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## **Austenitic high-strength TWIP steels for e-mobility applications**

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### **Abstract**

A new generation of austenitic stainless steels fulfills high-strength technological properties depending on their special cold work hardening mechanism in combination with their heat, acid and corrosion resistance properties. Therefore this family of steels is predestinated with their characteristics for application solutions in the area of e-mobility. Austenitic steels enable a direct material lightweight as well as an indirect construction lightweight potential with at the same time high energy absorption during crash situations. Concurrently the materials fulfill the social expectations in point of CO<sub>2</sub> emission reduction and all demands of life-cycle engineering with their 100% recyclability. Because of their alloying system (FeMnCr) the stacking fault energy results in a stable one-phase austenitic microstructure combined with a twinning induced hardening (TWIP) mechanism. As a consequence, the component manufacturing industry gets a material for cold forming with the right processing properties and desired application characteristics. Combining a special hardening mechanism, a ductile austenitic microstructure with a new alloying system, the ultra-high strength austenitic steels can help to solve the contradiction between lightweight and passenger safety for next generations of electric vehicles.

The paper will explain the history of austenitic stainless steels for automotive applications and lead over to today's requirements for battery electric vehicles. The way how to create very thin but stiff and hardened components will be given. The benefit of austenitic steels for components in battery electric vehicles like the battery housing will be worked out.

*Keywords: battery, BEV (battery electric vehicle), passenger car, recycling, safety*

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### **1 Introduction**

Since austenitic stainless steels were invented in 1912 by Benno Strauß and Eduard Maurer as so-called "V2A"-steels [1] and characterized by their natural and repassivating chromium-oxid surface layer, they offer in every decade high-performance properties to fulfill customer expectations and enable advances for next automotive generations. Derived by their name the first application reason was to create a sufficient

corrosion protection. Thereby the Ford Sedan Deluxe from 1936 represents one outstanding example of this time using austenitic stainless steels for corrosion protection in the outer skin of passenger cars. With a runtime of more than 200,000km and a lifetime of more than 80 years, the origin stainless steel patina looks like just manufactured, see figure 1.



Figure 1: Ford Sedan Deluxe with stainless steel patina after more than 80 years component lifetime [2]

Within the 1980ies, the “careless time” of fully galvanized car body [3] changed the focus of stainless steel as an automotive material away from corrosion protection as a primary question towards the application in high temperature areas like exhaust systems, manifolds or cylinder head gaskets. At the turn of the millennium stainless steels were able to implement their advantages in point of formability to create complex formed parts and to reduce the number of welded components. Two exemplary applications of this time are a strut dome of the Audi A6 or the Bugatti Veyron control arm, manufactured with a CrNiMn alloyed austenitic stainless steel (H400) characterized by a TRIP (Transformation Induced Plasticity) hardening effect, see figure 2.



Figure 2: strut dome from the Audi A8 (left) and Bugatti Veyron control arm (right)

Since then austenitic stainless steels were fixed parts of different chassis and crash-relevant car body applications. In the last years the automotive industry was driven by a continuous increasing usage of electronic assistance and entertainment systems. As a result the weight of the cars shows an increase, too [4]. But on the other hand new European regulations [5] enforce the CO<sub>2</sub> emission as from 2020 to a reduced level of 95 g CO<sub>2</sub> per driven km. Austenitic stainless steels with their special benefits of lightweight, energy absorption, formability and design possibilities can support automotive engineers to solve those contrary-seemed construction targets.

Today, new generations of ultra-high strength austenitic stainless steels reinvent themselves to be one of the big enabler for e-mobility components, fuel cell applications and hybrid-power trains.

## 2 Theoretical background of austenitic hardening mechanism

The alloying elements, their properties and their combination as well as the way of heat treatment during steel manufacturing determine the resulting microstructure which owns characteristic properties. There exist different subgroups like martensite, bainite and pearlite or combinations of microstructures known from dual-phase steels and Duplex stainless steels. But unalloyed pure iron shows initially two kinds of crystallographic microstructure: alpha-iron with a body-center-cubic (bcc) lattice called ferrite, and a gamma-iron face-centered-cubic (fcc) lattice called austenite, view figure 3.

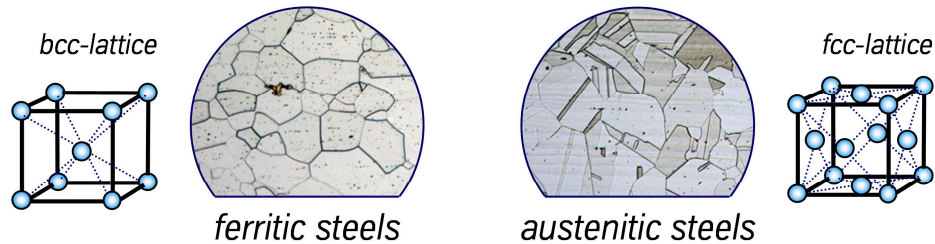


Figure 3: Difference in microstructure and lattice

With a view to the iron-carbon diagram, gamma-iron exists only at higher temperatures  $>911^{\circ}\text{C}$  because of the thermodynamic equilibrium. Special alloying elements called austenite formers like nickel, manganese, cobalt or nitrogen are necessary to expand and stabilize an austenitic microstructure also at room-temperature. Because of their characteristic microstructure, austenitic steels show different properties in comparison to ferritic steels, worked out in [6]. Thereby the austenitic stainless steels show different mechanism of cold-work hardening. In turn the cold-work hardening depends on the material-specific stacking fault energy (SFE) which is defined as a failure in the stacking order of the closed-packed lattice plane. Figure 4 presents in detail the different cold-working mechanism of austenitic steels.

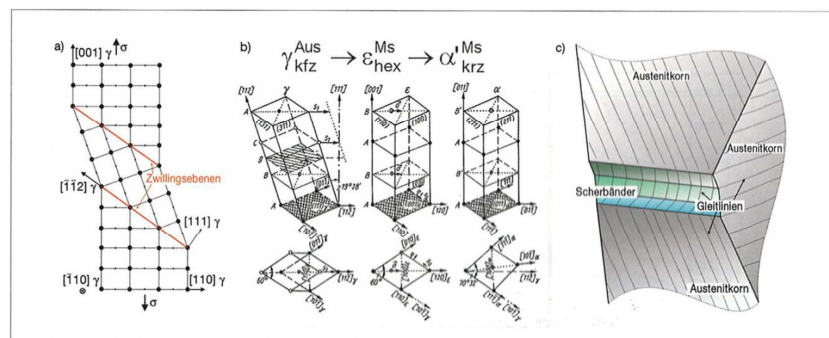


Figure 4: Cold-forming hardening mechanism of austenitic steels [7]

On the left side of figure 4, the hardening mechanism of Twinning Induced Plasticity (TWIP) with its specific SFE between  $20\text{mJ/m}^2 \leq \gamma \leq 30\text{mJ/m}^2$  is pictured. By having a stable one-phase austenitic microstructure, the TWIP effect ensures that under forming energy twin boundaries are created in the microstructure. Such twin boundaries can be described in a way that two crystals are building an undistorted grain boundary orientated symmetrically identical within a grain [8].

Compared with this, figure 4 shows in the middle of the picture the hardening effect of Transformation Induced Plasticity (TRIP) and on the right side the Shearband Induced Plasticity (SIP) mechanism. TRIP can be characterized by stacking fault energy lower than  $\gamma \leq 20\text{mJ/m}^2$  whereby the unstable microstructure affects during cold forming to change from austenite into, at least proportional martensite. The effect is well-known from CrNi-alloyed austenitic stainless steels like 1.4301 or austenitic spring steels like 1.4310.

### 3 Austenitic stainless steels with TWIP-hardening mechanism

Austenitic stainless steels showing a TWIP hardening effect are mainly alloyed beside chromium with manganese instead of Nickel as an austenite forming element. Additionally further austenite formers like carbon, nitrogen or copper can be added optionally to ensure the needed stacking fault energy. As a result of the well-defined tuning during steel composition, these steels have a full-austenitic microstructure. “Full austenitic” means that the microstructure shows in initial state as well as after forming, deformation (e.g. crash) or welding a stable austenitic microstructure without building of martensite. Because of this fact, the conditions defined in [9] are fulfilled to avoid any kind of delayed cracking. By using the TWIP hardening effect in the cold-rolling mills during steel manufacturing, different states in point of mechanical-technological properties can be manufactured with one constant chemical composition, view figure 5 and figure 6.

Material designation	Yield strength $R_{p0.2}$ [MPa]	Tensile strength $R_m$ [MPa]	Elongation at fracture $A_{80}$ [%]
	typical	typical	typical
Forta H500	530	900	51
Forta H800	800	1000	31
Forta H1000	1000	1200	13

Figure 5: Mechanical technological values of TWIP hardening austenitic stainless steels

Beside manganese, the other main alloying element chromium (ferrite former) influences the mechanical-technological values in a positive way [10], support the solubility and homogeneity of the other elements like nitrogen and build up a natural chromium-oxid passivation layer on the steel surface.

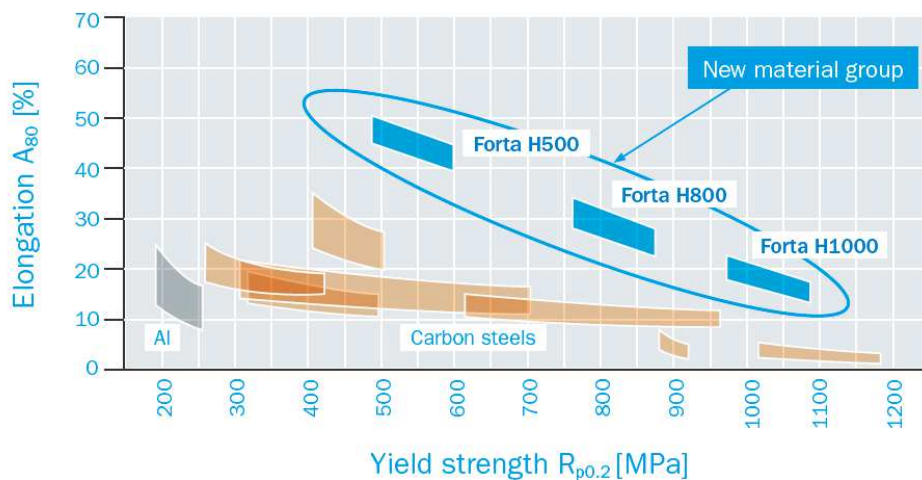


Figure 6: TWIP hardening austenitic grades in comparison to classical construction materials

Based on this passivation layer, the material doesn't need any kind of coating like a galvanizing. In combination with the traditional cathodic dip coating in the automotive manufacturing process, the passivation layer presents a good corrosion protection system even after a lattice cut or stone chipping. The chromium-oxid passivation layer re-passivates again after a local mechanical injury and avoids an undercut of the injured dip coating process.

The TWIP-hardening austenitic stainless steels feature a high crash performance connected with directly high energy absorption potential because of the well-defined strength-elongation ratio, view figure 7.

Dynamic axial-crash of a square-profile

Test conditions:

- Drop height  $h = 4.0\text{m}$
- Drop weight  $m = 433\text{kg}$
- Speed  $v_0 = 30.73\text{km/h}$

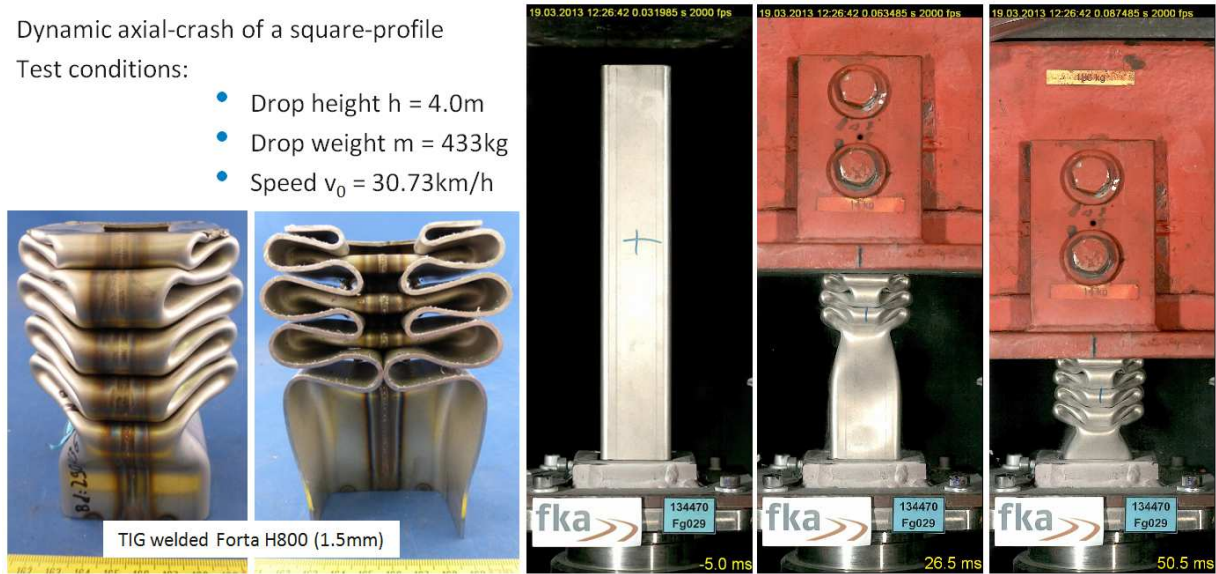


Figure 7: Crash performance of austenitic TWIP-hardening stainless steels during a high-speed axial crash

Because the TWIP effect also works during an impact, the material will harden in relation to the impact force and the therefore introduced forming degree, view figure 8.

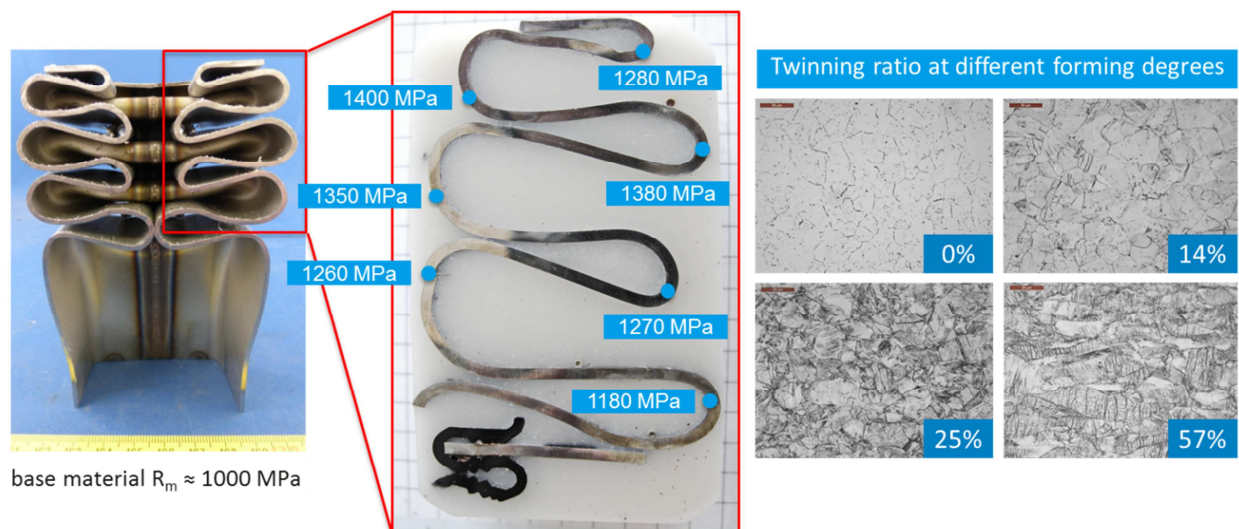


Figure 8: Crash performance of austenitic TWIP-hardening stainless steels during a high-speed axial crash

The performance of the base material is not the only demand in the weld-intensive automotive car body engineering. In fact the performance and behavior of the joined areas are also important to exploit the potential of the base materials. As a conclusion G. Meschut makes the statement that “joining technologies become a property-defining character during the manufacturing of lightweight structures” [11]. Thereby TWIP hardening austenitic stainless steels show a good weldability to all typical welding methods which are used for car body engineering like resistance spot welding or laser beam processes. The element manganese as an austenite former shows a direct influence to the character of the welds: The MnCr-alloyed TWIP steels are highly hot-crack-resistant [12], due to the fact that manganese don't build hot-crack forming phases. Because of the high manganese content it is further not allowed to use the traditional Schaeffler diagram to estimate dissimilar joints. New literature sources [13] which consider the influence of higher manganese contents have to be used.

Figure 9 points out the power transmission of similar resistance spot welded KS2-samples. The testing results can be valued as particularly suitable because of their high forces under every direction of loading and their ductile, exceptionalness plug fracture behavior.

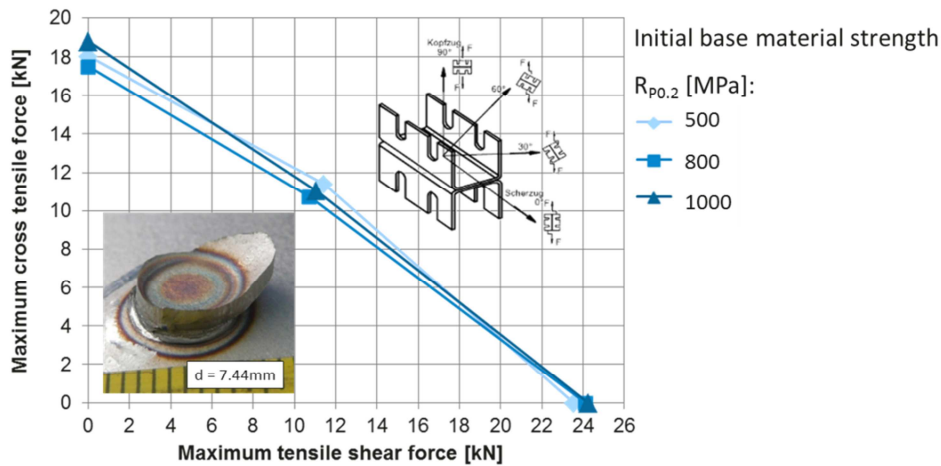


Figure 9: Power transmission of TWIP hardening austenitic stainless steels under different directions of loading

Independent from the initial base material strength, the tested forces of the spot welds show the same values. The explanation can be given with a view to figure 10, where a cross-section micrograph in combination with a hardness measurement is pictured. The sample exhibits the typical behavior of welded austenitic materials with a softening in the weld nugget. Metallurgical background of the visible softening effect is that the welding works like an annealing process and reverses locally the twins in the microstructure. The welded zone has the mechanical technological values of a base material in annealed condition.

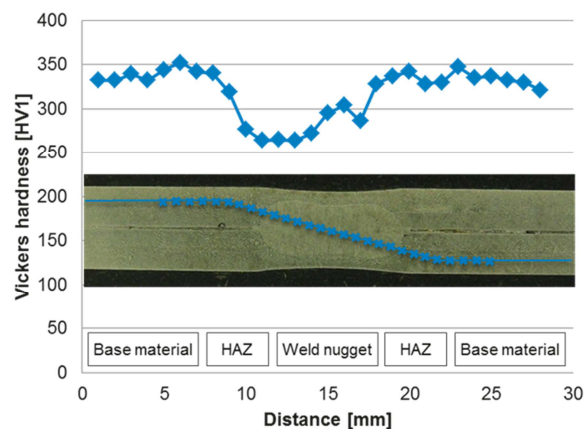


Figure 10: Micrograph and hardness curve of similar welded TWIP hardening austenitic stainless steels

In spite of the lost strength in the weld nugget, the welded zones are in general not a weak point for constructions using TWIP hardening austenitic stainless steels. The TWIP hardening effect works reversible and therefore such zones restart building twins in the microstructure again under a crash situation. As a result the material will harden locally again. All the time the microstructure remains in a stable one-phase austenitic condition. This effect can be worked out with a dynamic three-point bending test with a cup profile geometry. The profile was manufactured as a TIG-welded tailored blank of two different strength level TWIP steels ( $R_{p0.2} = 800\text{MPa}$  and  $1000\text{MPa}$ ) and finally spot-welded to a zinc-coated micro-alloyed steel as a locking plate. Figure 11 shows the resulting hardness measurement as a comparison of a non-tested and a tested profile.

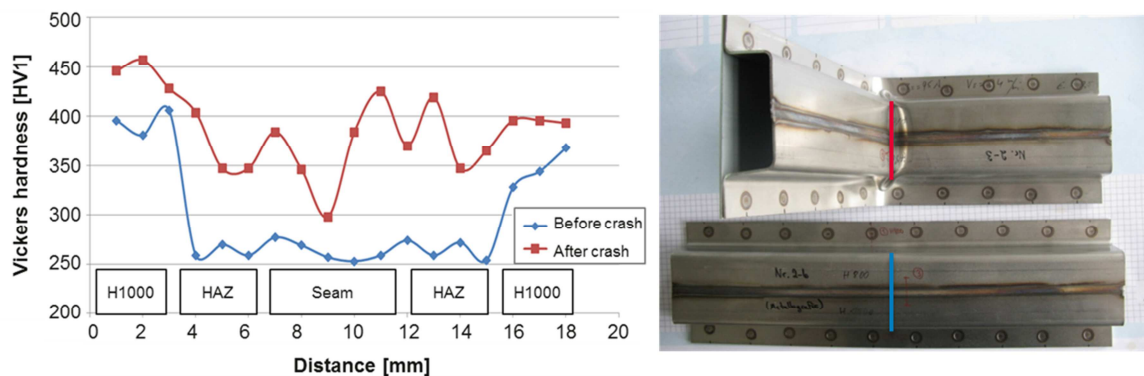


Figure 11: Comparison of hardness measurement with and without a dynamic bending test

For the non-tested profile the mentioned before softening effect takes place in the weld seam area. On the other hand the impact tested profile shows a significant hardening effect. The twins restart building in the microstructure during the impact. Further the hardening speed of the TWIP effect is much higher for the areas of a lower number of twins than in the already hardened base material.

Further details for TWIP-hardening austenitic stainless steels and typical application fields can be found in [14].

## 4 E-mobility applications

Already in 1882, Werner Siemens introduces his first electric coach car in Berlin [15] at a time when stainless steels were not invented. Today, austenitic stainless steels support battery electric vehicles (BEV), hybrid electric vehicles (HEV) as well as fuel cell hybrid electric vehicles (FCHEV) to put their advantages into practice.

One main decision at the starting point of developing a BEV is the question to use an existing platform, then it is called conversion design, or to develop a new independent car called purpose-design. In both cases austenitic stainless steels support the automotive engineer. Having a conversion design, austenitic materials can be formed into higher complex parts which can optimal customize to the existing assembly space (packaging) and reduce number of components at the same time. Component stiffness can be also increased using complex formed austenitic stainless steels. Especially when the intrusion way is limited by the conversion design, cold-hardened austenitic steels can be optimal adapted to the room situation and help to fulfill safety and crash requirements.

#### 4.1 BEV passenger compartment

Is it possible to use all degrees of freedom which are associated with a purpose designed BEV, TWIP hardening austenitic stainless steels show their benefits in point of lightweight, stiffness and safety at the same time. One example is the bionic-inspired lightweight demonstrator from e.Go mobile AG and the PEM institute of the RWTH Aachen using a TWIP hardening austenitic stainless steel with an initial yield strength of  $R_{p0.2} = 1,000\text{MPa}$ , see figure 12. This work was honored with the Gold Award of the ISSF New Technology Award in 2017.



Figure 12: Bionic-inspired lightweight demonstrator manufactured with Forta H1000 from PEM RWTH Aachen

This BEV-demonstrator is a crash-safety, high stiffness car body using bionic elements to conquer the contradiction between lightweight and passenger safety for electric vehicles. The car body fulfils the requirements of a L7E-category lightweight electric vehicle (under 450kg including battery components) as a 2+1 seater.

The benefits of the structure can be pointed out with the easy way of construction using such an ultra-high strength TWIP hardening grade: only laser processing and bending operations are needed, see figure 13.



Figure 13: Details of Figure 5 demonstrating the manufacturing advantages

Further no investment for tools is necessary, repair-friendliness is also given, combined with cost benefits for small batches and ramp-ups with nearly no cutting waste. Further the construction design is optimal coordinated with the physical material properties of austenitic stainless steels: Thermal distortion and

stresses because of welding can be successfully avoided by using this innovative modular design. The construction as well as the used material enables a significant lightweight potential. Passengers as well as the electric components are perfectly protected. Further body and material have a 100% recyclability.

## 4.2 Battery pack systems

Breaking down the idea of having a modular design and easy processing way from a complete BEV passenger compartment to a battery pack system, the Fraunhofer institute for laser technology (ILT) developed a multi-material designed battery solution in their “FSEM II”-project (german: Fraunhofer Systemforschung Elektromobilität II), see figure 14. The battery pack system was presented at the IAA 2015 [16].



Figure 14: Battery-pack system from “FSEM II”-project with Forta H1000

As mentioned before for the passenger compartment, also the battery pack system demonstrates a perfect construction aligned with the base material. The construction supports the austenitic microstructure of the used steel with a distortion-less and nearly stressless modular design. On the other hand, the TWIP hardening austenitic stainless steel offers necessary heat resistance properties to the component. In this case heat resistance properties specially mean that stable mechanical-technological values are present also at higher temperatures like a fire drill case. Additionally the austenitic stainless steels in general support a high resistance against external loads (crash situation) and internal defects (like an escape of battery liquid). Not for nothing the austenitic stainless steels are well-known as RSH-steels: “Rost-“ (rust), “Säure-“ (acid) and “Hitze-“ (heat) resistance steels. Taking these benefits into account, the TWIP hardening austenitic stainless steels help to fulfil the various requirements of the European regulation ECE-R100 [17] for electric vehicles perfectly.

## 5 Conclusion

Austenitic stainless steels with a TWIP hardening effect can be one big enabler for battery electric vehicles because of their outstanding properties but cost-efficiency at the same time. Various design possibilities are feasible.

The mentioned out materials are available in a big industrial scale as the so-called “Forta H-series” and successfully passed all tests of the steel iron data-sheet SEP1240 and SEP1220. Moreover additional tests like dissimilar joining also under corrosion atmosphere or tribology investigations demonstrate the operational suitability for the new material group.

Outokumpu as a world class leader for stainless steels supports their customers with material cards and simulation data for forming as well as for crash and attends the development from the first material tests to serial start of production. More than 85% of the production is made out of recycled scrap showing at the same time 100% recyclability.

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Stefan Lindner studied mechanical engineering (Dipl.-Ing.) at Hochschule Niederrhein finishing in 2008. With the addition of an International Welding Engineer (SLV Duisburg, 2008), he started working in the department of application development (R&D) at formally ThyssenKrupp Nirosta, now Outokumpu. While working full time, he pursued successfully studying “Metallurgy and metal forming” (M.Sc. at University of Duisburg-Essen, 2012-2015). Since 01/2015 he worked as a Senior Technical Manager for the areas of Automotive / Transportation / New Applications at Outokumpu R&D. Further priorities in his work are Six Sigma (BlackBelt), project management, patent system and new joining technologies for Multi-Material-Design.