Material design: Damascus steel produced in the traditional way, such as that seen here, is often used for decorative purposes nowadays because of its characteristic pattern. In contrast, producing a material of this kind in a 3D printer involves varying the properties of materials that can be processed using this technology.

A LEGEND FROM THE 3D PRINTER

TEXT: KARL HÜBNER

In ancient times, it was the material of choice for sword blades. Now, a kind of Damascus steel can be produced in a 3D printer using a technique developed by a team from the Max-Planck-Institut für Eisenforschung in Duesseldorf and the Fraunhofer Institute for Laser Technology in Aachen. Composite materials of this kind could be of interest for aerospace components or toolmaking.

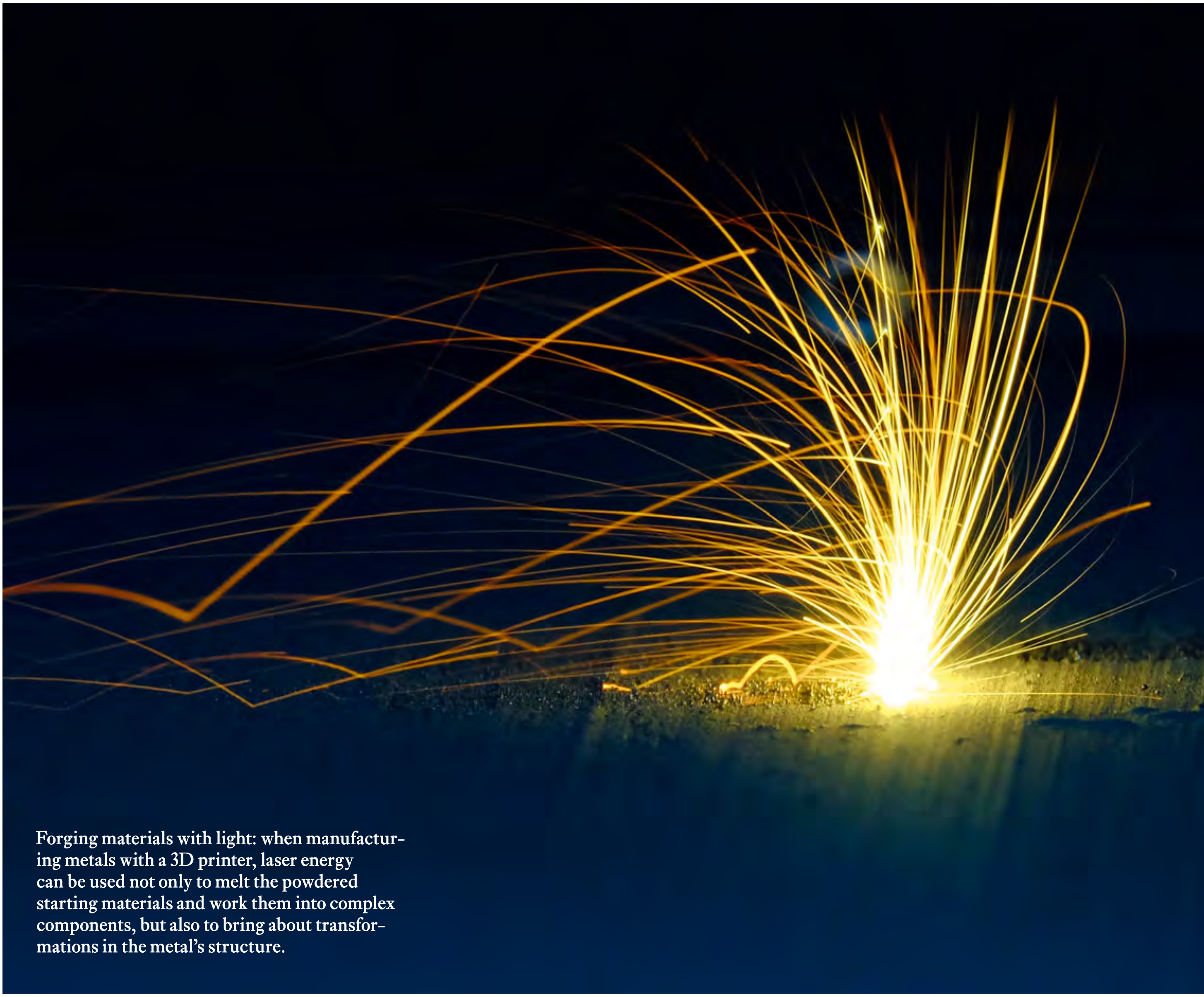

PHOTO: P. KÜRNSTEINER/MPI FÜR EISENFORSCHUNG GMBH

Forging materials with light: when manufacturing metals with a 3D printer, laser energy can be used not only to melt the powdered starting materials and work them into complex components, but also to bring about transformations in the metal's structure.

Born out of necessity and destined to become a legend. In the past, blacksmiths were able to influence the properties of iron alloys only by adjusting their carbon content. They obtained either a soft yet tough or a hard yet brittle steel. Especially for swords, a tough and hard material was needed so that the blades would not break or have to be straightened in the middle of a battle.

Celtic smiths combined various iron alloys – perhaps initially only to recycle the valuable iron – and thus obtained the material that later became known as Damascus steel or damask. It owes its name to the trading center through which the composite material of oriental origin entered Europe. While Indian and Arabic damask was created by a sophisticated smelting process, European smiths developed the art of folding two alloys into many thin layers. The layered structure of Damascus steel can usually be recognized by a characteristic stripe pattern.

Although there are currently ferrous alloys that are both hard and tough, they are often not specifically made for the 3D printing process and therefore do not fully exploit the ad-

SUMMARY

A team from the Max-Planck-Institut für Eisenforschung and the Fraunhofer Institute for Laser Technology is developing alloys for use in 3D printing.

The researchers recently presented a technique whereby 3D printing can directly convert a single starting material into a kind of Damascus steel with alternating hard and tough layers.

By fine-tuning various parameters, such as the printer's pause times, the laser energy, or the speed at which the metal is 3D printed, it is possible to make localized adjustments not only to the hardness but potentially also to other properties.

vantages of this manufacturing technique. Using 3D printing, scientists at the Max-Planck-Institut für Eisenforschung and the Fraunhofer Institute for Laser Technology have now developed a steel that consists of just one single starting material, but is made up of alternating hard and ductile layers – a kind of Damascus steel. "We have succeeded in specifically modifying the micro-structure of the individual layers during 3D printing so that the final component has the desired properties – and all this without subsequent heat treatment of the steel," says Philipp Kürnsteiner, post-doctoral researcher at the Max-Planck-Institut für Eisenforschung.

3D printers for additive manufacturing (the technical term for this process) have become standard in many industrial sectors in the space of just a few years. They are able to produce plastic as well as metallic components. The respective alloy is added as a fine powder, melted by a laser beam, and repeatedly applied layer by layer to form the target component. For the last few years, fuel injection nozzles for aircraft engines, for example, have been produced using this additive manufacturing method, which is also known as laser cladding.

The laser beam makes it possible to not only melt the respective material but also to heat the top layer of the already resolidified metal. This is exactly what the team of the Max Planck researchers in Duesseldorf used to specifically change the crystal structure of the steel in individual metal layers. In this way, they can influence the mechanical properties without changing the chemical composition.

They developed an alloy consisting of iron, nickel, and titanium. At first, this alloy is relatively soft. "Under certain conditions, small nickel-titanium micro-structures form. These so-called precipitates harden the material," explains Kürnsteiner. "When subjected to mechanical stress, they hinder the movement of dislocations within the crystal lattice that is characteristic of plastic deformation."

PHOTO: FRANK VINKEN/DWB

Freshly printed metal: Philipp Kürnsteiner inspects a cube-shaped sample of steel comprised of alternating tough and hard layers. The researcher created the material using a sophisticated method that allowed him to control the 3D printing process.

In order to be able to create the nickel-titanium structures, the researchers interrupt the printing process for a certain time after each newly deposited layer. The metal cools down to below 195°C. "Below this temperature, a transformation of the crystal structure occurs in the steel," explains Eric Jägle, head of the "Alloys for Additive Manufacturing" group at the Max-Planck-Institut für Eisenforschung and, since January 2020, professor at the University of the Bundeswehr Munich. "A 'martensite' phase is formed. It is only during this phase that the nickel-titanium microstructures can percipitate." However, in order to allow precipitates to form, reheating is necessary. To achieve this reheating the researchers exploit the laser energy used to deposit the subsequent layer.

This additional effect caused by the laser beam of the 3D printer is referred to as intrinsic heat treatment. Layers that have been directly covered with the next layer without interruption remain softer because they are not yet present as martensite at this point.

For the first time, the researchers are able to directly create a composite material consisting of layers with different properties from a single starting material during the production process. Kürnsteiner is impressed by the mechanical properties of the material produced in this way: "The tests confirm an excellent combination of strength and ductility."

Many different process parameters are suitable for influencing the micro-structures during 3D printing. Jägle explains that in addition to or instead of the pause time, which is varied in this study, martensite formation and subsequent precipitation hardening could also be controlled by varying the laser energy, laser focus, or printing speed as well as external heating and cooling techniques.

In their experiments, the researchers produced cube-shaped or cuboid steel pieces with side lengths of a few centimeters as models for objects with more complex geometries for which computer-controlled 3D printing is of interest. They also emphasize that the Damascus-like steel with its periodically changing layers is only one example of how the micro-structure of an alloy can be locally influenced during the manufacturing process. For example, it is equally possible to create tool components with a continuous soft core surrounded by a hard, abrasion-resistant outer layer. "Thanks to our concept of local control, this was achieved in a single manufacturing step – without the additional process steps previously required for surface hardening such as nitriding," stresses Jägle. According to the researchers, it might also be possible to use the technology to locally adjust other properties such as corrosion resistance.

"The technology opens new doors for adjusting the local micro-structures in a defined manner during the additive production of even complex work pieces and making post-treatment unnecessary," says Kürnsteiner. The researcher also suggests a paradigm shift: "Until now, it has been common practice to use conventional alloys in 3D printing. However, many known steels are not optimally suited for additive manufacturing. Our approach is to develop new alloys that can exploit the full potential of 3D printing."

←

GLOSSARY

3D PRINTING
Also known as additive manufacturing, this technique allows components with complex shapes or custom designs to be built up layer by layer. The method was originally developed for processing plastics but can now also be used for metals and other materials.

COMPOSITE
Composites are a combination of materials with various properties. Packaging made of plastic-coated cardboard is one typical example. Damascus steel is made up of iron alloys with differing degrees of hardness and is therefore both hard and tough at the same time.

For alloys designed using additive manufacturing, the Max Planck researchers begin by preparing a powder bed. A laser then produces the desired material directly from the powder – layer by layer – in order to manufacture the components.

PHOTO: YASMIN AHMED SALEM/MPI FÜR EISENFORSCHUNG GMBH