



Built with Light

Aachen cathedral in miniature:
3D printing can be used to create
very intricate structures.

3D printing is the future. But it's not yet possible to get the most out of the materials and the production processes used. Scientists at the **Max-Planck-Institut für Eisenforschung** in Düsseldorf, together with colleagues from the **Fraunhofer Institute for Laser Technology ILT** in Aachen, are therefore working to help the new method come of age.

TEXT **ALEXANDER STIRN**

The blindingly bright spot of light dances to and fro, from right to left and left to right, spattering sparks as it does so. It pauses briefly, only to restart its motion anew. It never tires and is extremely productive.

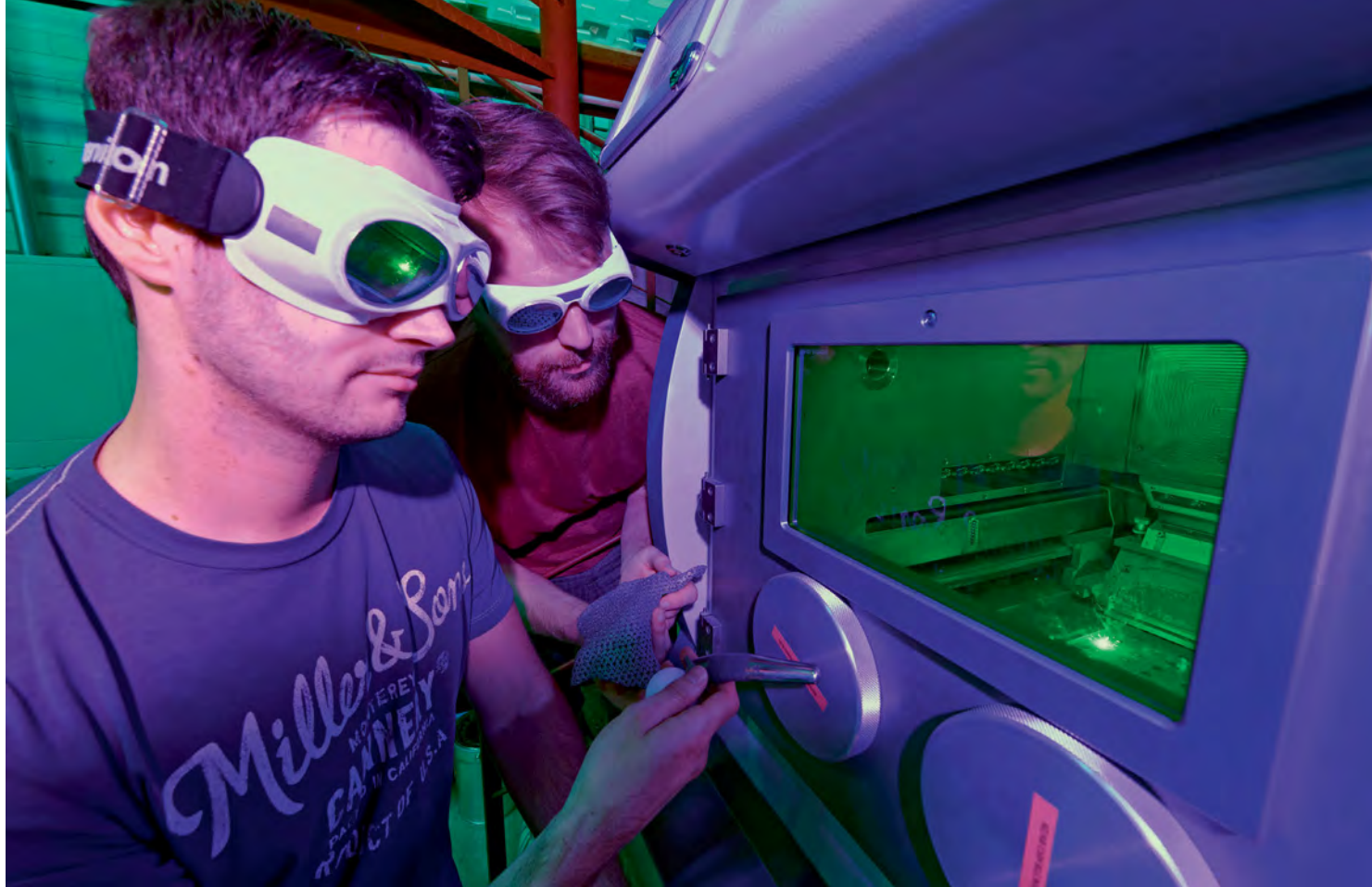
This blindingly bright spot of light whirling along in a laboratory in Aachen is pursuing an ambitious objective: it is expected to radically change materials research. Its light is produced by a powerful laser; its sparks are part and parcel of the process. They bear witness to the fact that the laser continuously melts metal powder that then solidifies on a surface – spot for spot, layer for layer, like a Lego structure made with tiny metal building blocks.

The process for which manufacturing engineers have such high hopes is known as 3D printing. It promises to produce highly complex components at relatively low cost, with little waste and short lead times. Although a great deal of progress has been made, the method, which scientists call “additive manufac-

turing”, still offers room for improvement. Particularly as regards the materials, 3D printing is still in its infancy.

“The materials that are used today in additive manufacturing are simply not optimized for this process,” says Eric Jägle, head of a working group at the Max-Planck-Institut für Eisenforschung in Düsseldorf. The materials aren't made to be particularly robust during printing, nor are the printing processes optimized for getting the most out of the materials. And the materials don't yet fully exploit the novel manufacturing methods – although this is precisely what could bring about tremendous progress, as history has shown.

“As casting was being developed in its day, the materials were adapted as well, and alloys were developed that were perfect for the new process,” says Andreas Weisheit, working group leader at the Fraunhofer Institute for Laser Technology ILT in Aachen. “Additive manufacturing will therefore achieve its full potential only when suitable materials are developed and, at the



same time, the processes are adapted to the new materials." The researchers are also experimenting with familiar materials that they are gradually improving.

This is precisely why the bright spot of light dances across the metal in ever wilder patterns. This is precisely why it spatters sparks from ever more complex materials: the laser is part of a research machine that Jäggle and Weisheit developed to jointly analyze which materials are suitable for 3D printing. Their goal is to optimize production processes so that, for instance, the properties of known alloys can be improved and steels, for example, become particularly strong as a result of the laser treatment. The research project goes by the name of AProLAM (Advanced Alloys and Process Design for Laser Additive Manufacturing of Metals). The cooperation project between the two institutes was launched two years ago; now the intermediate report is available – with highly promising results.

But expectations are high, too. High hopes are pinned on 3D printing in the production process: currently, the first step in almost all manufacturing processes is to make special tools, such as

casting molds or press molds. "This is incredibly expensive and is worthwhile only when large numbers of pieces must be produced," says Eric Jäggle. Additive manufacturing, in contrast, requires no special tools – apart from the expensive 3D printer.

COMPLETELY NEW APPROACHES FOR OPTIMIZING STEELS

Small batches or individual parts such as prototypes, customized prosthetic joints and spare parts for planes can thus be manufactured without high one-time costs. In the future, printers could output them directly on site – without the need for expensive logistics or time-consuming shipping.

Moreover, additive manufacturing facilitates the production of highly complex components. "Production technology normally has its limitations: a metal is milled and turned, sheet metal is bent and welded, and if that doesn't do the job, the parts have to be assembled," says Jäggle. With 3D printing, however, daring designs with cavities are also possible – similar to a Lego structure. Furthermore, the often

intricate components are produced in one shot, with no bolted joints and no waste produced by milling machines or lathes.

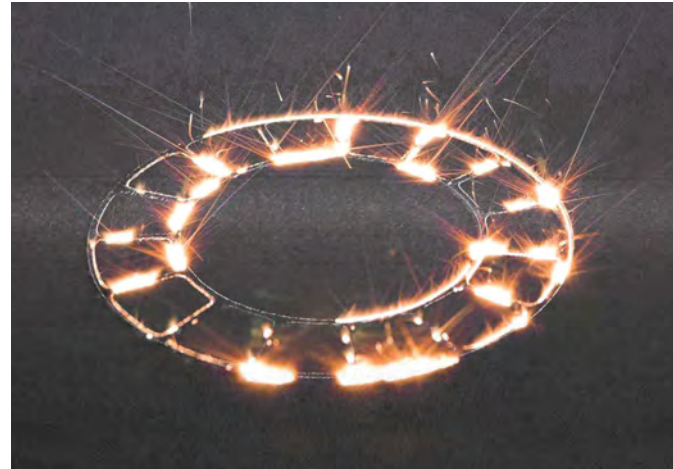
"If desired, entire assemblies that were originally composed of 20 to 30 individual parts can be printed in a single part," explains Jäggle. In addition, as far as materials science is concerned, 3D printing opens up completely new approaches for optimizing steels and other alloys.

The focus is currently on two printing processes. Both use lasers and both use metal powder. Eric Jäggle grabs a small tube containing a gray substance from the windowsill and gives it a slight shake. The powder is so fine that it appears to slosh to and fro in the tube. The individual particles measure a mere 20 to 40 micrometers (thousandths of a millimeter), or around one-fifth the diameter of a human hair.

A fine powder of this sort is required particularly for the first of the two methods. In selective laser melting (SLM), a slider spreads a very thin layer of powder, just 50 to 100 micrometers thick, on a substrate. A laser beam that can be controlled via a mirror is

Left Researchers at the Fraunhofer Institute for Laser Technology ILT in Aachen watch the selective laser melting process: a laser beam, which can be seen here as a bright spot, forms structures out of a very fine metal powder that was previously spread on a substrate.

Right The AProLAM project is investigating two 3D printing methods: laser metal deposition (left), where metal powder is sprayed into the laser focus on a metal plate, and selective laser melting.



fired at it. This beam writes contours into the powdery layer, hatches areas and exposes individual points to the light. Where it strikes, the metal melts.

A short time later it solidifies again and bonds to the layer below. When one level is printed, the substrate is lowered 50 to 100 micrometers, the slider spreads the next layer of powder, and the laser sets to work again. Hundreds or thousands of layers are produced. They are so fine that they will later be unrecognizable in the finished product.

The other process that the AProLAM researchers started with is somewhat coarser. It is called laser metal deposition (LMD), produces thicker metal blocks than SLM and is hidden behind heavy, opaque sliding doors in Aachen. When it is in operation, a red warning light denies access to the room. Markus Benjamin Wilms, a member of the AProLAM project at the ILT, slides open the door. Behind it, a vertically mounted "laser gun" comes into view – not as slick and gleaming as those used by Goldfinger and other James Bond villains, but just as powerful.

Yellow cables with an optical fiber, almost as thick as a garden hose, lead to

the actual laser source, a box the size of a cabinet. There, infrared laser light – which is invisible to the human eye – is produced with a power of up to two kilowatts. It is focused at the other end of the yellow cable in such a way that the beam impinges on a metal plate with maximum intensity. The material liquefies and starts to glow blindingly bright.

THE INTERPLAY OF METAL COMPOSITION AND PROCESS

"But we don't want to simply melt the metal, we also want to deposit something," says Wilms. Three nozzles are therefore located in the tip of the supposed "laser gun," grouped around the beam. They hurl metal powder that is transported by the noble gas argon into the focused laser beam – and thus into the tiny melt pool on the surface. The powder melts, emits a spark or two, and solidifies abruptly as soon as the prancing laser moves on, leaving behind a firmly welded tiny Lego block.

In the past, before the start of the AProLAM project, materials scientists primarily tried to optimize the conditions of the laser process so that service-

able products with no pores or cracks were produced from alloys that had been around for some time. Or they considered which new materials could be particularly suitable for 3D printing.

For Eric Jägge, the two approaches are inseparably intertwined. "It's the interplay of the composition of metals and a very specific process path that leads to microstructures with the properties we want," says the Max Planck researcher.

Regardless of whether it is strength, ductility or resistance to cracks or corrosion – it isn't only the physical properties of the individual constituents of an alloy that are crucial, but also their spatial arrangement after solidifying. "With additive manufacturing, we now have a new, interesting process – and therefore the opportunity to create completely new properties," says Jägge.

Take the maraging steels, for example – a portmanteau of "martensitic," the name of the microstructure, and "aging." These steels, which Eric Jägge and his colleagues optimize and refine for 3D printing, contain aluminum and titanium in addition to iron and other elements. Both metals can form tiny precipitates. >

These precipitates prevent dislocations from moving freely within the structure of the steel. The material doesn't deform as easily, and it becomes much stronger. The problem is that it normally takes a lot of effort to produce the precipitates. The material must initially be subjected to intense heat in order for the foreign substances to dissolve. It is then quenched and finally hardened at high temperatures for a long time so that the precipitates can form.

"Interestingly, all these steps are also found in additive manufacturing," says

Eric Jägle. Here, a laser initially subjects the material to intense heat. The melt pool, however, is tiny – smaller than the tip of a pin. This is why it cools down immediately as soon as the laser moves on to the next point. When it returns and prints a neighboring row right next to it, the original tiny block is heated again. The effect is repeated in the row after the next, but is slightly weaker. The peak temperatures become lower and lower with increasing distance.

But if the next layer is applied directly on top of the tiny block, the

lump of metal is again subjected to such intense heat that parts of the material melt. "What we have here is an enormously complex, completely wild temperature profile," says Philipp Kürsteiner, AProLAM member at the Max Planck Institute in Düsseldorf. "This is precisely what could help us obtain precipitation-hardened materials directly from the machine in the future – without the need for any subsequent heat treatment whatsoever."

To test this, ILT researcher Markus Benjamin Wilms has in recent months



repeatedly donned his green-tinted protective goggles and a respirator to protect his lungs from metal dust. He set the spot of light dancing and printed cubes of an iron-nickel alloy – at the bottom, in the first layers, with no aluminum at all, then with an ever-increasing proportion until the aluminum content in the top layers finally reached 25 percent.

“As the material is what we are interested in, we usually print small blocks. This is the simplest conceivable geometry,” says Wilms. Provided they

have no cracks, the samples are then sliced through the middle and polished – with a finer and finer polish whose particles, in the final pass, have a diameter of just 0.04 micrometers (40 nanometers). The smooth samples are etched and inspected under an optical microscope. Then they are polished again and put under an electron microscope to obtain information about the material’s microstructure.

A 3D DIAGRAM SHOWS THE PRECISE COMPOSITION

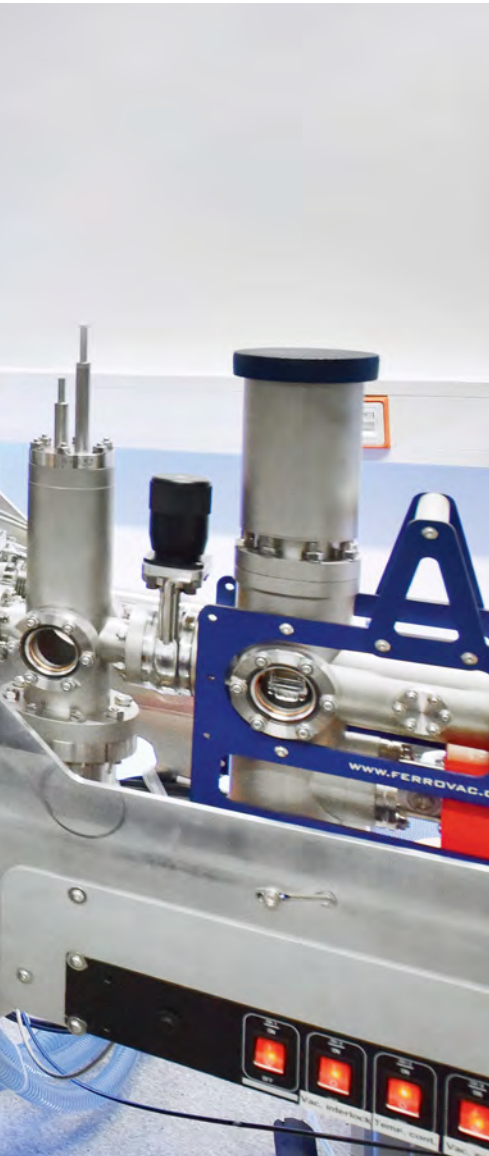
But the real acid test for the printed steel cube awaits on the ground floor of the Max-Planck-Institut für Eisenforschung. Here, side by side with historical forging hammers, stands one of the most advanced analytical instruments for metal structures: a 3D atom probe. Its maze of stainless steel tubes has a silver sheen; a blue decorative strip lights up along the top of the control unit, and the staccato tones of a helium pump, which cools the inside of the apparatus to minus 220 degrees Celsius, pounds away in the background.

In the high vacuum here, the materials researchers position a tiny pin

with a radius of less than 50 nanometers. The pin was previously cut out of the printed material by a beam of gallium ions, which then sharpened the point as if it were a pencil, with increasingly tighter circular movements. The pin ends up under a detector system to which a high voltage is applied – around 5,000 volts – and a pulsing laser beam further tortures the sample.

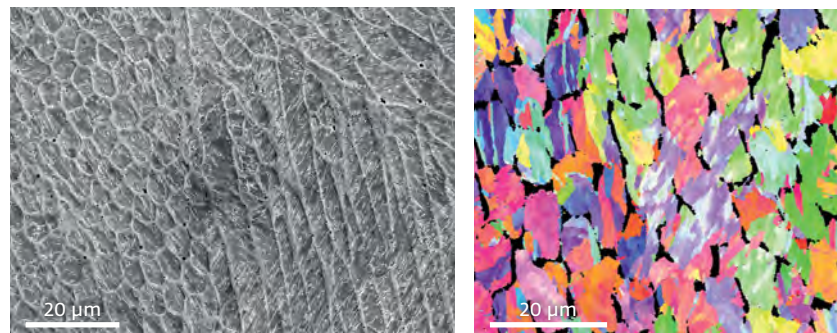
“The aim of this ordeal is to dislodge a single atom from the material with every pulse,” says Eric Jäggle. As it is positively charged, this ion moves along the electric field lines to the detector, which registers the exact position and the exact time of the impact. This data can be used to determine the point on the pin from which the particle was sent on its way, how heavy it was and how much charge it carried. At the end, the instrument produces a three-dimensional diagram that shows the composition of the tip of the pin in detail.

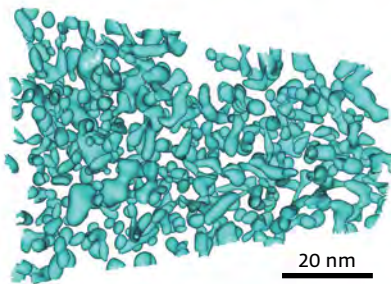
In his office within the brick walls of the Max Planck Institute in Düsseldorf, Jäggle makes a couple of mouse clicks and brings one of his measurement results onto the screen. The iron atoms, shown in gray, are found to be



Left Philipp Kürnstener (in the background) and Eric Jäggle check measurements made by an instrument that can act as a scanning ion microscope and also as a scanning electron microscope. They use the former to cut samples for atom probe analyses.

Below The image taken by the scanning electron microscope (left) shows the cellular structure of a steel sample that was first polished and then etched. In the electron backscatter diffraction image (right), the same cells are delineated by the black regions. The colors show the orientation of individual crystals.





This page Eric Jäggle introduces a new sample into the 3D atom probe, which measures how different metals are distributed in a material atom by atom (above). The turquoise areas in the image to the left show the regions in the sample of a maraging steel that contain more than 20 percent aluminum. The structure with the high density of aluminum-rich precipitates formed during additive manufacturing – this is precisely what the Max Planck researchers wanted to achieve to make the steel stronger.

Right-hand page In the AProLAM project, Eric Jäggle is attempting to optimize the properties of steels and alloys with the aid of 3D metal printing.

distributed homogeneously throughout the pin. At many locations, however, finely distributed, aluminum-rich precipitates measuring only a few nanometers can be found; they show up in turquoise on the screen. These precipitates originate directly from the 3D printer – precisely what the AProLAM researchers were looking for.

The experiments also showed that the aluminum content must be at least 5 percent for them to appear – but it mustn't exceed 14 percent, otherwise the steel's desired microstructure will be lost. According to Jäggle, an aluminum content of 9 percent has proven to be ideal. And compared with a pure iron-nickel alloy, the hardness values of a steel with aluminum precipitates are almost twice as high.

As their next step, the AProLAM researchers want to repeat the same exper-

iments with titanium as the reinforcing additive, and then again with a combination of titanium and aluminum. They also plan to study other materials in the future, including aluminum alloys reinforced with the rare metal scandium, which are very popular in aircraft construction. Or steel in which embedded oxides promise enormous stability values even at high temperatures.

MATERIALS WITH IMPROVED PROPERTIES ARE THE GOAL

At the same time, the researchers are tinkering with the printing processes – in the hope of finding the optimum conditions for particularly effective precipitates. “The major challenge here is to not introduce either too much or too little heat into the material,” says Philipp Kürnsteiner. The researchers

have a lot of parameters at their disposal behind the heavy sliding doors of the lab in Aachen. Markus Benjamin Wilms can change the diameter of the focused laser beam – from 0.6 to 1.8 millimeters. A spot of light of this size leads to a large melt pool; it then takes much longer for the material to cool down.

The speed at which the laser dances across the metal and deposits new material also has an effect on the precipitates, but the pattern used to print the individual layers offers the greatest scope. The spot of light can always race across the metal from right to left. It can meander along a rectangle. It can pause after each layer so that the material has time to cool down. It can even change the printing direction by 90 degrees between two layers.

All this affects how each individual block in the big metal Lego construc-



tion heats up, cools down and is reheated again. The temperature profile, in turn, is responsible for how easily the aluminum islands form during the printing process, how large they become, and how they are distributed in the steel.

“It takes a great deal of experience to find the right parameters in each case,” says Wilms. Nevertheless, the first attempt is usually unsuccessful. A quick look at the blindingly bright spot of light is all it takes to appreciate this: “Sometimes it lights up there as if in a thunderstorm; then you know that the process is running unevenly and the laser has to move more slowly.”

Ultimately, despite all the experience gained, only an iterative process can help: Wilms has to tinker with one of the many parameters until the printed blocks don’t get any better. The value is then fixed and the next parameter is dealt with – until finally a material is produced that outshines all of its predecessors.

And that is the ultimate goal of the AProLAM researchers, whether they work behind the brick walls in Düsseldorf or the sliding doors in Aachen. They want to facilitate the creation of new materials that not only can be manufactured more easily and without complex heat treatment, but that also

surpass conventional materials with their improved properties. “The whole technology will only really take off when people recognize one thing,”

says ILT researcher Andreas Weisheit: “If you want to have such a novel material, the only way to achieve it is with additive manufacturing.” ◀

TO THE POINT

- The pioneering 3D printing – known as additive manufacturing – offers many advantages, but its development still offers room for improvement, particularly as far as the materials are concerned.
- The research project AProLAM (Advanced Alloys and Process Design for Laser Additive Manufacturing of Metals) involves Max Planck and Fraunhofer researchers joining forces to pursue two objectives: first, they want to find out which materials are suitable for 3D printing; and second, they want to optimize the production processes to improve the properties of known alloys.
- There are primarily two printing processes in use: selective laser melting uses a layer of powder just 50 to 100 micrometers thick on a substrate; laser metal deposition produces thicker metal blocks.
- The materials that the researchers are optimizing and refining for 3D printing include, for instance, maraging steels. Besides iron, these contain, for example, aluminum and titanium, and don’t deform easily.

GLOSSARY

Laser: The word is an acronym for light amplification by stimulated emission of radiation and refers both to the physical effect and to the device. Laser beams are sharply focused, have a high intensity and usually a very narrow frequency range. They can also produce extremely short and intense pulses of radiation. In manufacturing, they are used as cutting and welding tools.

Alloy: A metallic material that is composed of two or more elements, at least one of which must be a metal.