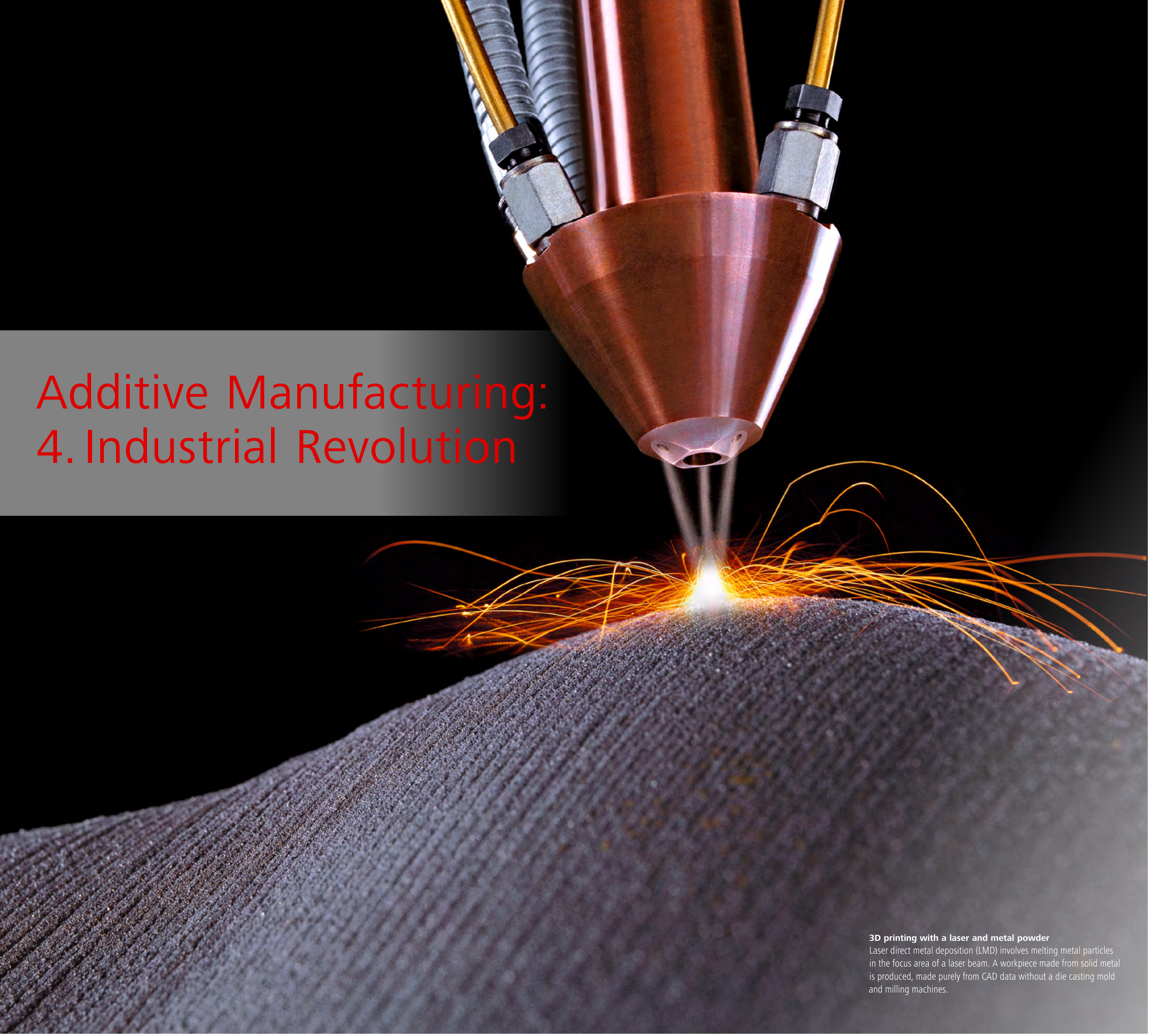
Additive Manufacturing: 4. Industrial Revolution



3D printing with a laser and metal powder
Laser direct metal deposition (LMD) involves melting metal particles in the focus area of a laser beam. A workpiece made from solid metal is produced, made purely from CAD data without a die casting mold and milling machines.

TEXT: Rainer Klose / PICTURE: Trumpf GmbH + Co. KG

The next industrial revolution is imminent. It's called 'Industry 4.0' and is expected to fundamentally change the production methods used in industrialized countries. The leap in development will be similarly dramatic to that experienced in the three industrial revolutions in the past: mechanization with water and steam power in the 19th century – mass production on Henry Ford's production line from 1915 – the use of electronics and IT from the 1970s onwards.

Experts estimate that Industry 4.0 will result in virtual data merging with real production equipment. The resulting "smart factory" will bring customers and suppliers closer together, as production orders will be sent by the customer directly to the machine, and the production data will be transferred to the distribution partner in real time. Manufacturing will become leaner and faster.

Additive Manufacturing – 3D printing in metal

A key component in making Industry 4.0 a reality are machines that can produce the desired components faster, more flexibly and more precisely than ever before. Less prototype construction, fewer dies, less post-processing. In future it will have to be possible to turn data into components and products at an incredible speed.

3D printers give a sneak preview of what this type of production might look like. The first of these devices were created in the 1980s, and nowadays you can buy entry-level devices for less than 700 Swiss francs. But so far, 3D printers have generally been used to make objects from plastic. The mechanical properties and the temperature stability of these objects are pretty limited as a result, which is why they are mainly used for illustrative purposes, i.e. as visual models. This is why 3D printing is often described as "rapid prototyping". For the next industrial revolution, the technique used for 3D printing will have to go one step further: from rapid prototyping to Advanced Manufacturing, the production of lasting and functional components with defined mechanical and thermal properties: products made from metals or ceramics.

Switzerland won't miss the boat

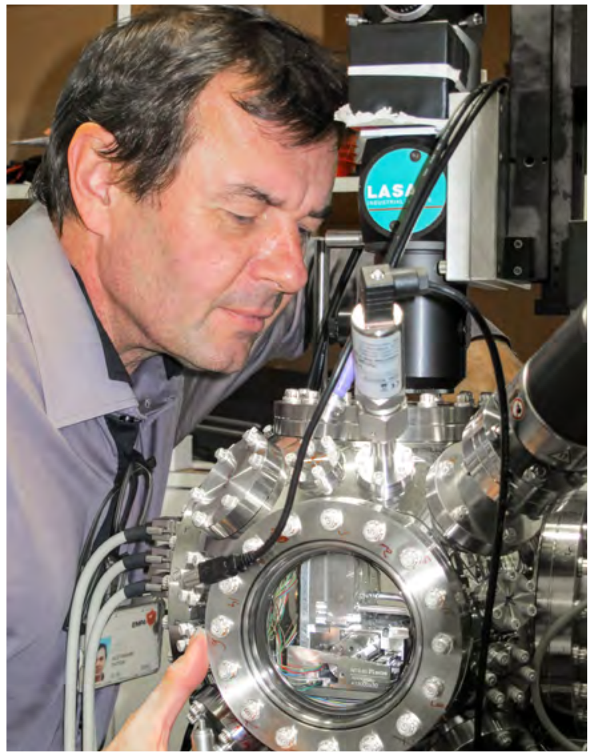
Within the framework of the focus area "Advanced Manufacturing Technologies", the strategic planning of the ETH Board for the ETH Domain for 2017 to 2020 provides for investment totaling 10 million Swiss francs in infrastructure, new academic chairs and technology platforms. The Board has appointed Empa CEO Gian-Luca Bona to coordinate this endeavor. He is tasked to harmonize the interdisciplinary research activities of ETH Zurich, EPF Lausanne, PSI and Empa.

In this issue, we present the challenges that need to be overcome in the development of 3D printing of metal parts – along with the significant opportunities that this technology offers. Empa is working on this topic with different research groups. One group is examining the optimized use of lasers, while another is researching new types of alloys that this technology makes feasible for the first time. A further lab is using Additive Manufacturing to build new, geometric forms that were not possible up to now with the traditional production methods available.

Looking for the magic formula

3D metal printing is simple – or so you might think. But that's not really the case. A lot of details are still complete unknowns. Patrik Hoffmann is tracking down the inside story.

TEXT: Amanda Arroyo / Pictures: Empa



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Basically, it's just a single, long welding seam." Patrik Hoffmann is talking about Additive Manufacturing, the process by which metal powder is melted with a laser. And when it comes to welding, this researcher knows his stuff. Patrik Hoffmann is head of Empa's Advanced Materials Processing lab in Thun, Switzerland, and has also been teaching "Laser Processing" as a subject at EPFL for almost 20 years now. He and seven of the staff from his lab have set about making Additive Manufacturing more reliable.

"In terms of how lasers and materials impact on each other, no-one knows yet what's really going on", Hoffmann explains. When you look carefully after the workpiece is finished, you can see that material has melted and you can imagine that the original loose powder volume has reduced. But it is not yet quite clear how much of the material vaporizes and spatters off. Hoffmann is convinced that there is a formula for this process. Finding that formula is challenging because the process is highly dynamic and non-linear.

In order to better understand the influence of the process parameters like the laser power, how fast the laser beam moves or the focus diameter, Hoffmann is using a research laser unit designed at Empa. This allows him to use cameras and microphones to track the laser welding process.

Laser processing: an abrupt affair

Laser processing is a tricky and abrupt affair: when someone from Hoffmann's research team focuses the laser with a certain intensity on a gold surface, nothing happens at first. The light is reflected, and just one per cent of the radiated energy flows into the material. "If I look in there, I will turn blind before the gold even gets warm", says Hoffmann. When the laser power is gradually increased, a point is reached where the gold gets warm enough to start melting. Melted gold reflects much less light, and suddenly the material absorbs so much energy that part of it vaporizes right away. It's not possible to prevent that from happening. The more gold that vaporizes, however, the denser the steam above the workpiece becomes, until the laser beam can no longer penetrate it. This effect caused by the steam is known as shielding.

Hoffmann and his team use high-speed cameras to measure how the metal steam escapes and where droplets fly to, and they examine the speed of the small shock wave created by the laser. They also monitor the process acoustically, with three microphones attached to the test device, which then record the welding signals. When something goes wrong in welding, you can hear it.

In addition, the Empa scientists also measure the melting pool that the laser creates in the metal. While it's quite easy to visually measure the melting pool diameter, the test device has to be cut open subsequently in order to calculate the depth of the melting pool.

When you look at the cross-section of a test device resulting from Additive Manufacturing, you see not only the horizontal growth of each metal layer deposited, but also vertical crystal growth through the layers. "That's not really surprising to anyone who knows about metallurgy", says Hoffmann. The individual layers are melted up to ten times in this type of production process. This allows crystals to form that spread over several layers. Another challenge is that, because metal is a very good conductor of heat, the melted material cools down very quickly. On the one hand, this property can be exploited to manufacture new materials, for example for powder-enhanced ODS alloys (ODS = oxide dispersion strengthened). On the other hand, the fast cooling rates can also lead to stresses and cracks in the material, rendering the produced workpieces unusable.

His goal: closed-loop process control

To solve this puzzle of understanding the process, the material properties and internal stresses, Hoffmann now intends to involve a range of different experts. To cover all aspects, he will need physicists, solid state chemists, mechanics, acousticians, metallurgists, spectroscopy specialists, electronics technicians and computer simulation experts. His long-term goal is closed-loop process control, where all of the processes in laser welding or Additive Manufacturing are monitored in real time. If something goes wrong, the control has to automatically correct the laser immediately to make sure that the desired component emerges from the manufacturing process without any internal material flaws, stresses or cracks. According to Patrik Hoffmann, there are still quite a few ob-stacles for the international research community to overcome before we have a dream factory that is fed with virtual design data and spits out perfectly formed, ready-to-use metal parts. He and his team want to help make the vision of a 3D printing factory ultimately come true. //

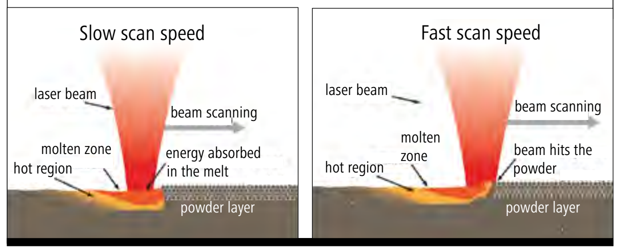
1
A chain made using Additive Manufacturing (AM): the links of the chain are interlinked yet made from one piece. (Design and production: La Manufacture CSC).

2
Patrik Hoffmann using the Empa-built laser unit: cameras, microphones and mass spectrometers can be connected to the housing of the laser unit. This allows Hoffmann to analyze the mutual interaction between the laser and the metal powder with very high precision.

3
A watch casing produced using AM: the blank is on the left, with a supporting structure beneath the ring that is later broken out. The finished, processed workpiece is on the right. (Design and production: La Manufacture CSC).

What's better: fast or slow?

The trick to Selective Laser Melting (SLM) is to keep production at a slow enough pace. Left: The laser creates a pool of molten metal that solidifies in a controlled manner. Right: The laser hits grains of metal. Some vaporize and some melt partially. This results in pores and inclusions in the workpiece.

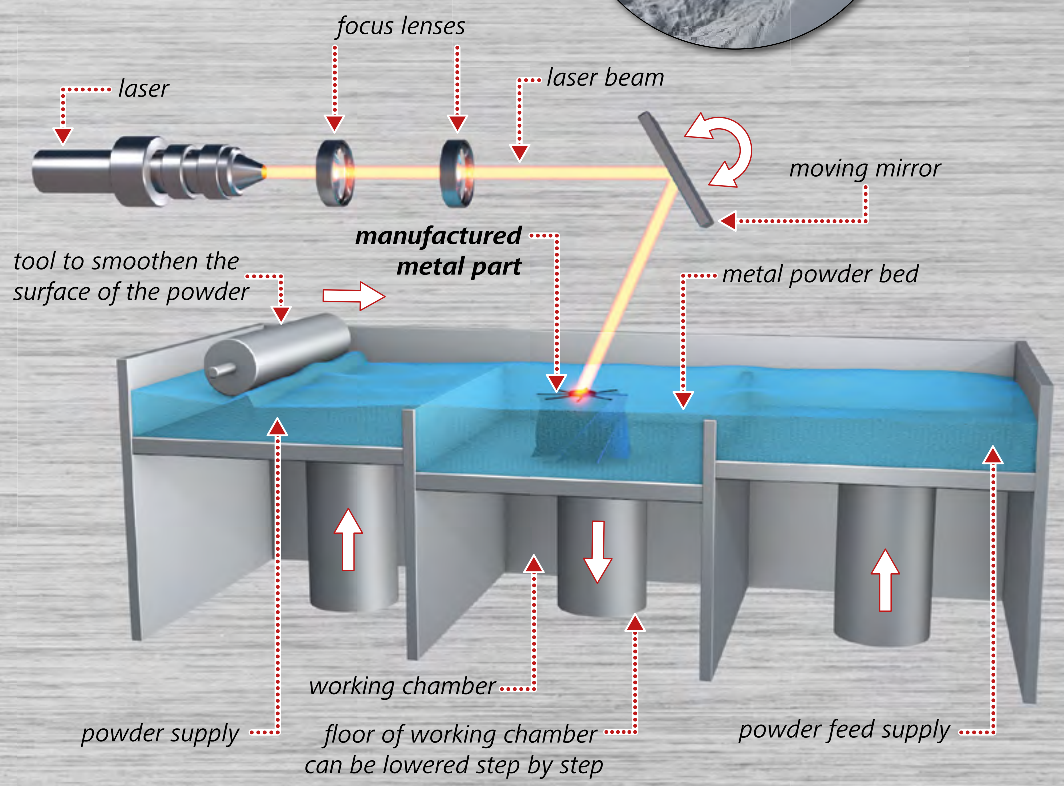


Additive Manufacturing

The first 3D printing processes were developed in the 1980s. Nowadays, 3D printing as part of rapid prototyping is an established technology used to fabricate scale models from plastic very quickly and very flexibly in areas like architecture, engineering or surgery. In future, 3D printing is to be used to produce not only models but real, functioning components with sufficient mechanical properties and adequate heat resistance – as individual pieces and on a small series scale. This is only possible with metals or ceramics. At the moment, there are two methods for forming metallic objects with the help of metal powder and laser beams.

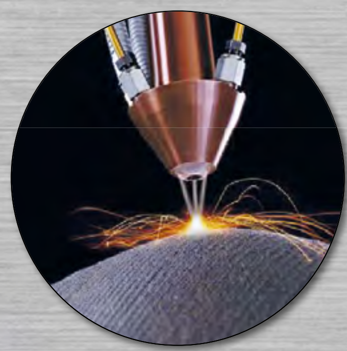
Selective Laser Melting (SLM)

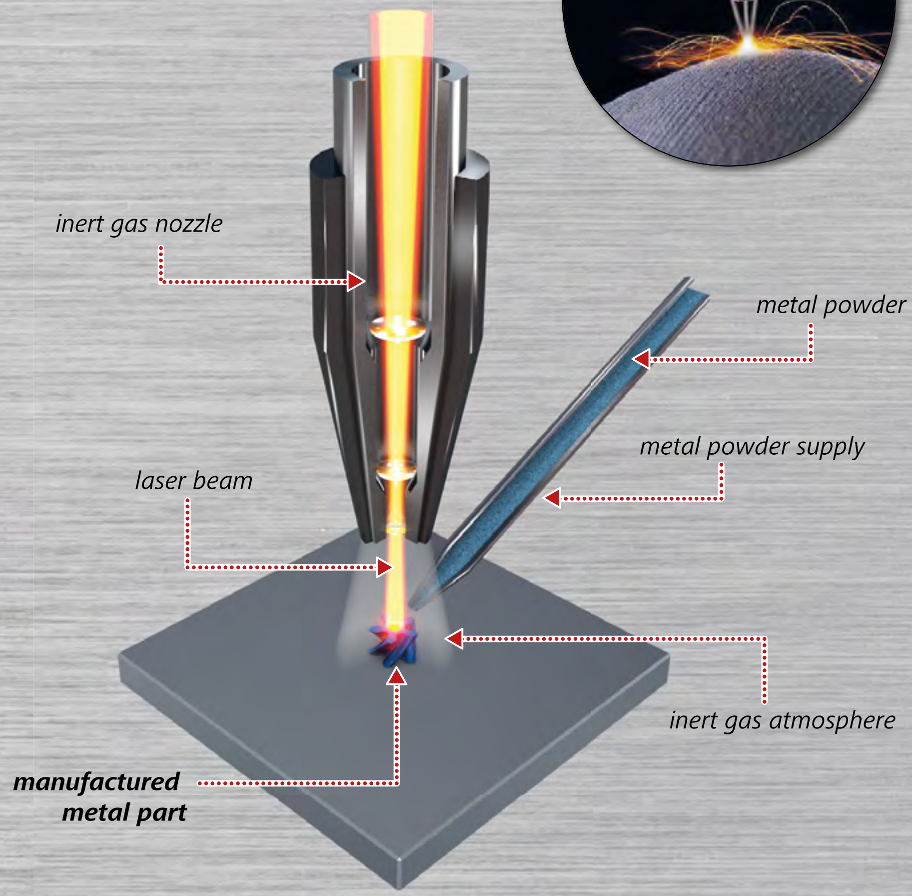
A laser melts powder in a powder bed. After each work step a new layer of powder is added to the resulting workpiece. Then the laser is used again and melts the next layer.



Laser direct Metal Deposition (LMD)

Powder is blown from nozzles into the laser beam and melts at the place where the new layer is required. Up to four different metals can be combined to form an alloy.





From Lab to Industry

In order to form a completely new industry from 3D laser printing, we need more than just special machines. Lots of things have to be reinvented. New possibilities are opening up in the fields of engineering, high-temperature technology and design as well as in the gearing of companies. Empa is involved in many of the key parts of this process.

Functionalizing powder

New, pourable metal powder for SLM and LMD *(Empa)*

Optimized laser use

Optimized control of laser beams or electron beams allows for improved material quality and higher production speeds at the same time. *(Empa, EPF Lausanne, Inspire AG)*

Microstructure of the printed component

What alloys are created? Can new types of alloys be formed with material gradients? New types of composite materials with a degree of hardness, toughness or temperature resistance never achieved before? *(Empa, EPF Lausanne, PSI, Inspire AG)*

External form of the printed component

What is the surface like? What about trueness to scale? Are there internal stresses in the component – how can they be prevented? Quality control using non-destructive testing methods. *(Empa, ETH Zurich, Inspire AG)*

Post-processing

What post-processing is needed for the component before it can be installed? *(EPF Lausanne)*

Recycling

Can the metal granulate from the SLM process be reused? What kind of treatment is necessary? *(Empa)*

Design

Engineers can design components with a geometry that would not be possible in milling processes. New lightweight design concepts, new assembly strategies, new combinations of components become possible. *(ETH Zurich, Inspire AG)*

New 3D printing machines

New concepts for 3D production machines and machine fleets. From laboratory manufacturing to mass production „on demand". *(ETH Zurich, Inspire AG)*

New business models for "Industry 4.0"

Business model for 3D production "on demand". Legal solutions for product liability and certification for individual 3D pieces and small 3D series. *(ETH Zurich)*

Impossible materials get real

There are lots of attempts under way at processing existing metal powder in the best possible way, i.e. adjusting the printing machine to the powder. Empa is going one step further: its researchers are searching for new alloys that are better suited for 3D printing. They are also trying to create new types of composite materials that cannot exist without 3D printing.

TEXT: Rainer Klose / PICTURES: Empa

Sample pieces made from titanium aluminide with embedded ceramic particles. Because of its low density, this alloy is of interest for aircraft a engines for example, but it is difficult to process. The sample pieces show which parameters are best for 3D printing.

The last week in November 2015 was a moment that Christian Leinenbach and Christoph Kenel had been waiting for for a long time: the 3D printing machine "M2 cusing" is installed and connected up in the new lab on the Empa campus. This means that from 2016 onwards it will be possible to carry out trials with different metal alloys, laser speeds and line distances. The machine by the German manufacturer Concept Laser can use a fiber laser to create complex 3D components made from metal with dimensions of up to 25 cm each. "However, most of our test devices are much smaller", says Christian Leinenbach. "On the one hand we want to develop new materials adapted to the manufacturing process, and on the other we want to research how we can use Additive Manufacturing to create completely new materials."

Searching off the beaten path

Research into 3D printing with metal is booming, with conferences on the topic taking place constantly all over the globe. Leinenbach has been following the articles published on the scene and has discovered a certain imbalance. Out of over 200 contributions presented at various international conferences over the past two years, an astonishing 75% deals with just three different classes of materials: the famous titanium alloy Ti-6Al-4V, commercially available nickel-chromium alloys and stainless steel. "It is easy to see why so much research is being carried out into precisely these alloys", Leinenbach tells us. "They are of huge commercial interest for aviation and aerospace, for the defense industry and offshore construction. In contrast, little or no research has been carried out into many of the materials that are of interest for Swiss industry, such as tool steels or precious metals." A fundamental understanding of the mutual interaction between the material and the laser is also often forgotten about. As a metal specialist, Leinenbach is critical of this approach: "With a complex system of three or more metals and numerous phases, it's very hard to develop functioning components on the basis of trial and error. There are just too many variables."

Basic research with titanium aluminides

Together with his doctoral student Christoph Kenel, Leinenbach has, therefore, focused his attention on alloys made from titanium and aluminum as part of an EU project. The low density of these materials makes them interesting for parts in aircraft engines for example, but they are very difficult to process. These two metals alone develop more than a dozen different phases with different mixing ratios and temperatures, and only one mix of two phases is suitable for technical use. This phase system has long since been carefully researched, and it's precisely in this well-researched field that it's worthwhile uncovering new processing methods with the help of AM.

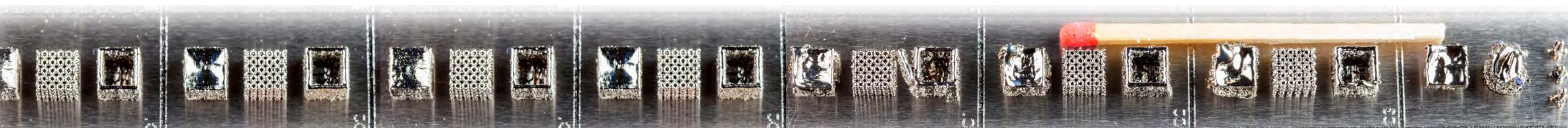
Left side: Christian Leinenbach at the newly installed 3D laser printer.

The two researchers already started with their first experiments long before the laser unit was installed at Empa. One experiment examined the influence of the cooling rate of the bath on phase formation. While classic methods like molding with maximum cooling rates of several tens of degrees per second are well understood, there has been a virtual lack of research to date into the events that take place during laser melting. Cooling rates of more than 10,000 degrees per second are possible in the very small melting pool created by the laser. This means that suddenly phases stabilize at room temperature that do not usually occur at that temperature at all. Leinenbach and Kenel experimented on titanium aluminide with a special test set-up in different compositions with cooling rates of up to 15,000 degrees per second. They compared the results with simulated calculations. In this way, they more or less created a map of an area of metallurgy that was largely uncharted. With these findings, the Empa researchers were able to identify a new alloy that is significantly better suited to processing in a 3D laser printer than the titanium aluminide materials currently available.

Dream materials for grinding machines

One initial tangible result of the high cooling rates in the 3D printer could be new types of composite materials made from metal and diamonds. Sintered diamond tools with a simple geometry are already used to grind ceramic components. But it is very difficult to produce metal-diamond composites using conventional melting methods. If you put diamonds in contact with fluid metals, they generally dissolve or swim to the surface due to their low density. Also, diamonds are made from pure carbon, and they melt at air temperatures above 400 degrees. Together with partners from ETH Zurich and inspire, Leinenbach and Kenel succeeded in producing metal-diamond composites in the 3D printer. They did this by mixing small industrial diamonds with a powder made from a copper, tin and titanium alloy. The diamonds remained intact after the process and are also coated with a thin titanium carbide layer that puts them firmly in the metal matrix from a chemistry perspective. In future it should thus be possible to produce tools with a more complex geometry than those that exist today.

Here too though, it's fair to say that the alloys we know today are definitely not best suited for processing with 3D printers. Further developments will follow. So the newly installed 3D printing unit on the Empa campus will soon be running round the clock. //



Pierangelo Gröning is a member of Empa's General Management. He coordinates research into AdditiveManufacturing. In the EmpaQuarterly, he explains where the journey is taking us.

INTERVIEW: Rainer Klose / PICTURES: Empa

"We want to provide know-how for machines of the future"

Mr. Gröning, what role does Empa play in Additive Manufacturing (AM)?

The ETH Board has named Advanced Manufacturing as a strategic research focus area for the period from 2017 to 2020. The method of 3D printing using metals is just one of various different elements of Advanced Manufacturing, which in general involves new and more modern production techniques. These new techniques are of major importance to Switzerland as an industrial location. We have to be strong in this area in order to hold our own in the face of international competition going forward.

What different areas, materials and AM methods is Empa focusing on?

As a materials research institute, we see the major challenges for 3D printing in the processing of metals and ceramics. The methods we are looking into include Selective Laser Melting (SLM), Laser direct Metal Deposition (LDM) and Selective Laser Sintering (SLS).

Is Empa also going to offer courses to teach skilled specialists about Additive Manufacturing?

Empa is a research institute first and foremost. We firstly want to understand all the laser processing methods thoroughly. Subsequently we will develop new raw materials that will be optimized for 3D printing. The aim of the research is to take 3D printing of metals from where it is today in terms of manufacturing and transform it into a robust and reliable industrial method. We are not going to get involved in the actual process engineering, i.e. operating lines or designing and optimizing the printing process for components. We feel that Switzerland's universities of applied sciences and institutes like the ETH spin-off inspire would be better suited to that task. The same applies with regard to training skilled specialists.

Nevertheless you have just commissioned a 3D laser printer at Empa. What are you going to do with it?

We do of course need machines for our research that we can use to process the newly developed materials in real-life conditions and with the best process monitoring possible. One of those machines is a commercial 3D printer that has been modified to incorporate sophisticated process monitoring functions. But we will also set up our own research equipment and use it to examine very closely the mutual interaction between the laser and the materials as the creation process of the workpiece and thus also of the material and to one day control that process.

So the aim is to control the process in real time?

Exactly. We want to provide know-how for machines of the future that can control the laser processing process.

What changes can industrial firms expect when they start using Additive Manufacturing?

One of the consequences is that quality management has to be completely reorganized. Today, we produce a number of parts in series construction using traditional process engineering. We remove samples, test them and use the findings to draw conclusions about the quality of the manufacturing process. With Additive Manufacturing, we will be creating individual parts or small series, so it will no longer be possible to work with samples. This means that we will have to monitor the whole production process, from the provision of the powder to the completion of the workpiece. Because you can't use destructive testing if you only have one part. The manufacturer will have to provide the complete production logs to the customer that buys the individual part, as that's the only way to guarantee the quality of the product. As researchers, it is our job to provide the basics for this new type of production. We have to learn to understand fundamentally how such a workpiece is created by the laser beam, what errors take place and how to recognize and avoid these errors.

A magic crystal kills vibrations

Soaking up vibrations with the help of crystal structures? It sounds a little esoteric, but it's not. Two Empa researchers have shown that it is possible. The 3D printer helped to build the test models.

TEXT: Rainer Klose / PICTURES: Empa

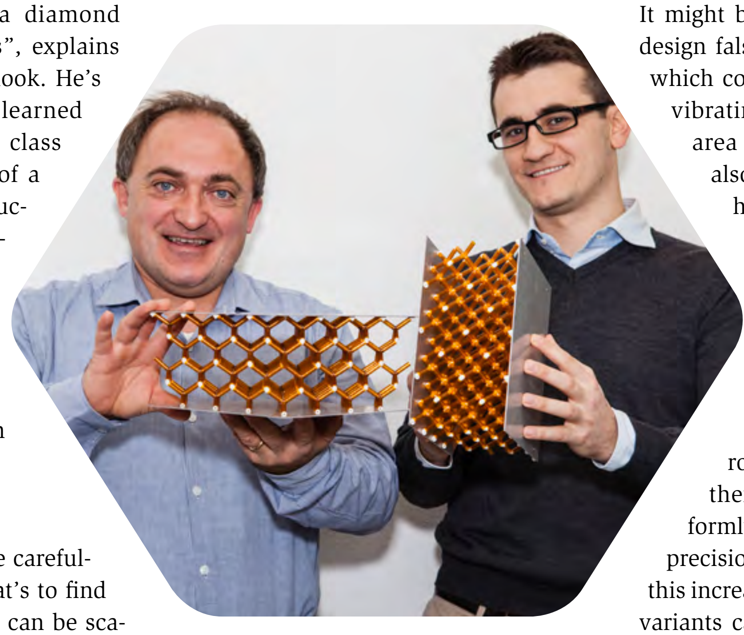
What do you see there?", asks a smiling Andrea Bergamini. In his hands he is holding a sandwich design made from two thin aluminum sheets. In between there is a grid structure made from orange-colored pipes and white connecting pieces. It looks like a carefully executed and very tidy DIY project that doesn't have any purpose. "There's a diamond structure between these sheets", explains Bergamini, and I take a closer look. He's right: anyone who has ever learned about diamonds in chemistry class and looked at a crystal model of a diamond can recognize the structure. The white connecting pieces in the model are tetrahedrons, just like the carbon atoms in a diamond. But what's it all about? What's the point of a model of a diamond in between two aluminum sheets?

On the trail of Paul Scherrer

There's a daring idea behind the carefully prepared DIY project, and that's to find out if the properties of a crystal can be scaled up several notches and made usable. Exactly 100 years ago, the Swiss physicist Paul Scherrer together with his Dutch colleague Peter Debye developed the Debye-Scherrer method, which is still in use today. The method makes it possible to determine the structure of crystalline substances by means of X-ray diffraction. But X-rays are nothing more than electromagnetic waves that are diffracted by the crystalline structures. Some of the waves cancel each other out, while others amplify, creating the characteristic blot pattern around the crystal. The incident X-rays waves are broken up into small bundles of waves and thrown back in different directions.

The secret life of macrocrystals

If you now magnify the crystal structure millions of times, could this structure break up and diffract bigger waves? Like sound waves or vibrations? That's the question that Andrea Bergamini and his colleague Tommaso Delpero set out to answer. They built the sandwich model from aluminum sheets and parts of a molecule-building kit. For comparison, they made a second model with just hard foam between the aluminum sheets. Together with their colleagues from Empa's Acoustics / Noise Control lab, Armin Zemp and Stephan Schönwald, they then secured the two models in a vibrating device and watched what happened. And hey presto! As expected, the foam swallowed up the vibrations uniformly, while the crystal structure developed a life of its own. Some of the vibrations were practically reflected back, with the aluminum sheet that was being shaken moving faster, while the underside of the sandwich structure was not vibrating at all. The researchers had discovered what is known as a "band gap" in the macrocrystal – a property that also plays a central role in semiconductor technology. Within this band gap, the macrocrystal does not transmit any vibrations.



Andrea Bergamini and Tommaso Delpero

Precise models from the 3D printer

It might be possible to use this finding to design false ceilings that absorb vibrations, which could be used as a base to support vibrating machines. Other uses in the area of mechanical engineering are also feasible. But now the researchers have to move beyond their DIY model with all of its typical flaws. To do this, they can use the metal 3D printer now available at Empa. The device can convert geometrical data from theoretical calculations directly into a crystal structure. The macrocrystalline intermediate layer is then printed permanently and uniformly from metal, eliminating the imprecisions of the DIY project. Thanks to this increased precision, different structural variants can be easily compared. Research into the vibration-swallowing crystal will take off as a result. //

Publication: Delpero T., Schoenwald S., Zemp A. and Bergamini A. (2015). Structural engineering of three-dimensional phononic crystals. Journal of Sound and Vibration, 1–10. doi: 10.1016/j.jsv.2015.10.033