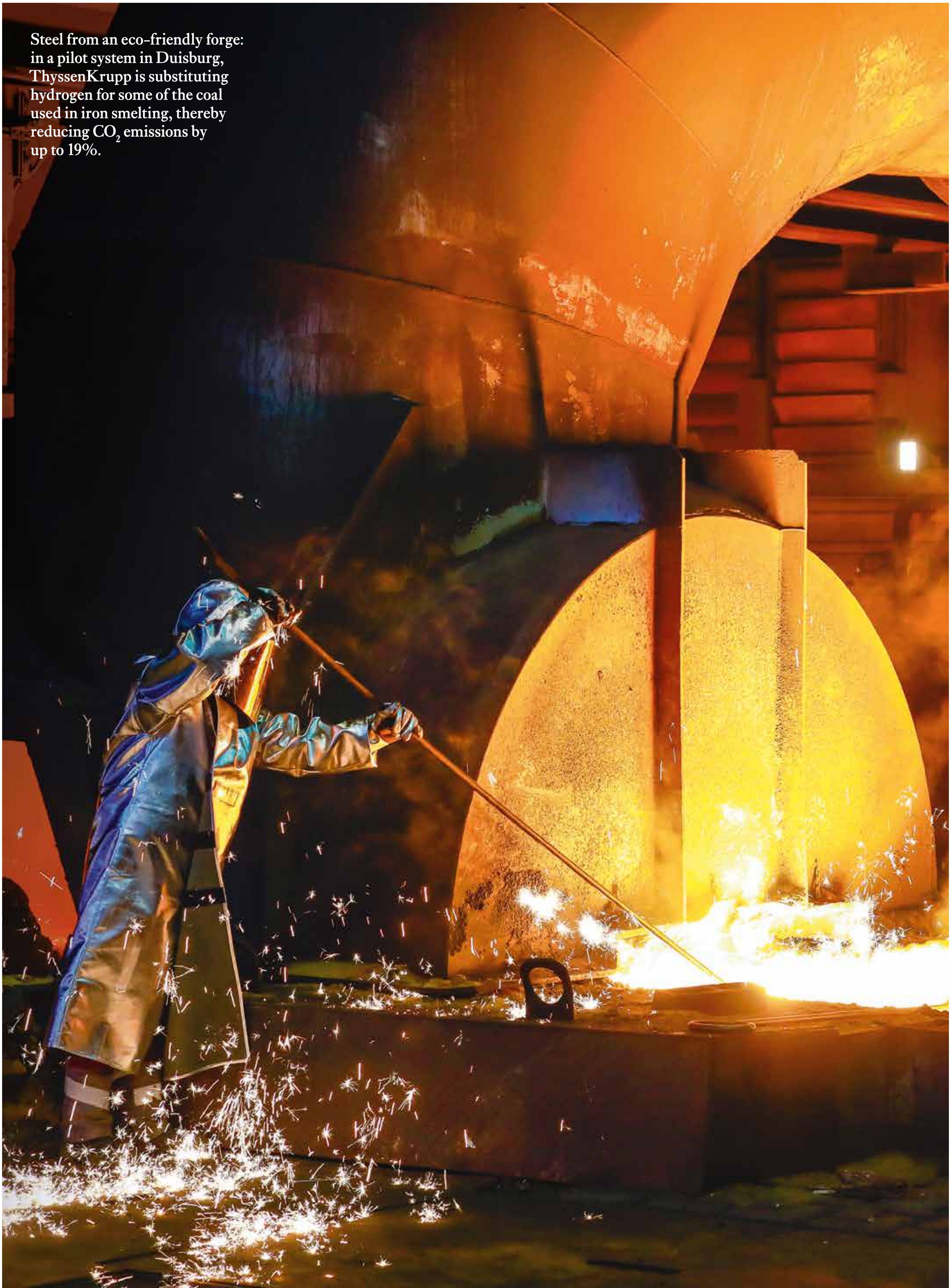

Steel from an eco-friendly forge: in a pilot system in Duisburg, ThyssenKrupp is substituting hydrogen for some of the coal used in iron smelting, thereby reducing CO_2 emissions by up to 19%.

PHOTO: PICTURE ALLIANCE/RUPERT OBERHÄUSER

ENERGY REVOLUTION IN THE BLAST FURNACE

TEXT: TIM SCHRÖDER

It's impossible to imagine modern life without metals, but today's metal industry is responsible for a third of all industrial greenhouse gas emissions. Dierk Raabe and Martin Palm, scientists at the Max-Planck-Institut für Eisenforschung in Duesseldorf, are working on a more sustainable way of producing – and using – metals. Their ideas could completely revolutionize the metal industry.

Everyone knows that extracting and forging metal requires heat. Indeed, the production of iron has not fundamentally changed in thousands of years: the ore is heated with charcoal or coke, the molten metal is collected and allowed to solidify, and the material is then formed into the desired shape. This method was already used 3,500 years ago in Asia Minor when the Hittites needed iron for their swords – although in those days, production was limited to a few piles of charcoal burning here and there. Today, the production of steel, aluminum and many other metals is big business – and presents a problem in terms of climate change. Around a third of all industrial carbon dioxide emissions originate from metal production, which also accounts for almost one-tenth of global energy consumption.

There are certain behavioral changes that we can make in order to tackle climate change: flying less, traveling by bus or train instead of by car, or limiting meat consumption. But how can we make metal production more climate-friendly? Producing metal requires a lot of heat – that's unlikely to change. And it would be hard to make do without metal – steel is an essential construction material for buildings, bridges and industrial facilities, and today's society would be unwilling or even unable to get rid of cars, ships and aircrafts, which primarily consist of metal. Even bicycles are made of steel or aluminum. That is why it is imperative for the metal industry to reduce its CO_2 emissions. "There's growing interest in climate-friendly production," says Dierk Raabe. "In the future, industry innovators will want to advertise these sorts of products in order to set themselves apart from competitors." Raabe, a materials scientist and Director at the Max-Planck-Institut für Eisenforschung in Duesseldorf, is part of a growing group of experts around the world who are working on more-sustainable forms of metal production and manufacturing. This will require the industry to bid farewell to long-established principles, some of which stretch back thousands of years.

Steel is largely made up of iron, which is extracted from iron ore in blast furnaces the size of lighthouses. Iron ore is essentially the same thing as pure rust – in other words, iron oxide (Fe_2O_3). In order to turn iron oxide into iron, the oxygen must be removed. Even today, this is still

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achieved by heating the ore with coke so that – via several intermediate steps – the oxygen from the ore bonds with the carbon from the coal. Iron is left behind, and the resulting CO_2 escapes. “If we can succeed in establishing sustainable new methods in this area, they will be a powerful tool for reducing global greenhouse gas emissions,” says Dierk Raabe.

The scientific community is currently discussing various approaches to green steel production. For example, steel could be produced by electrolysis – as is done with other metals, including aluminum. This would be a clean undertaking if the necessary power were obtained from renewable sources. However, the processes are still nowhere near sophisticated enough and would presumably be incapable of producing the huge quantities of steel that are used around the world each year. So at least initially, Raabe sees greater potential in replacing a proportion of the coal with biogas, methane and, above all, hydrogen. These substances are also capable of extracting oxygen from iron ore (Fe_2O_3). Hydrogen would be the best option from a climate protection perspective, provided it was produced using electricity from renewable sources. Following several intermediate stages, water vapor would then be formed as the exhaust gas instead of carbon dioxide. Before hydrogen can be used to produce pure iron on an industrial scale, however, Dierk Raabe and his team still have a few issues to clarify – such as how the hydrogen can penetrate far enough into the ore for the iron oxide to react quickly and completely. After all, this reaction

PHOTO: PICTURE ALLIANCE/JOCHEN TACK

faces an obstacle: the conversion of iron oxide (Fe_2O_3) to pure iron passes through an intermediate product known as wustite (FeO), which has only one oxygen atom per atom of iron. The problem is that wustite likes to surround itself with a shell of pure, newly formed iron, which is produced during the reaction with hydrogen. It takes a long time for the hydrogen, as well as the released oxygen, to pass through this iron cladding, which can therefore slow down the production of iron considerably. "With that in mind, we're trying to break down the grains of wustite so that they fully react with hydrogen," says Dierk Raabe. His team is studying the reaction between ore and hydrogen at different pressures and temperatures with a view to identifying the ideal conditions for the conversion of wustite into a sort of permeable nanosponge. "I'm also currently reading some specialist articles published around 80 years ago by Fritz Wüst, the founder of our Institute," says Raabe. "He worked intensely with iron oxide, which is why the compound was named after him. His work provides us with vital information to this day."

An industry facing radical change: steel production – for example, at the Tata Steel iron and steel works in IJmuiden, Netherlands – is indispensable for industrial companies. However, if climate goals are to be met, the metal industry will need to make greater use of energy from renewable sources in the future.

There are other challenges when it comes to the reaction between iron oxide and hydrogen. Gaseous hydrogen occurs as a molecule of H_2, but it is only reactive in the form of an ion – that is, as H^+. Accordingly, it must first be split up (or cleaved) quickly and without expending a great deal of additional energy. "Iron ore always contains a small proportion of foreign atoms that, like the iron, are present in the form of oxides," Raabe explains. "We want to find out whether some of these impurity oxides could act as catalysts to accelerate the splitting of H_2 molecules." In that case, the ore itself would produce reactive H^+ ions. "Accordingly, we then have to turn our minds to the issue of catalysis, which isn't usually the focus of our work," says Raabe.

Who will foot the bill for the transition?

So hydrogen might not be the most sustainable way of producing iron in the long term, because it must first be converted into its reactive form. Overall, the more efficient method would be to use hydrogen plasma. This is the most reactive form of hydrogen and is made up of atoms that have been separated into H^+ ions and electrons. Formed in the flash of an electric arc, for example, hydrogen plasma reacts with iron oxide much more vigorously. "Here, we're working on a completely new alternative to the traditional process," says Raabe. In the new technique, iron oxide is converted into iron within a plasma state, and the material it contains is smelted down simultaneously. "All in all, hydrogen is going to be a major focus of our work over the next 10 to 15 years," says Raabe. "With the equipment available here at the Institute, we can perfectly control iron production with hydrogen and observe it as far down as the atomic scale." This equipment includes atom probes, which can determine a material's composition atom by atom, and transmission electron microscopes, which the researchers can use to inspect the ore right down to the electronic level, as well as equipment usually used to study the quantum mechanical properties of metals and semiconductors.

However, switching over to hydrogen and green steel will not be without cost, says Christian Vietmeyer, managing director of the Association of the Steel and Metal Processing Industry (WSM). The association's members include companies that process raw metals, including making automotive parts out of steel. "We strongly suspect that the automotive industry will be the first to express a clear demand for steel with a significantly smaller carbon footprint. But this steel will initially be more expensive." Steel producers have already called for state subsidies for the green transition, so that German steel production can remain competitive in the face of cheaper, conventionally produced steel from abroad. "We are very critical of this approach, as it would lead to long-term subsidization." It remains unclear, therefore, how the transition to green steel production could be financed. "We take the view that regulatory policy must seek to achieve this the other way around – by way of customer demand." He suggests a reformed motor vehicle tax as one possibility. Today, cars are taxed according to their CO_2 emissions, but Vietmeyer says that, in the future, it will be possible to consider the entire life cycle, including the quantity of greenhouse gases a vehicle had given rise to →

during its manufacture and the production of the steel used to build it. Dierk Raabe also recognizes that the development of climate-friendly methods of iron and steel production won't be enough: "There is a need for a continuous chain from the basic research through to a good understanding of the steel manufacturing process." The transition to lower-carbon or even carbon-neutral production of iron and steel will require companies to invest large sums of money. "Hasty and potentially incorrect decisions could pose a threat to their survival," says the researcher.

It is certainly a gargantuan undertaking, with global demand for steel standing at 1.8 billion tons per annum – an almost inconceivable quantity of metal that corresponds to almost twice the weight of all cars currently on the road. With this in mind, a more sustainable method of steel production would indeed be an important tool when it comes to climate protection. But there are also other aspects to consider, says Raabe. One major issue is longevity. "It's estimated that some 3.5% of global GDP is lost to corrosion alone – and these huge losses could be avoided if metals, buildings and products were more durable." The fact that car bodywork is fully galvanized is, he says, a testament to the value of corrosion protection and has meant that – unlike 30 years ago – cars are no longer destroyed by rust. However, corrosion protection is about more than simply sealing the surfaces of metals, says Raabe. For example, many bridges are apparently now being demolished after standing for only a few decades, because we don't know how advanced the corrosion is inside the structures. "There are neither sensors nor pH meters nor voltmeters to give us information on the material's condition – it's like we're in the Stone Age." For Raabe, self-monitoring features of this kind are indispensable in the modern era.

In addition to this measurement technology, another possible solution would be metals with self-rejuvenating or self-repair capabilities – which already exist in plastics. These capabilities can, for example, be achieved by melting capsules containing liquid plastic ingredients into components in order to fill cracks if the need arises. "The plastics themselves notice when damage occurs. Aluminum and iron haven't reached that stage yet – there's still a lot of work to do," says Dierk Raabe. That being said, some initial ideas have already been floated. One possibility is that, when oxygen enters the material as a result of damage, solid metal oxides could form in order to repair minor defects. Likewise, pores in some alloys can seal themselves at high temperatures by means of atomic transport processes. Indeed, the Duesseldorf researchers have been involved in another project, in which steel was mixed with small quantities of molybdenum that can seal up fine pores. In other words, in order to reduce greenhouse gas emissions in the metal industry, it also makes sense to preserve these products, instead of building them again.

SUMMARY

Approximately one third of the world's industrial CO_2 emissions come from the production of metal. Emissions from steel production could be reduced if at least part of the required coal were replaced with methane, biogas or, above all, hydrogen.

In order to use hydrogen to produce steel on an industrial scale, Max Planck researchers are working to speed up the chemical reaction. They are also investigating the possibility of producing steel in a completely new process using hydrogen plasma.

Improved corrosion protection and a higher recycling rate could also help to reduce the carbon and energy footprints of metal products.

As iron aluminides are corrosion-resistant, lightweight and readily recyclable, they represent a sustainable alternative to steels. By adding boron, Max Planck researchers have also succeeded in optimizing the alloy for use at high temperatures – for example, in turbines.

Recycling is to become simpler

When it comes to sustainability, aluminum faces similar problems to those affecting iron and steel. Aluminum is produced in "electrolysis cells" that operate at very high temperatures and consume large quantities of power, so its production is every bit as energy-intensive as that of steel. "Aluminum recycling is therefore a key factor, because melting down scrap aluminum only requires about 5% of the energy," says Dierk Raabe. However, many industries take a dim view of aluminum that contains recycled material, because it could contain impurities. In particular, contamination with iron and copper – from screws or cables included in the scrap aluminum, for example – can influence the properties of the aluminum during processing or when a part is exposed to mechanical loads. In the aviation industry, for instance, aluminum that contains recycled material is mostly ruled out due to safety concerns. "Aluminum alloys have to satisfy 20 or sometimes 30 parameters laid down by the manufacturers," says Dierk Raabe. "Impurities can change their properties." However, many manufacturers won't even use the unmixed production waste from their own manufacturing process. Nowadays, for example, a laptop housing is milled from a block, and more than half of the material is lost as chips. It is still mostly less expensive for the manufacturers to buy new aluminum alloy than to process their own scrap.

For some time, Dierk Raabe has been working with his team to conduct a systematic study of how the behavior of aluminum changes in response to the tiniest recycling-related impurities – and is one of the first scientists in the world to do so. He is initially fo-

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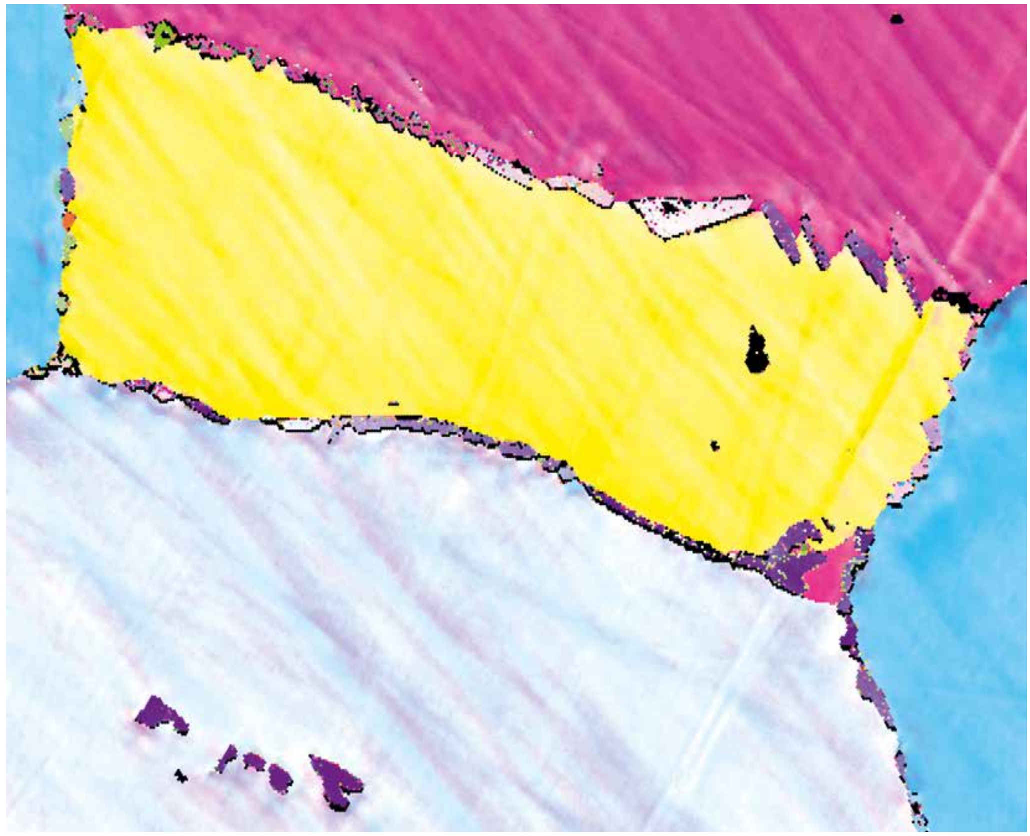
PHOTO: FRANK VINKEN FOR MPG

On the hunt for sustainable metallic materials: Martin Palm and Angelika Gedsun produce lightweight, durable and cost-effective iron aluminide alloys in an induction furnace.



GRAPHIC: ANGELIKA GEDSUN / MPI FÜR EISENFORSCHUNG

Heat-resistant, thanks to nanoparticles: the alloy is prevented from softening at high temperatures by tiny boron-containing deposits at the boundaries between the iron aluminide structures, which are shown in different colors in the microscope image.

25 µm

cusing on what he terms the "big problem bears" – iron and copper. Working in a vacuum, his team deposits pure aluminum onto a surface and then gradually mixes in iron to produce an iron gradient within the material sample. This allows the researchers to seamlessly track detailed changes in the aluminum's characteristics as the iron content increases. Their objective is clear: in the future, it should be possible to mix increasing amounts of scrap aluminum into aluminum alloys without reducing the quality of the products. "How dirty can the child get and still stay healthy? That's what we want to find out," says Raabe. "If we achieve 90% of the desired product parameters with recycled aluminum, that will be sufficient for many applications." Although safety-relevant applications would initially be ruled out, this green aluminum is easily good enough for use in elevator cladding or spare tire wells in car trunks.

Considerable interest from industry

Whereas Dierk Raabe tends to view iron in aluminum as an impurity, this is not the case for Martin Palm, head of the "Intermetallic Phases" research group at the Max-Planck-Institut für Eisenforschung. Indeed, Palm sees a bright future for materials that deliberately combine the two elements. For a number of years, his work has focused intensively on iron-aluminum alloys, which are seen as a future substitute for expensive steels with admixtures of nickel, chromium or cobalt. Iron aluminides are corrosion- and wear-resistant and hence extremely durable. They are also relatively light and could therefore help to improve the sustainability of metal products. For a long time, however, one factor has stood in the way of a major breakthrough: the materials lose their strength at temperatures above 700 degrees Celsius. At the same time, their low weight means they would be especially suitable for turbines in power stations and aircrafts – because less mass requires less fuel. In the last few years, however, the materials scientist Martin Palm and his team have solved the temperature problem. Specifically, they have made iron aluminides heat-resistant by using sophisticated methods to penetrate deep into their microstructure.

If you look at solidified metal under an electron microscope, you can clearly make out light and dark areas alongside one another – like countries on a map. Experts refer to these "countries" as metallic phases. They differ in terms of their chemical composition and atomic arrangement, because atoms join together in different ways from one place to another as the alloy solidifies – forming phases that contain more iron or more aluminum, for example. This separation into different phases is what gives iron aluminide alloys their strength – at least at low temperatures. "Unfortunately, when they get very hot, the phases tend to merge with one another, causing the material to soften," explains Martin Palm. However, his team has succeeded in finding ways to suppress this merging of phases, including by mixing low concentrations of boron into the alloy. When the alloy solidifies, the boron forms boride nanoparticles that accumulate at the phase boundaries like poppy seeds on a bread roll. And, as borides are among the most heat-resistant materials, they prevent the iron aluminide phases from merging with one another at high temperatures. Martin Palm has therefore paved the way for a prosperous future for iron aluminides. "There's no doubt about it: the industry will inevitably turn its attention to iron aluminides in the next few years, because all of the other elements in today's alloys are gradually becoming scarce." Iron and aluminum are the most common metals on earth and are available in large quantities, whereas reserves of chromium, cobalt and nickel have already shrunk significantly. These scarcer metals are therefore becoming a plaything for speculators – and their prices are becoming incalculable. "Even today, iron aluminides would be 20% cheaper than chromium steel and as much as 80% cheaper than nickel-based alloys," says Palm. "This trend is set to intensify."

There is another characteristic iron aluminides have that makes them unusually sustainable: they require almost no other alloying elements and therefore offer excellent recyclability. Moreover, unlike certain chromium compounds, for example, they are not ecotoxic. Given the advantages of these materials, there is considerable interest from industry. Martin Palm's partners therefore include Siemens, Rolls-Royce Deutschland and the company Leistritz Turbinentechnik, among others. In Palm's view, the Duesseldorf researchers can clearly put their unique expertise regarding alloys to good use – after all, this know-how is almost non-existent in industry today. "We have the plant technology to produce the alloys, but above all we have the fundamental knowledge about phase transitions – in other words, how alloys and their phases change with temperature." We can therefore look forward to the day when the first lightweight iron aluminide turbine goes into operation. And, of course, it should ideally run on environmentally friendly biofuel – or even hydrogen. This outcome would represent a big achievement in terms of sustainability.

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GLOSSARY

ELECTROLYSIS
This is a process in which electricity is used to break down substances such as water or metal oxides into their constituent parts. Industry produces hydrogen and aluminum electrolytically, but steel can also be produced in this way.

PHASE
In chemistry, this term refers to an area of matter with uniform physical and chemical properties. In a material, areas with different compositions are described as different phases.

PLASMA
In the fourth state of matter, the particles of a gaseous substance are entirely or partially ionized – in other words, they take the form of positively charged ions and free electrons.

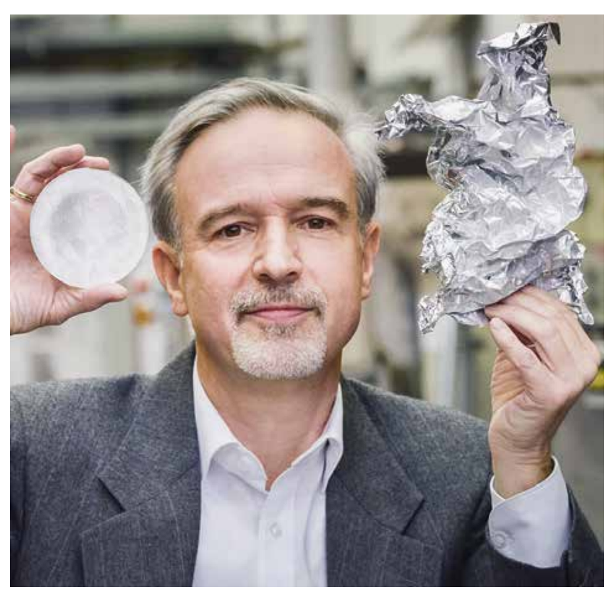

PHOTO: FRANK VINKEN FOR MPG

Masterminding a sustainable metal industry: Dierk Raabe sees the increased recycling of scrap aluminum, for example, as an opportunity to reduce the industry's carbon footprint.