Cooking Steel
for the Cars of Tomorrow

Scientists working with **Georg Frommeyer** at the **Max Planck Institute for Iron Research** in Düsseldorf have developed lightweight steels that are not only particularly strong, but also very ductile. Their low specific weight and exceptional mechanical properties make them ideal material for applications in the automotive industry.

Photo: Frank Vinken

TEXT **TIM SCHRÖDER**

The mention of iron and steel making usually conjures up images of huge blast furnaces in which molten raw (pig) iron glows white-red, bubbling gently. Once it has reached the correct temperature and composition, it is simply poured off in a submarine ladle, or it rapidly solidifies to masses of pig iron. Or so it may seem. Yet steel making is more than just this large-scale tableau. It can, in the truest sense, be compared to the high art of gourmet cooking: producing steel with specific properties requires the right ingredients, the right recipe, and creativity on the part of the cooks.

Georg Frommeyer is a steel expert with the requisite ingenuity. He is professor of materials technology at the Max Planck Institute for Iron Research in Düsseldorf, where he and his colleagues have developed new kinds of steel that major players in the steel industry have called "a significant leap forward in development." These steels are very light, extremely tough and particularly ductile. Known at the institute as "high-strength, supraductile TWIP/TRIP lightweight construction steels," they are especially suitable for the automotive industry.

Regardless of whether they are intended for the road or the railway, the focus is always on making vehicles tougher, lighter and safer. Bodyworks are expected to offer higher and higher levels of occupant safety in the event of accidents. At the same time, engineers aspire to create increasingly lightweight designs in order to reduce fuel consumption and emissions. Steel manufacturers have long since realized that they are facing increasing competition from aluminum and new materials, such as magnesium and plastics. To stay in the running, they must make their steels lighter, stronger and more ductile than their competitor products.

A MATERIAL THAT IS NOT YET EXHAUSTED

Steel consists mainly of iron. It takes on different properties when, for example, different metals are added – or alloyed – such as manganese, nickel or chromium. This is how stainless steel and high-strength or even super high-strength steels are created – the right material for the application at hand. Automobile manufacturers are particularly demanding when it comes to steel for autobodies, which must be strong enough to take the weight of the vehicle without deforming or vibrating. They must also be rigid enough to form a protective structure around the vehicle's occupants in the event of a collision. And it should be possible to calculate precisely how they will deform to absorb the impact energy in an accident.

Although a single material will not have all of these properties, the steels from the Max Planck laboratories in Düsseldorf are truly multipurpose, and are able to take on several different functions. "A few years ago, experts were saying that the properties of steel had been exhausted," says Georg From-

Like working at a steel mill: Scientists at the Max Planck Institute for Iron Research cook up and cast steel samples weighing up to a hundredweight.

meyer. “Alloying steel with other elements had already made it suitable for numerous functions.” Nevertheless, the Max Planck researchers were convinced that there was more to be coaxed from this well-established material, although initially their assumptions were based only on theoretical considerations and many years of experience.

LIGHTWEIGHT STEELS THAT CAN BE CALCULATED

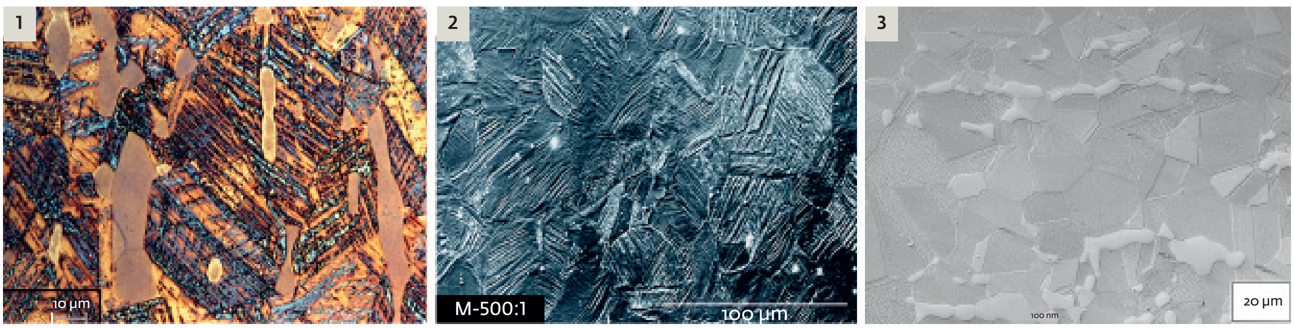
The properties of different steels depend on, for one thing, their crystal lattice structures – the spatial arrangement of the atoms in the tiny crystals that form when molten steel solidifies. The properties are also determined by how the crystals are arranged, which in turn depends on the structure of the crystals themselves. Adding alloy elements makes certain crystal structures more likely to form. Materials scientists speak of energetically favored crystal lattice structures. This allows the properties of the steel to be fine-tuned.

The researchers use thermodynamic calculations to reveal which crystal structures are energetically favored. From these calculations, they concluded that a combination of manganese, silicon and aluminum would probably be suitable for the development of the new lightweight construction steels. These elements are lighter than iron, and force the crystal lattice into certain structures. Iron can thus switch between different crystal lattices. There is, for example, a face-centered cubic (FCC) arrangement, which experts call “austenite.” In this case, the iron atoms sit on the corners of the crystal lattice cube, and in addition, one atom occupies the center of each face of the cube.

Then there is the body-centered cubic (BCC) variant. Again, the iron atoms are arranged on the corners, but with another in the cube’s center. In the hexagonal type, the iron atoms are distributed in a hexagon shape. Both the body-centered cubic and the hexagonal structures are also referred to as

Photo: Wolfgang Filser

TRIP steel | TWIP steel | TRIPLEX steel



The different microstructures of TRIP, TWIP and TRIPLEX steels can be seen under the optical microscope (1 and 2) and the scanning electron microscope (3).

martensite. The crystal lattice changes, and with it, the character of the steel, depending on the alloy element content – the substitutional alien atoms in the crystal lattice.

In the man-sized melting furnaces in the large workshops at the Max Planck Institute, the scientists cook up different steel compositions and investigate the microstructures and mechanical properties of the alloy variants. Ingots weighing over a hundredweight can be prepared with different smelting processes and then rolled into sheets. On separate machines, engineers test finger-thick steel samples that are held tightly in a sort of clamp and subjected to tensile stress. How strong is the steel? When does it break?

The test results of the newly developed steels were astonishing. The steels proved to be both extremely strong and very ductile, particularly when alloyed with 15 percent manganese and 3 percent each of aluminum and silicon. It stretches by more than 50 percent, and it hardens without breaking. It resists tensile stresses up to 1,100 megapascals, which is roughly equivalent to the weight of ten bull elephants on a postage stamp.

CHANGING CRYSTAL STRUCTURE MAKES STEEL DUCTILE

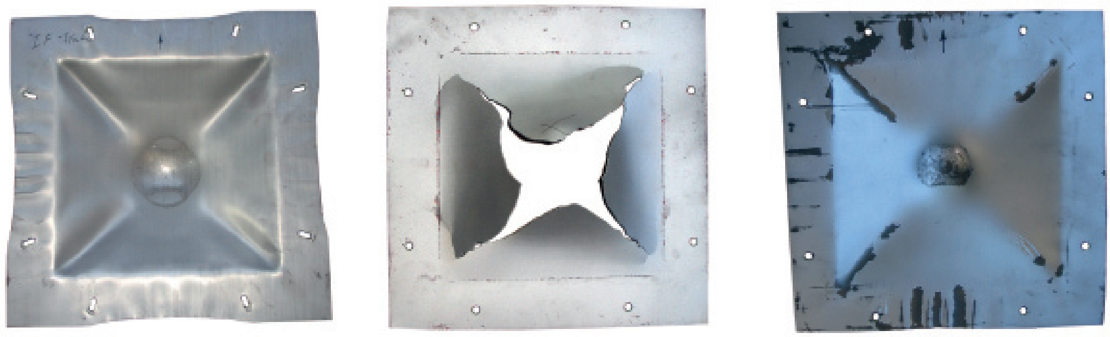
Conventional high-strength bodywork steels fracture at around 700 megapascals or even less. Steel with 25 percent manganese and 3 percent each of aluminum and silicon (MnAlSi 25 3 3) also presented a few surprises. Although it did not harden to quite the same strength, it could be stretched to approximately 90 percent of its length without breaking. “Even gold, which is considered to be extremely ductile, doesn’t achieve ductility of this magnitude. It reaches, at most, 60 percent,” says Frommeyer.

The new alloy is similar to the conventional “TRIP” steels, which have been on the market for about ten years. TRIP stands for transformation-induced plasticity. Like the steels from the crucibles in Mülheim, traditional TRIP steel is also very strong, typically up to 700 megapascals. However, its ductility is moderate, at approximately 35 percent. This characteristic – ductile yet strong – is the result of changes in the crystal lattice.

When forces act on the steel, it changes from the face-centered cubic form – austenite – to the body-centered cubic form – martensite. It is the collective shear of the crystal lattice planes that makes traditional TRIP steel ductile.

This is very important for the automotive industry, as the metal for autobodies is usually shaped by stretch drawing or deep drawing. In this process, a steel sheet is placed in a huge press and deformed into the final shape with a rather complex geometry. The more ductile the steel, the easier it is to shape it without breaking it. With conventional TRIP steel, however, a certain amount of the austenite portion is transformed into martensite – a rigid crystal structure that allows hard-

Photos: MPI for Iron Research (3)



top | Steel put to the test: To test their formability and fracture properties, a soft IF steel – effectively pure iron with little carbon and phosphorous –, conventional TRIP steel (middle) and TWIP steel are punched in a drop tower.

right | The steel sample is still glowing as Georg Frommeyer takes it from the furnace to the rolling mill (top). The testing lab at the Max Planck Institute in Düsseldorf is part laboratory, part factory (bottom).

ly any stretching. In the event of a vehicle crash, the steel would offer only about 5 percent reserve ductility.

DOUBLE RESERVE PROVIDES SIDE-IMPACT PROTECTION

The steel from Düsseldorf also has TRIP properties. However, with the special composition of the manganese, silicon and aluminum atoms in the iron crystal, the TRIP effect is twice as pronounced, giving it double the reserve ductility. This is because the alloy elements make two martensitic transformations possible. When forces act on the steel, as in the deep or stretch draw process, at least some of the austenite is transformed into the hexagonal martensite structure. When the steel is put under increasing stress, the hexagonal lattice switches to the final, body-centered cubic structure, similar to conventional TRIP steel.

This means that the steel retains a good share of its ductility even after deep draw processing. In a collision, the material can still deform by up to 35 percent before it fails, making Frommeyer's TRIP steel particularly useful for side-impact protection. The material deforms and absorbs the energy of the impact. It also becomes very strong as it hardens, which prevents the side sections from collapsing too much and protects vehicle occupants from injury.

However, the double TRIP effect does not explain why an alloy with a manganese content of 25 percent is particularly ductile. "This is caused by small faults, called "stacking faults," in the stacking sequence of the atomic planes of the crystal structure," explains Georg Frommeyer. Stacking faults can be visualized as a shift in the neatly arranged layers of atoms.

A crystal structure can fold at a stacking fault, causing the crystal layers to stack up in exactly the opposite order starting at the shift. The fold creates a mirror plane, on both sides of which the crystal areas appear mirrored. Experts call this twinning, which manifests itself externally as extreme ductility.

The challenge to the materials researchers was to facilitate this mechanism. To initiate twinning, the stacking fault energy – a kind of ignition temperature – must be achieved. If the stacking fault energy is too high, twinning will not take place. In this case, the steel will deform by moving dislocations – line defects in the crystals caused by unordered microscopic faults in its structure. The steel can still be shaped, but ductility is much reduced, as the dislocations soon block each other and prevent any further deformation – the material breaks.

In the MnAlSi 25-3-3 alloy, the stacking fault energy is so low that twinning is quickly initiated. The steel starts to deform at around 300 megapascals. Experts refer to this as the TWIP effect, short for "Twinning Induced Plasticity."

The TWIP effect is also important for the steel used in vehicle construction. A vehicle has various crash components – for example, in the engine compartment – that are intended to

Photos: Institute of Automotive Engineering, Aachen (3, this page), Frank Vinken (2, right-hand page)

The result of the drop tower test in a lateral view: IF steel buckles six centimeters out. Conventional TRIP steel cracks because it is very hard but not very ductile. The TWIP steel from Frommeyer's furnace comes away with just a two-centimeter dent because it absorbs the impact energy particularly well.

crumple in a collision. They have to absorb a lot of energy. That is precisely what the TWIP steels do with their unique reserve ductility.

Their ability to absorb impact energy extremely quickly is even more important. The TWIP effect manifests itself even in high-speed collisions. However, the movement of dislocations depends on the impact velocity and deformation rate of the car body components. The more violent the collision, the less they propagate. In extreme cases, the steel fractures – it is unable to absorb any more energy. The ability of TWIP steel to stretch quickly is of particular interest for automobile manufacturers.

Consequently, Frommeyer's group has been working for some time with various carmakers, such as BMW AG, Daimler AG, Volkswagen AG and the Ford Research Center in Aachen. Deep draw capability and other properties are tested on prototypes and various bodywork components. Salzgitter AG and ThyssenKrupp Stahl AG are also part of the partnership. "We think that TWIP/TRIP steels harbor great potential, due to their combination of strength, ductility and density. In addition, there is a huge amount of interest on the market," says Hans Fischer, Executive Board member and Head of the Steel Division at Salzgitter AG. In his opinion, Frommeyer and his colleagues have laid an excellent foundation.

Research into these classes of steel is also being undertaken in other countries, where materials scientists are working on the practical application of these steels in the laboratories and development departments at international steel companies, such as ArcelorMittal, Hoechst-Alpine, BAO Steel in China, Nippon Steel in Japan, and companies in South Korea.

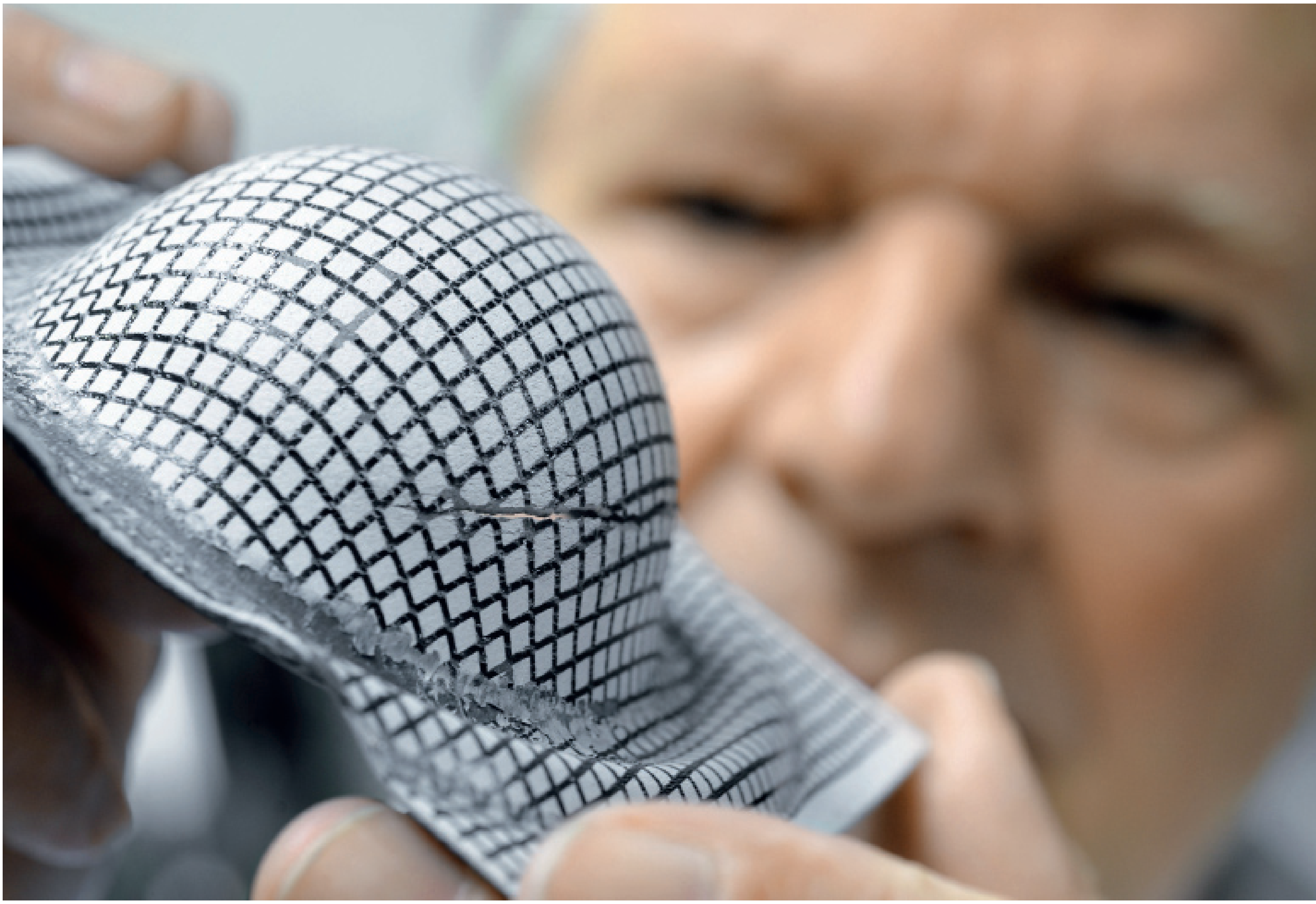
However, they will not be supplied under the name of TRIP steel. After all, the new generation of superstrength TRIP steels behaves quite differently than conventional TRIP steel, with which they now have little in common. Salzgitter AG will launch them on the market as HSD (high strength and ductility) steels. "In addition to the excellent mechanical properties, these steels are 5 to 6 percent less dense," says Dr. Matthias Niemeyer, who heads Salzgitter Mannesmann Forschungs GmbH, the research company of the Salzgitter Group. Automotive manufacturers will have a very new lightweight material to work with. After all, the car body accounts for a quarter or more of the total vehicle weight.

INNOVATION PRIZE FOR LATEST STEEL DEVELOPMENT

According to experts, using HSD steels will mean considerable weight reduction. For one thing, these steels are extremely light due to the low density of their alloying elements. For another, they are not as flexurally rigid, but are about twice as strong as the higher strength bodywork steel currently used. The new TWIP/TRIP steels can therefore be used in thinner sheets.

Niemeyer cannot yet say how much weight will be saved in the end. It depends on how the carmakers use the material. "At the moment, I'm assuming

Photos: Institute of Automotive Engineering, Aachen (3)



weight savings of between 10 and 20 percent; it might even be as much as 30 percent for some components," he says.

Recently, another lightweight steel – triplex steel – was developed at the Max Planck Institute for Iron Research, Düsseldorf, for which the researchers received an award in the category "Steel in Research and Development" as part of the Steel Innovation Prize 2009 granted by the Steel Institute VDEh.

Triplex steel consists of three phases: austenite, ferrite and nano-sized carbides, which are finely and homogeneously dispersed throughout the austenitic matrix. Georg Frommeyer's former colleague Udo Brüx, who now works with Ford Research Center in Aachen, made a significant contribution to the development of this steel.

Triplex steel is even lighter than its TWIP/TRIP cousins, by 10 to 16 percent – but it has some very impressive properties. It is harder than TWIP steel and more ductile than TRIP. This is mainly due to the finely distributed carbides, which allow the austenite and ferrite phases to deform easily, even at a high strength level. The material and the manufacturing process still need to be optimized, but in all likelihood, Triplex steel will be a bestseller in automotive manufacturing in a few years. MI 0041-4075-WT-JK ◄

Tensile test: Georg Frommeyer examines a sheet that was drawn into a hollow dome shape until the first crack appeared. The black gridlines show where the strain is strongest.

GLOSSARY

TRIP effect
Transformation-induced plasticity: Under stress, the crystal structure changes – for instance from austenite to martensite – increasing the ductility.

TWIP effect
Twinning-induced plasticity: Under stress, the crystal structure folds at a stacking fault, and a twin is formed. The process absorbs a very large amount of impact energy.

Stacking fault
Irregularity in the order of the layers of atoms in a crystal.

Crystal twin
Occurs when the order of the crystal layers is reversed at a stacking fault – for example from ABC to CBA. Two crystals are formed that grow symmetrically from a common layer.

Photo: Frank Vinken