNOLOGY.

stand, scanner-based laser welding is the only process that is able to meet the requirements in terms of precision, speed and safety in a cost-effective manner. The scanner optic guides the spot across the workpiece, with sensors ensuring the required process reliability.

Stationary fuel cells lead a quieter life and therefore have fewer bipolar plates than their mobile cousins. Here, the bipolar plates usually consist of layers of graphite film bonded together. Here too, lasers have established a place for themselves in the process, as the graphite has to be cleaned to prevent dirt at the adhesive points. The laser vaporizes dust and grease—and prepares the surface for the bonding process.

TANKS AND PIPES Laser technology enables the mass production of fuel cells. But things really start to become exciting when you consider the entire infrastructure underpinning an interconnected hydrogen economy (see graphic on page 20). Companies will not only build many more fuel cells than they do today, but also countless kilometers of stainless-steel pipework and thousands of hydrogen tanks. When it comes to the tanks fitted in vehicles and those used to transport hydrogen over land and sea, weight plays a vital role. This is why manufacturers favor lightweight composite materials, whose processing involves the use of lasers. Lasers even ensure speedy, airtight welding joints on the large, high-pressure steel hydrogen containers that will be found at ports and gas stations.

And whatever direction the H_2 journey ultimately takes: hydrogen will need to flow through stainless-steel pipes of the very highest quality. There are even plans for new pipelines measuring many kilometers. This plays right into the hands of the laser, which has been established as the most cost-effective pipe-welding method for many years. The increased requirements in terms of the welding joint's airtightness also represent an argument in favor of the laser. After all, hydrogen is the smallest molecule in the world (much smaller than natural gas, for example) and can slip through even the tiniest gap. In other words, more hydrogen means more lasers.

The plans have been drawn up and government funding is already being paid to companies that are investing in hydrogen. And whether we're thinking about Jules Verne or not: laser technology will demonstrate to humanity that the bearded French writer was onto something with hydrogen—just as he was with the moon landings, submarine travel, neon signs, skyscrapers and calculators. ■

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Whenever colors are talked about in reference to hydrogen, this has nothing to do with the gas itself, but rather how it is generated:

Green hydrogen is generated through the standard electrolysis of water. The energy for this process originates solely from renewable sources such as wind power and does not release any CO_2.

Gray hydrogen is produced by heating natural gas in so-called steam reformers to convert it into hydrogen and waste CO_2. This process is still significantly cheaper than electrolysis, but is harmful to the environment.

Blue hydrogen is also generated using natural gas in steam reformers. This time, however, the CO_2 is captured and buried deep underground, such as in depleted natural gas fields.

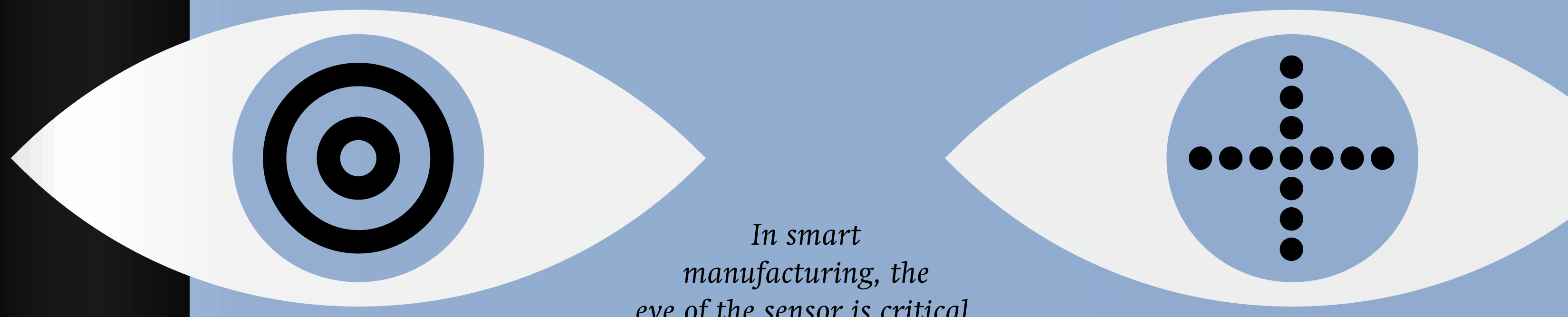
Turquoise hydrogen is extracted from natural gas by means of energy-intensive high-temperature methane pyrolysis. The process also produces solid carbon that can be used elsewhere. It is only climate-friendly if existing excess heat can be repurposed for the process.

Colored hydrogen is an umbrella term for all other methods of generating hydrogen. However, none of these processes is currently ready for industrial use.

Timo Müller

Die Magaziniker

DOUBLE VISION!



In smart manufacturing, the eye of the sensor is critical. Or, to be more precise, two eyes.

How can a factory be intelligent when the machines are blind? Take hairpin welding on an electric motor, for instance. Here, the tips of copper wires (hairpins) are welded together to form the motor's coil—through which electricity will then flow. This creates a magnetic field that, in turn, gets the electric motor started. Therefore, everything hinges on the quality of each individual weld. The problem is the positioning of the pins. It is often the case that not all copper wires are packed closely together at the same height so that they can be firmly welded together. It goes without saying that the laser optic comes with a camera—and that it has a look before welding; however, it only sees two copper surfaces and is unable to deduce the height relationship between them.

Therefore, we solved the problem with a sensor based on optical coherence technology (OCT). This sensor also looks at the hairpins through the laser optic. It guides a measuring beam onto the workpiece, compares the trajectory with a reference beam, and generates a height profile of the pins. As such, the OCT sensor ascertains whether the two surfaces—i.e. the tips of the hairpins—are actually at the same height. The camera also detects the position of the pins. Together, the two sensors provide an exact picture of how the wires are positioned within the machine. Armed with this data, the smart factory can now do its job. It can utilize this data for the welding process and store it for subsequent quality control. It can also enter it into a database, where algorithms may be able to recognize typical misalignments, thus allowing the machine to automatically make corresponding adjustments. A smart factory thrives on data. The more sensors, the more data. And the better the quality of data sourced by the factory from cold, hard manufacturing processes, the smarter the factory becomes. That's because it can then adapt the process to reflect reality—and is not reliant on reality evolving to fit the process. ■

Wilrid Dubitzky
Head of Product Management for Pulsed Lasers at TRUMPF.

Michael Siebert

TORNADO POWER!

Mechanical engineering firm Bergmann & Steffen creates a mini whirlwind around the scanner optic, thus boosting the performance of remote laser welding.

What works twice as fast as a scanner optic? Two scanner optics. But when they weld side by side, one of them can easily blow traces of powder in front of the lens, thus disrupting the welding process. Normally, a crossjet blows a horizontal current of air perpendicular to the laser beam in order to keep the scanner's work area free from vapor and welding spatter. More and more often, however, we are seeing that the area to the left and right of the scanner unit is not occupied by empty space, but rather a second optic. Mechanical engineering firm Bergmann & Steffen has found an elegant solution to the problem of excess powder. And did so almost by accident, because they were actually working on something completely different.

EASING THE PRESSURE CEO Uwe Bergmann is one of the pioneers of remote laser welding. For 20 years now, he has been providing automotive suppliers with laser systems of this kind. And a thought has been preying on his mind the whole time: "The compressors for the crossjet consume too much energy. And this unnecessarily drives up the system's operating costs." Crossjets work at pressure levels of between 2.5 and 10 bar. "Over the service life of our systems, the compressed-air costs for our customers mount up." What's more, the crossjets still don't prevent every single splash from fogging up the optic, despite the energy-intensive airflows. As a result, the protective glass eventually becomes so dirty that it has to be replaced, which, of course, interrupts the production process and results in further costs. "All in all, I was of the opinion that it had to be possible to achieve better results at less expense," says Bergmann.

IN A SPIN In partnership with TRUMPF, Bergmann & Steffen spent three years examining the issue. The underlying idea is beautifully simple: instead of a lateral jet of compressed air from a compressor, a simple, ring-shaped swirl around the protective glass keeps excess powder at bay. Bergmann: "We have extensive experience of airflows in our systems." Therefore, it soon became apparent that the secret to solving the problem lay in a whirlwind. The system of airflows creates a mini tornado along the working axes of the optic, thereby diverting the spatter downward at the sides. Bergmann & Steffen aptly named their new product "Tornado Blade." And because the distance between the optic and the workpiece is considerable, a mere 0.3 bar is required to divert the excess powder.

GOOD NEIGHBOR "Our tornado ensures that the laser always operates in a clean environment. Not only are the weld results optimized, but we were also able to increase the processing speed, as the whirlwind encloses the working beam and thus keeps up with every movement of the optic," says Bergmann, explaining the benefits of the tornado, which is compatible with all TRUMPF scanner optics and can also be retrofitted. Moreover, it considerably increases the service life of the protective glass. And without even intending to, it also solves the problem of excess powder for neighboring optics. Thanks to the tornado, their work area is also kept free from powder residue. ■

Contact: Bergmann & Steffen GmbH, Uwe Bergmann, CEO, phone: +49 5225 8786-15, u.bergmann@bergmann-steffen.de

The circular jet around the optic generates a tornado-like swirl that encompasses the working beam. This keeps vapor and spatter away from the optic and facilitates a clean and speedy welding process.

Uwe Bergmann, CEO of mechanical engineering firm Steffen & Bergmann, based in central Germany, is one of the pioneers of remote laser welding.

Bergmann & Steffen provides automotive suppliers with remote welding machines. The system shown here welds seat structures and is one of the firm's best sellers.

> *"The compressed-air costs mount up. I was of the opinion that you could achieve better results with less expense."*
>
> **Uwe Bergmann, CEO**

“I have gotten used to the impossible”

Professor Jörg Wrachtrup is calling for more quantum mechanics in mechanical engineering. We spoke to him about ultraprecision sensors and connecting minds and machines.

Tobias Gerber / Fotogloria

In real life, it is not possible for a physicist to be in more than one place at once. His quanta, however, do possess this ability. And this is now revolutionizing sensor technology.

Professor Wrachtrup, do you understand quantum physics?
Let’s put it this way: I have gotten used to it. It’s part of my day-to-day life; I observe quantum physics phenomena in my work by carrying out experiments. I therefore know, for example, that the principle of locality does not exist in quantum physics. In other words, I am sitting on this chair. This does not apply to quanta, which are sitting on multiple chairs at once. This is what our models predict—and we can measure it with pinpoint accuracy. To sum up: that’s just the way nature is. I understand that. And we are now harnessing this knowledge to build sensors for machinery.

What kind of sensors?
Highly sensitive ones. Even with the finest nanoscopic sensors, the signals are lost in thermal or technical noise sooner or later. With quantum sensors, however, it is even possible to show the magnetic moment of an individual electron—that’s how sensitive they are. Technically speaking, we are using individual atomic defects in diamonds, such as the so-called nitrogen vacancy center. In simple terms, this comprises individual nitrogen atoms trapped in a pure carbon cage. A well-controlled laser light enables the optical analysis of quantum phenomena such as spin—and at room temperature. In turn, this makes it possible to draw inferences about surrounding magnetic fields. This facilitates improvements in areas such as magnetic resonance imaging, autonomous navigation and neuromagnetic prosthesis control.

What can quantum physics offer mechanical engineering?
A completely new concept in terms of ultraprecise measurement. This ranges from temperature and electrical or magnetic fields through to geopositioning—and anything else in between! Mechanical engineers always want to know the answers to questions such as “Where is the robot arm now?” and “How do these two components interact with each other?” In the field of mechanical engineering, the requirements in terms of precise measurement of distance, length and position have been increasing for many years. Just think about EUV lithography in terms of microchip production, where just a few nanometers open up the possibility of large circuit structures. In the future, the following question will crop up more and more often when dealing with scales of this kind: “Can I still find a traditional technical item of equipment that can achieve the required level of precision?” Increasingly, the answer will be no—and a quantum sensor will be required.

> *“Using brain waves to operate technical devices – is that revolutionary enough?”*

Is your quantum sensor simply a better sensor or does it represent a revolutionary approach?
You talk as though it were simple to distinguish between the two.

Isn’t it?
Absolutely not. Sometimes, a better sensor enables things that were previously just not possible. Let me give you an example. We are currently working in tandem with quantum technology company Q.ANT to develop a viable sensor that can measure magnetic fields in the brain. Magnetic field sensors have been around for a long time, but they are huge, not particularly robust, and relatively imprecise when it comes to measurement accuracy. In that regard, our sensor is “just” a better version. But the consequences are immense, namely the ability to connect minds and machines. It suddenly becomes possible to track cognitive processes and use them to control machinery. People could use brain waves to communicate with artificial limbs or operate other complex technical devices. Is that revolutionary enough?

Absolutely. And is that everything? Or will there be even more?
Definitely. Whole new areas of application. Colleagues of mine are currently working on sensors that will measure the earth’s gravitational field.

Why do we need that?
You could use it to determine the distribution of mass under your feet and thus work out what is located there: rock, caves, metal, the geographic composition in general. Think about the analysis of construction sites or the deep-sea navigation of submarines.

Jörg Wrachtrup is a professor of physics at the University of Stuttgart and a fellow of the Max Planck Institute for Solid State Research. In the world of physics, he is known for his work on diamond quantum sensors. He is one of the most-cited physicists of the current era.

Tobias Gerber / Fotogloria

What gave you the idea of developing quantum sensors?
It would seem that we scientists think the other way around to engineers. A mechanical engineer thinks: “I need to place this here, with a degree of accuracy of one micrometer. What sensors are available and how much do they cost?” By contrast, we ask ourselves: “To what extent can we utilize a quantum phenomenon? How close can we get to a theoretical degree of accuracy?” As a researcher, I freely admit that I always start by thinking about scientific applications. Basically, we build the sensors for ourselves, using them, for example, to examine completely new materials. And then we are struck by an idea such as “We could also use them to measure the brain’s magnetic fields, or particles, more precisely.” At this point, we need a partner from the field of mechanical engineering.

So you are a kind of interface between research and real-world application?
Yes, you could say that. Particularly in recent years, we have been working closely with SMEs, contributing ideas and helping to develop prototypes. Once the prototype has been built, we gradually step back from the project. By the standards of quantum physicists, this represents pretty practical work.

What drew you to quantum physics?
I think every physicist is fascinated by quantum physics, because nature simply does not behave in the usual way at this scale. As I say, I have become used to the impossible. Some of the theories posited—by Niels Bohr and others—sound so crazy that they were often dismissed as theoretical constructs, nothing more than intellectual flights of fancy. I still want to continue studying these ideas in the laboratory and bring them to life through experimentation. What are the limits of our current assumptions? And how should we build on our existing model? These are my questions.

Have you found any answers?
Plenty! I am happy to say that I can look back on many eureka moments. It’s a bit like mountaineering; as soon as you reach one summit, you see the next highest peak—and you want to scale that one, too. And all our experiments over the past 20 years are now maturing in practical applications such as the quantum sensor—amazing! ■

DISSONANCE À LA HINDENBURG

WHY HYDROGEN CAN ALSO CHALLENGE SOCIOPSYCHOLOGICAL THEORIES AND WHY THE LASER HAS BEEN SWITCHED OFF FOR A CHANGE.

In its career as a chemical wonder element, hydrogen has had its fair share of ups and downs. The hype surrounding hydrogen—“water broken down into its constituent parts”—as a source of energy dates back to the 19th century and science-fiction author Jules Verne (see also page 18). The fact that hydrogen harbors tremendous energy was tragically illustrated in 1937 by the burning zeppelin *Hindenburg*, which went down in flames in a matter of seconds just before its scheduled landing in Lakehurst, New Jersey. The airship was filled with hydrogen.

Can you already sense a certain dissonance? So many hopes and endeavors invested in hydrogen, only to realize that the result did not live up to expectations. US social psychologist Leon Festinger coined the term “cognitive dissonance” in 1957 to describe precisely this kind of unpleasant feeling. The fatal disaster that befell the *Hindenburg*, a photo of which entered pop culture in 1969 thanks to an album cover by British rock band Led Zeppelin, may have brought the curtain down on airship travel, but not on the dreams invested in hydrogen. After all, dissonances can be dispelled, such as by attributing other causes to the disaster (sticking with our example). It has never been conclusively established whether the *Hindenburg* went down in flames due to a technical defect, sheer bad luck or deliberate sabotage.

Assuming it ever went away, hydrogen is now more in focus than ever, whether as an alternative to traditional electric cars or as a storage medium for renewable energies in the context of the energy transition. Cognitive dissonances persist, however. Hydrogen is still mostly sourced from fossil fuels, meaning that its carbon footprint leaves a lot to be desired. We dispel this dissonance by playing down the contradiction to a certain extent and pointing to hydrogen’s potential and its glorious future. Incidentally, Elon Musk—the pioneer of Tesla—may well have felt a dissonance between his dream of electric vehicles and the “old” automotive world. He is now solving his dissonance by adapting reality to reflect his dream.

The fact that this column makes no direct reference to the laser is my own personal cognitive dissonance. It makes me feel a little uneasy. And how do I solve it? By simply denying it! After all, who says that this column always has to be about lasers? ■

Laser Community’s editor-in-chief Athanassios Kaliudis writes a regular column on the laser as an object of popular culture.

➔ *With which technology have you ever felt dissonance?*
Send your answer to: athanassios.kaliudis@trumpf.com

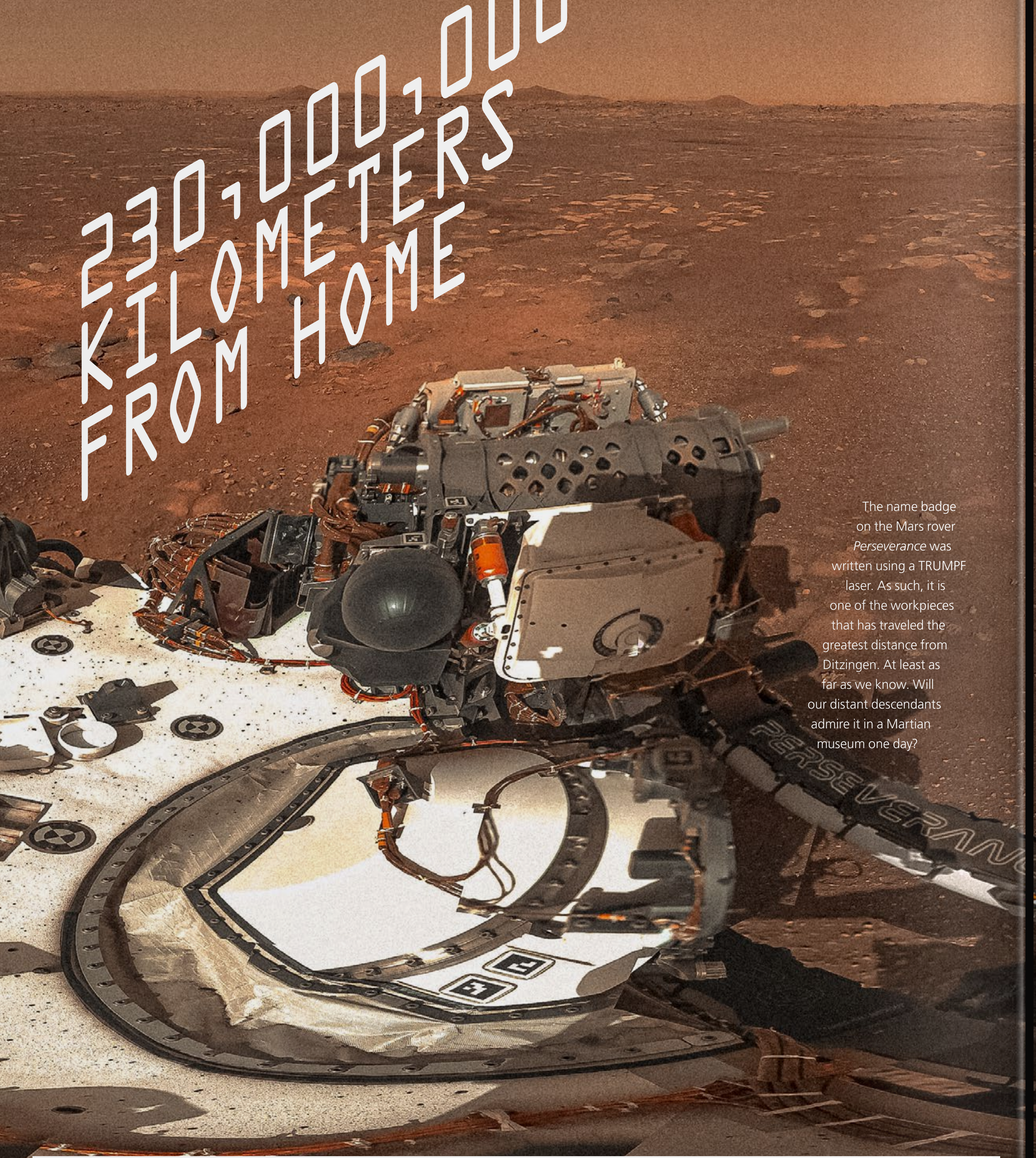
Nationaal Archief @ Flickr Commons / Sam Shere; Illustration: Gernot Walter

WHERE’S THE LASER?

In a bottle of premium whiskey. If you are wondering what to do with all your money, why not buy a rare whiskey for one million euros? Whether for your own enjoyment or as an unusual investment. But beware: there are plenty of fakes out there. How can you tell that the content of the bottle actually corresponds with what is on the label? Researchers from the University of St Andrews in Scotland (where else) have turned to Raman laser spectroscopy to help answer this question. The laser beam travels through the unopened bottle. The molecules of the liquid scatter the light back at different wavelengths, with distortions due to the glass taken out of the equation. Each premium whiskey has its own characteristic profile in the researchers’ database, i.e. a kind of “fingerprint.” As such, it only takes a few seconds to separate the wheat from the chaff. That said, they still don’t really know whether the whiskey tastes any good or not. ■

Gernot Walter

230,000,000 KILOMETERS FROM HOME



The name badge on the Mars rover *Perseverance* was written using a TRUMPF laser. As such, it is one of the workpieces that has traveled the greatest distance from Ditzingen. At least as far as we know. Will our distant descendants admire it in a Martian museum one day?

NASA/JPL-Caltech/MSSS/ASU

TRUMPF

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