Ultra-high-strength stainless steels for automotive engineering

Outokumpu experts explain how a new generation of stainless steels is opening up new design possibilities for automotive engineers.

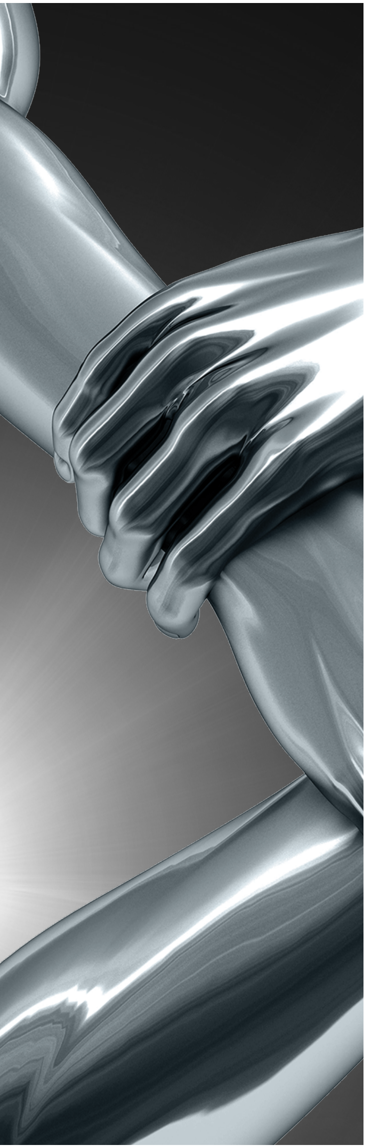
Introduction

The automotive industry is facing major challenges. On one hand it needs to reduce CO_2 emissions, especially by weight saving. But at the same time, passenger safety must be increased. In addition, new megatrends such as alternative drive technologies with a special focus on electric mobility or autonomous driving require a rethink in vehicle development.

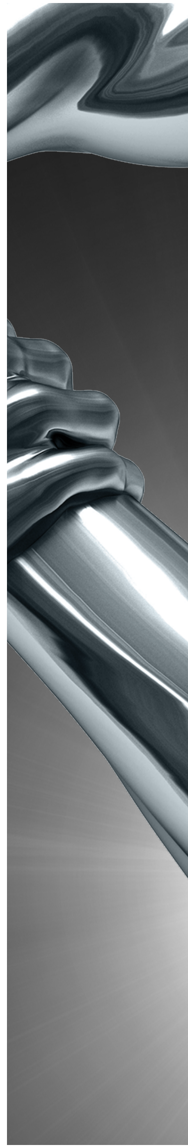
Fig. 1. 22MnB5 (left) and Forta H1000 (right).

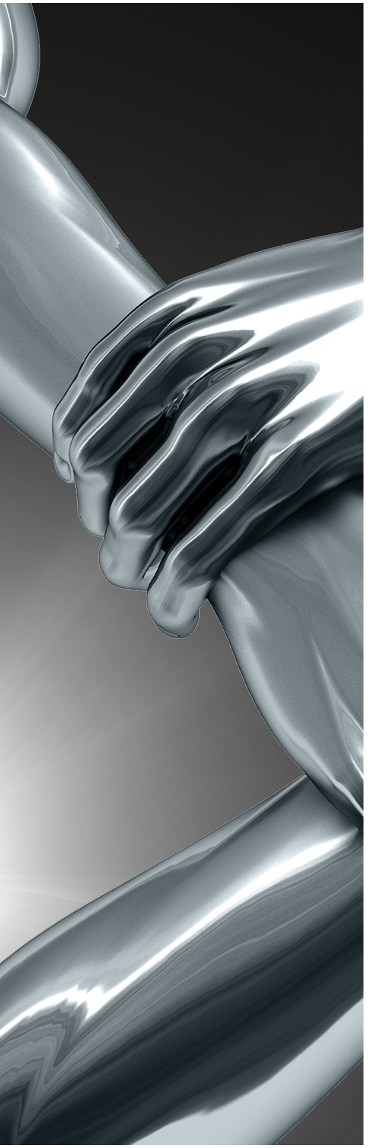
High-performance materials such as ultra-high-strength stainless steels are set to play an important role in this evolutionary process. These highly strain-hardened materials demonstrate new possibilities for lightweight structures that also offer improved crash performance and a reduced carbon footprint due to longer component lifetime and excellent recyclability. Their exceptional formability and good weldability also enables reliable component production processes with optimized cycle times. This results in cost advantages in the overall manufacturing process.

However, to optimize the advantages of these new materials requires suitable production methods allied to a tailored structural design. Additional advantages such as resistance to high temperatures and corrosion allow this material to be used for various applications, which is why stainless steel has been an essential part of the automotive world for around 90 years.



Contents





Protection provided by a self-passivating layer

According to DIN EN 10020, stainless steels must have a chromium content of at least 10.5 percent by weight. In addition to chromium, other alloying elements and their content determine the steel microstructure, from which its respective physical and mechanical-technological properties are derived. Due to the significant proportion of chromium, stainless steels have a non-oxidizable, re-passivating chromium oxide surface layer that has a naturally high resistance to corrosion. Therefore, cost-intensive additional coatings such as electrolytic galvanizing are not necessary. This makes recycling easier and reduces CO_2 emissions.

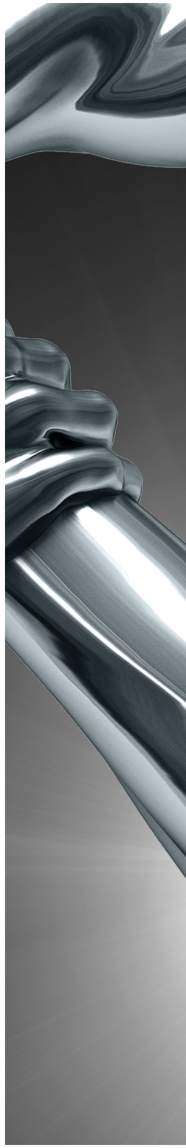
A sustainable material

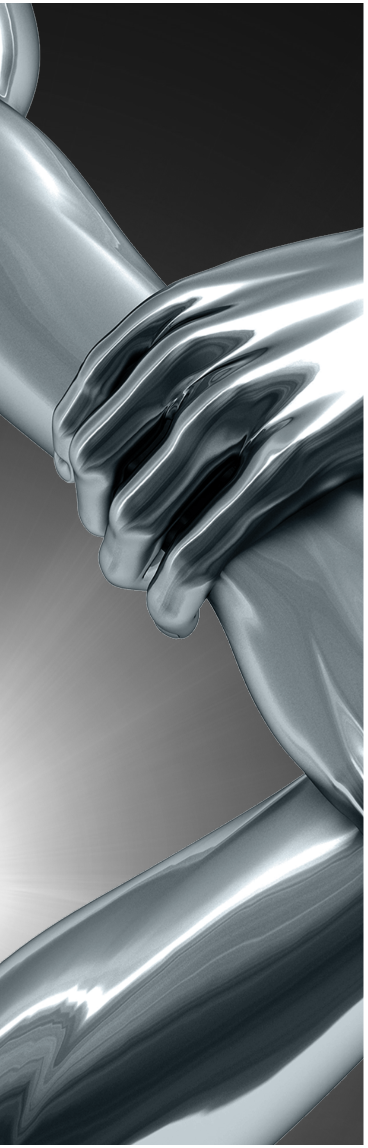
When manufacturing stainless steels, a blast furnace process is not required. Instead, alloyed steel scrap is melted in an electric arc furnace (EAF). The amount of scrap used is very significant, in excess of 85 percent, and the resulting material is 100 percent recyclable at the end of its life. This high percentage of recycling enables significant savings in CO_2 emissions during material production compared to other construction materials such as coated steel or aluminum. Stainless steels are the most frequently recycled materials worldwide, and they also have an established scrap and reutilization cycle

Alloying determines microstructure

Depending on the alloy composition of stainless steels, microstructural properties are obtained that are stable at room temperature and which result in a ferritic or martensitic microstructure. Since the ferrite-forming element chromium is the only main alloying element in this group of ferritic and martensitic stainless steels, they are also known as chromium steels.

By adding austenite-forming elements such as nickel, manganese, but also carbon or nitrogen, austenitic stainless steels can be produced. A further group of stainless steels is the duplex materials, which have a balanced combination of a ferritic and austenitic microstructure and therefore have special corrosion and toughness properties. They are characterized by a high proof strength even in annealed condition.





Automotive applications

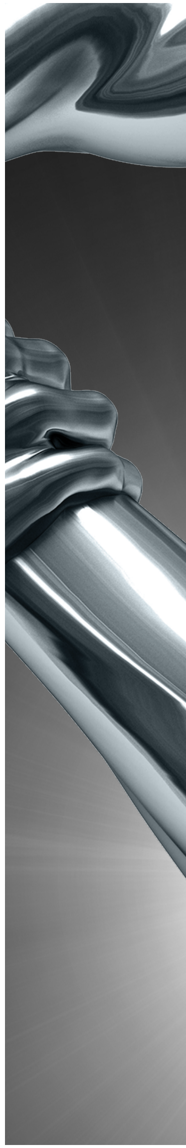
For many decades, stainless steels have been established as high-performance materials in automotive engineering where their wide range of properties makes them suitable for a variety of components. These include exhaust systems, airbag pipes, gasoline injection systems, complex-shaped filler necks, cylinder head gaskets and trims, as well as crash-relevant structural parts or chassis components.

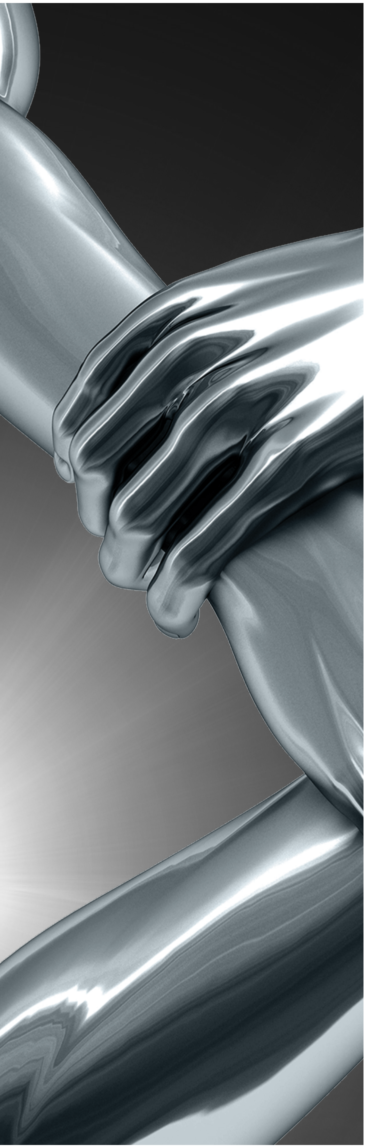
While historically stainless steel was used for vehicle bodies, the focus from the mid-1970s was on its excellent heat and high temperature corrosion resistance, which are decisive for applications in the exhaust system.

By the turn of the millennium, stainless steels were increasingly used in automotive applications due to their remarkably good forming properties. Their high ductility enables the production of more complex shapes that can reduce the number of individual components in a structure with a consequently lower number of welding operations and an increase in component stiffness. Application fields are strut domes, crash boxes or seat cross members. Furthermore, the high ductility guarantees excellent crash safety. When considering the ratio of energy absorption capacity to specific weight, stainless steel is superior to all materials which are available on a large industrial scale.

Fig. 2. Porsche 911 produced in 1967 with a stainless steel body (exhibited in the transport center of the Deutsche Museum).

Focus on ultra-high-strength material properties
In recent years, the focus has shifted towards ultra-high-strength material properties. Ultra high-strength stainless steels enable lightweight engineering due to reductions in wall thickness; compared to unalloyed steel, 35 to 50 percent weight savings can be achieved depending on the component. By cold forming, the desired component properties can be achieved without impacting the positive properties.





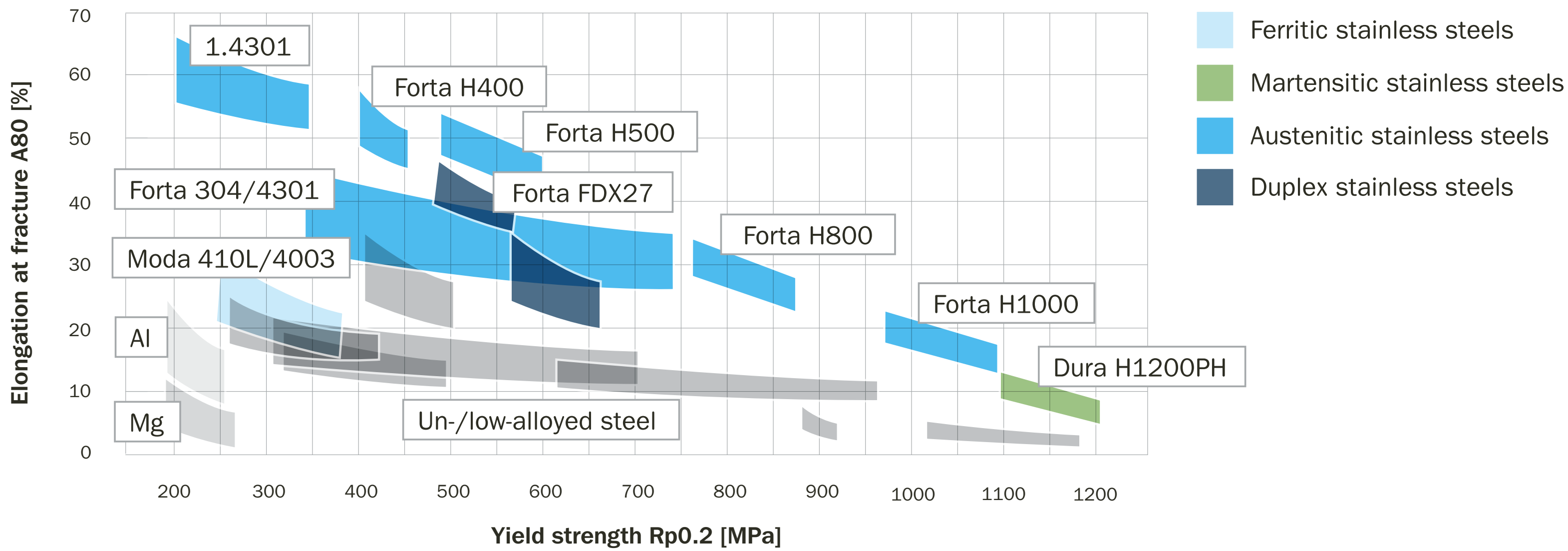
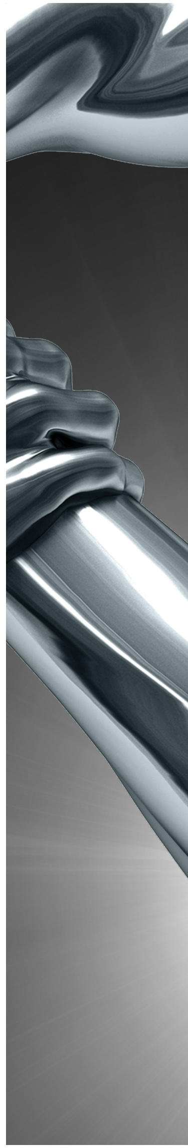


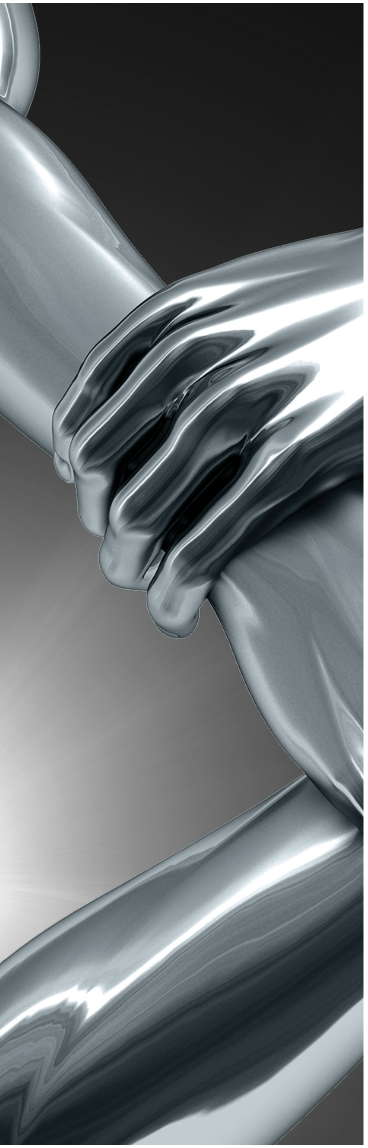
Fig. 3. Elongation at fracture over yield strength diagram of metallic materials.

Even in annealed condition, stainless steels have a high proof strength (yield strength) and high tensile strength. By systematic work hardening, their proof strength and tensile strength can be further increased, so that they can be classified into the group of high-strength (tensile strength R_m ≥ 700 MPa) and ultra-high-strength construction materials (tensile strength R_m ≥ 950 MPa).

In addition to high proof and tensile strengths, stainless steels are also characterized by a high elongation at fracture, which enables the forming of very complex components as well as very good energy absorption capacity under crash loads. Depending on the microstructure they can have different deformation and strain hardening mechanisms.

Due to the high proof strength in combination with the high elongation at fracture, in most cases ultra-high-strength stainless steels enable significant material savings compared to other construction materials used in the automotive industry.





Based on the respective microstructure at room temperature, the high-strength stainless steels can be divided into three product groups: martensitic steels, ferritic-austenitic duplex steels and austenitic steels, which in turn are subdivided into full austenitics and metastable austenitics. These product groups are available as metal sheets produced by cold rolling on a large industrial scale and are approved in terms of process technology for many series applications. In addition, most of the stainless steel grades are also available as hot strip or heavy plate as well as precision strip and long product (e.g. rod material).

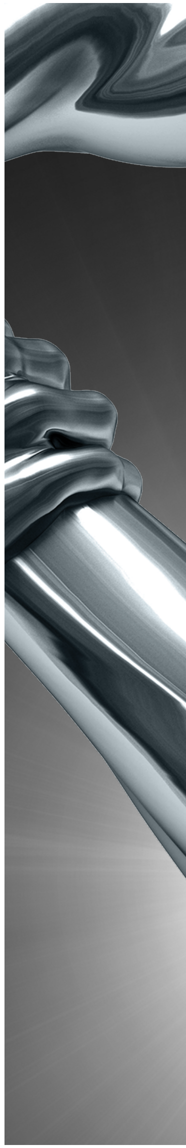
Strengthening mechanisms – TRIP and TWIP

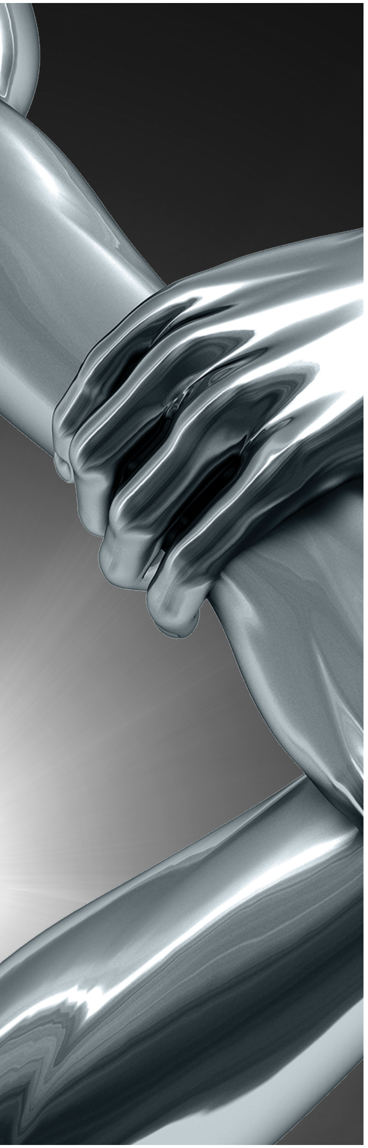
The high strength values of ultra-high-strength austenitic stainless steels are already provided by their alloying system and, depending on the type of microstructure, can be achieved either by deformation mechanisms during work hardening (austenitic and duplex stainless steels) or by suitable heat treatments in steel production as well as component manufacturing (martensitic stainless steels). In addition, increases in strength for cold strip together with improved flatness can be achieved by skin-passing and tension leveling.

The austenitic microstructure has the greatest work hardening potential and at the same time the highest residual elongation at fracture values. It is important to distinguish between between metastable austenitics which harden during the cold-forming process by the formation of martensite (TRIP) and full austenitics that harden during the cold-forming process by the formation of deformation twins (TWIP).

Metastable austenitics have good corrosion resistance and high strength and elongation at fracture. Due to the formation of martensite, these materials can have a tendency for delayed cracking when subjected to a high degree of forming. This must be considered when designing components. Basically, metastable austenitics can be used to realize a wide range of component geometries with high strength and good energy absorption capacity, while at the same time having good corrosion resistance.

Compared to metastable austenitic steels, fully austenitic steels have an even better work hardening potential due to the deformation mechanism of twin formation as well as the highest strength and ductility values. The addition of austenite-forming alloying elements such as manganese (Mn), nickel (Ni) or copper (Cu) stabilizes the austenitic structure so that the material does not form any martensite even at the highest degrees of forming or during similar levels of welding.





The work-hardened austenitic microstructure is non-magnetic and shows no susceptibility to delayed cracking. Fully austenitic steels are suitable for components with complex geometries which at the same time require a high energy absorption potential.

Work hardening of ferritic-austenitic duplex stainless steels

Duplex steels have a precisely balanced ferritic-austenitic hybrid microstructure. This quantitative ratio, adjusted by the combination of alloying elements and suitable heat treatment, is decisive for their range of properties. In general, they are characterized by a combination of high strength and elongation at fracture, high resistance to delayed cracking as well as good corrosion resistance due to the addition of molybdenum. The work hardening mechanism that acts during the cold forming of duplex steels corresponds to the TRIP mechanism of metastable austenitics.

Due to the reduced content of nickel, which often fluctuates in price, duplex steels are significantly more price-stable than common CrNi alloyed metastable austenitics. Duplex steels are suitable for safety-relevant components that are subject to corrosive conditions. For components with complex shapes, certain restrictions must be noted.

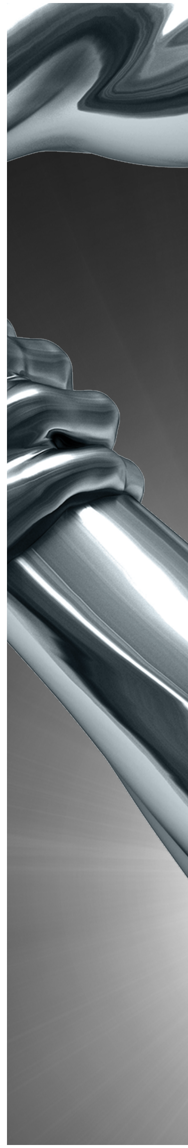
Forta H-Series

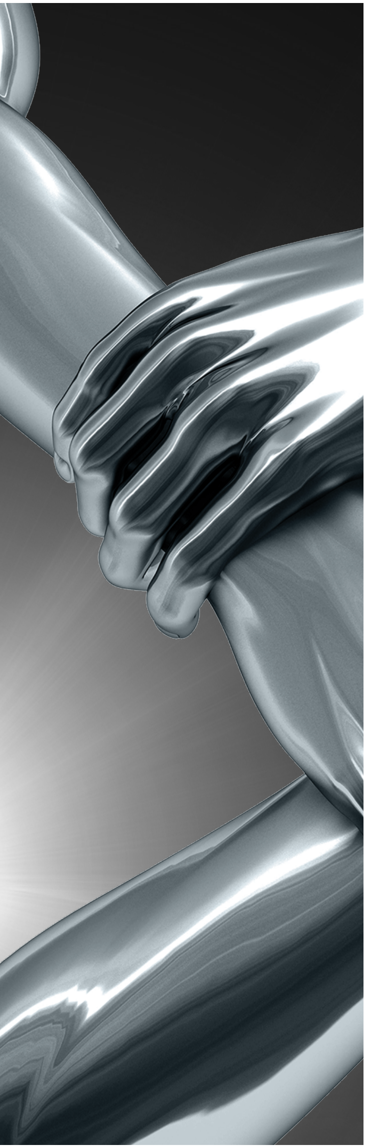
A new group of ultra-high-strength stainless steels with properties optimized for vehicle construction is represented by the fully austenitic Forta H-Series. This material group can be divided into the annealed variant “Forta H500” (1.4678) and the two work-hardened variants “Forta H800” (1.4678 +CP700) and “Forta H1000” (1.4678 +CP900). The chemical composition of all three variants is identical.

Characteristic property values for material 1.4678. Table 1

Material	Yield strength $R_{p0.2}$ [MPa]	Tensile strength R_m [MPa]	Elongation at fracture A_{80} [%]
1.4678	530	900	51
1.4678 +CP700	800	1000	31
1.4678 +CP900	1000	1200	13

In addition to chromium, austenite-forming manganese is the main alloying element, while at the same time nickel, an alloying element – which fluctuates strongly in price – can be dispensed with completely. This ensures high price stability over a period of serial production.





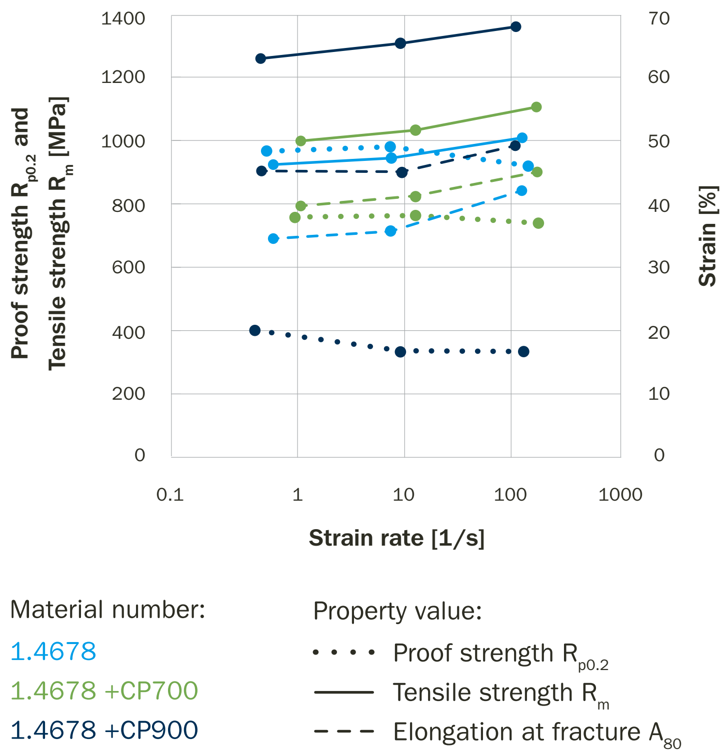
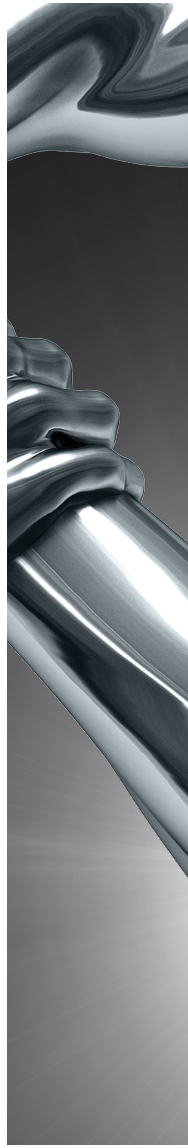


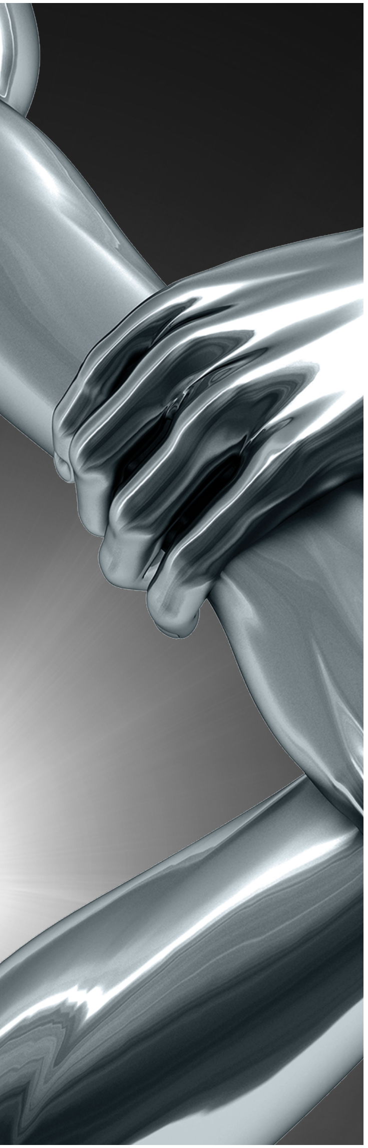
Fig. 4. Property values as a function of strain rate.

The stainless steel material 1.4678 was specially designed for use in composite automotive structures. In combination with cathodic dip coating (CDC), the material develops an excellent corrosion protection system and reduces the electrochemical potential difference to an uncritical level compared to other metallic materials commonly used in automotive engineering, such as unalloyed and low-alloy steels or aluminum. The natural passivation layer prevents the coating from dis-bonding even if the CDC is locally damaged since the layer has re-passivating properties. This means the layer re-forms after mechanical damage, as is common with all stainless steels. The balanced corrosion behavior of the material in the overall system has a positive effect on the safety and durability of the entire vehicle.

In addition, the material 1.4678 offers very good active protection in the event of a crash. This is because of its high strength and elongation at fracture and an increased active energy absorption capacity due to the formation of twins. It is possible to harden it by cold forming to over 2000 MPa tensile strength. This level of strength is not only an advantage in the event of a crash but can also be used in component design. The work hardening potential of the material is significantly increased at higher strain rates or under multiaxial stress conditions.

This extraordinary energy absorption potential means that components made from material 1.4678 can be made thinner than standard solutions, thus offering lightweight potential. Since the material can actively absorb intrusion energy to a considerable extent, the amount of energy transmitted to the surrounding components via load paths is lower. This means that adjacent components can also be made thinner so that additional weight can be saved. Clearly, with this new material group, completely new application areas for lightweight automotive construction can be explored.



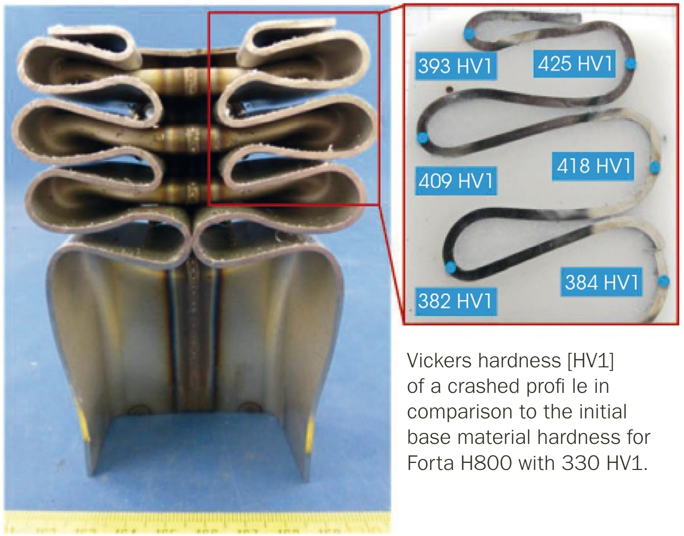


Crash behavior

Ultra-high-strength stainless steels stand out for their excellent energy absorption potential under crash loads because of their combination of a fully austenitic micro-structure and the TWIP strain- hardening mechanism that provides an enormous increase in strength. Due to the stable microstructure of fully austenitic stainless steels, particularly high intrusion resistances in a crash can be generated.

Although the initial strength of the strain-hardened fully austenitic stainless steels is lower than for already hot-formed materials ($R_m \approx 1500$ MPa), the strength increase resulting from the impact energy creates a strength which significantly exceeds that of the hot-formed materials. Therefore, a weight saving of 35 percent can be made in the example of a B-pillar in comparison to hot-formed materials, enabling the realization of lightweight design.

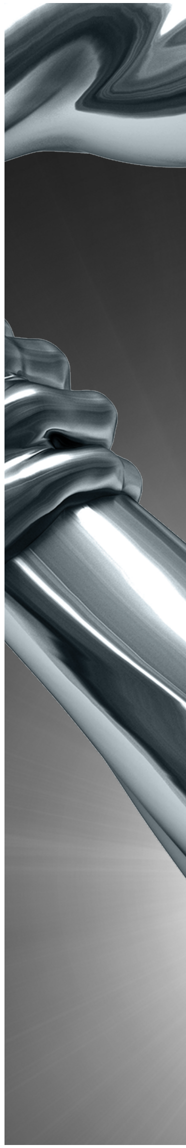
One key aspect for both lightweight design and also vehicle safety is the connection technology. Only when the joints can transfer high forces will the full potential of the base materials be realized. With closer examination of the dynamic behavior of welded components, a further advantage of austenitic stainless steels becomes obvious: Initially the ductile welding area prevents undesirable failure inside the weld seam under sudden loads. At the same time, by introducing forming energy into the joining area, renewed strain hardening and therefore a local increase in strength of the welding zone to the level of the base materials occurs.

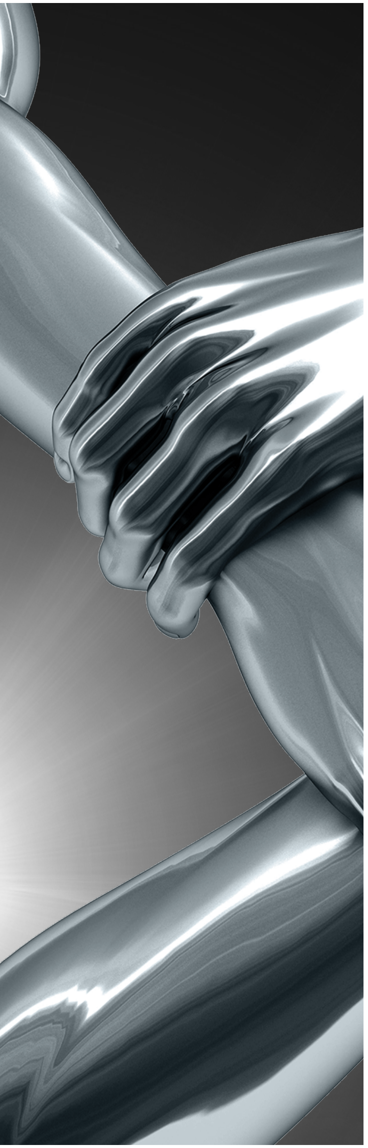


Vickers hardness [HV1] of a crashed profi le in comparison to the initial base material hardness for Forta H800 with 330 HV1.

Fig. 5. Hardening of an axial crash profile.

The high ductility of the weld seam or rather the spot weld in combination with the strengthof the base material enable high energy absorption potential as well as crack-free forming of the component. At the same time, the increase in strength of the weld seam under deformation provides it with sufficient resistance to withstand the external load. The properties of austenitic stainless steels in both the base material and the welded areas means that they can meet the highest safety demands for intrusion- and crash-relevant structural parts.





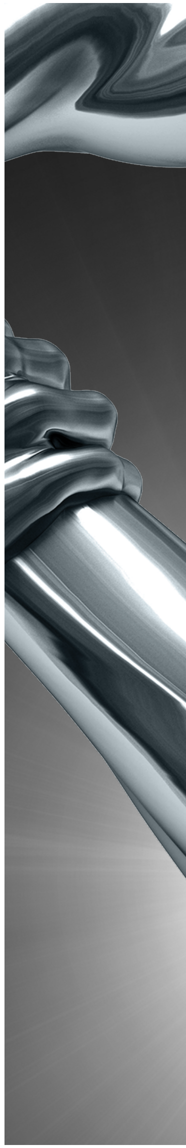
Corrosion protection behavior

The structural material must perform safely when exposed to various environmental influences over the complete component lifetime. The corrosion behavior of the materials used both on their own and in combination with other materials also has a significant influence on passenger safety.

Whereas with unalloyed steels, a porous iron-oxide or rust layer forms on the material surface because of the reaction between iron with the surrounding air, stainless steels have a passive layer which protects them against corrosion. This results from the chromium content of stainless steels. This causes a reaction between chromium and atmospheric oxygen on the material surface, which forms an impermeable, non-oxidizable passive layer that will re-develop in the case of damage.

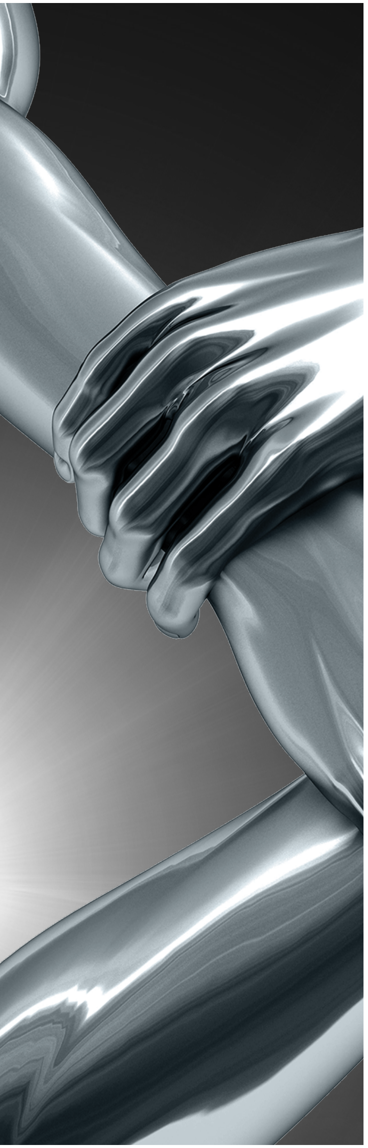
Stainless steels are nevertheless not always protected against corrosion. Depending on the chemical composition of the specific stainless steel, a small inhomogeneity of the passive layer, for example during contact with an aqueous chloride solution, can be a potential starting point for chloride-induced corrosion. Such inhomogeneities can be in the form of foreign particles resulting from mechanical processing. Accumulation of chlorides, decreasing pH values and unfavorable ratios of the anode-cathode area result in progressive pitting corrosion. By a suitable combination of alloying elements, the corrosion resistance of stainless steels intended for use in contact with aggressive media can be significantly improved.

If at risk of contact with chloride-containing media, the material must be additionally protected against corrosion with a cathodic dip coating (CDC). The paint-adhesion of the untreated surface of the material 1.4678 and its strain-hardened variants is very good despite the increased strain hardening resulting in a decreased surface roughness. Because of the corrosion inertia of the base material, infiltration of the dip coating layer does not occur even if the CDC is damaged, for example by stone chipping, as the exposed surface immediately re-passivates.



Usually, the dip coating of the complete automotive vehicle structure takes place in the joined condition. Due to its chemical composition and its exclusively occurring strain hardening by twinning without martensitic phase transformation, the material 1.4678 is not vulnerable to delayed cracking even during the manufacture of complex component geometries with significant forming processes.

Because of the application of lightweight concepts and for safety reasons, multi-material design is a preferred approach in automotive engineering. This results in different materials coming into electrochemical contact. Therefore, the electrochemical potential of the material 1.4678 was approximated to the free corrosion potential of other constructional materials used in automotive engineering. The target is to reduce contact corrosion or rather galvanic corrosion in the joined areas of adjacent components. By the choice of suitable welding procedures and filler metals it is even possible to further moderate the corrosion tendency between two different noble materials when they are joined together.



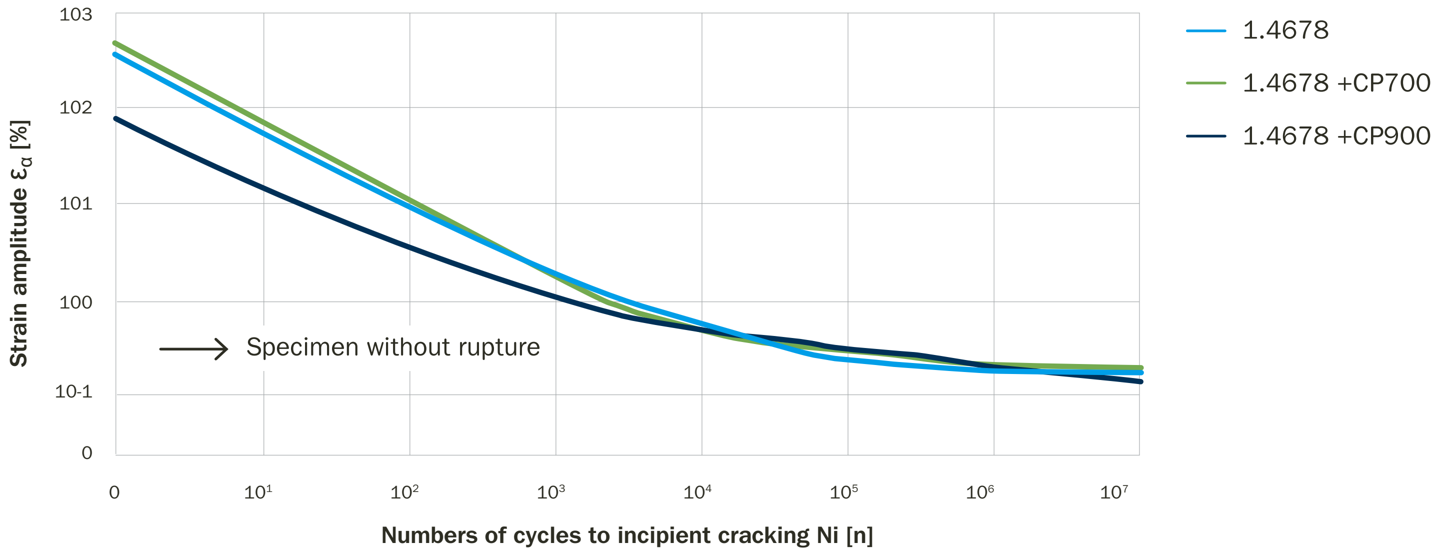
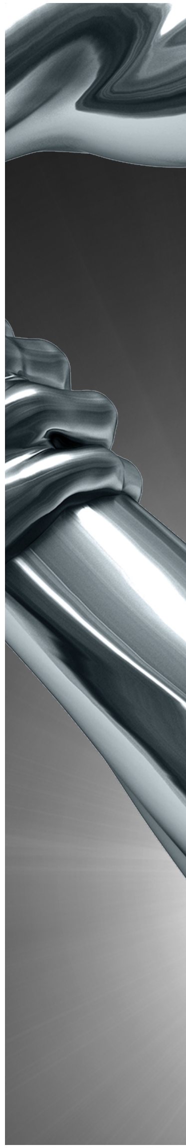
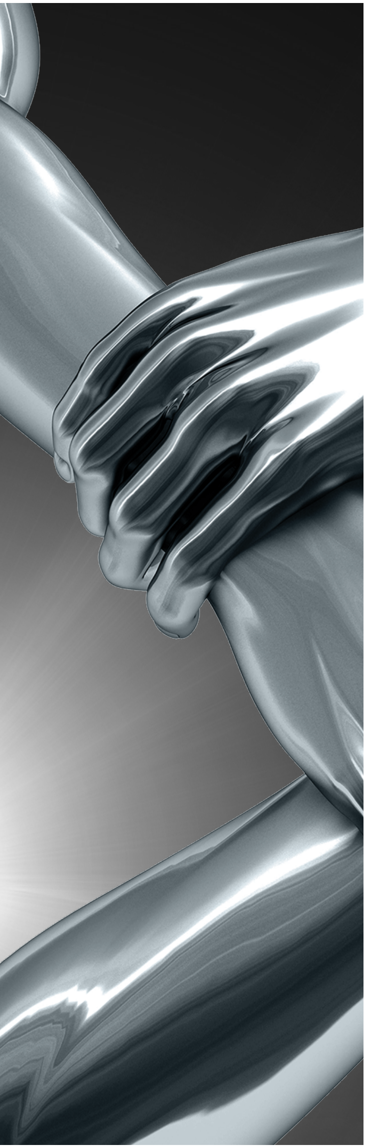


Fig. 6. Wöhler curves for different strain-hardening levels for the fully austenitic stainless steel 1.4678 according to SEP1240.

Fatigue strength

Even more important than static strength values, cyclic values such as fatigue strength make a significant contribution to the evaluation of durability and operating life of the component, besides its corrosion resistance. A component can, in principle, withstand any number of load reversals (cycles) below the fatigue limit of its material, while higher loads (above the fatigue limit) ultimately lead to component failure. The fatigue strength is expressed by a number of cycles that can be achieved and as a function of the load type as well as the static load. The high strength of strain-hardened austenitic stainless steels under static load is also illustrated in the cyclic Wöhler curve.





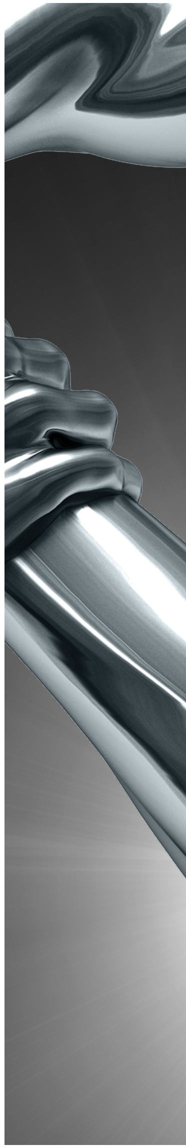
Overall cost calculation

The material costs of stainless steels are made up of the base price together with the alloying surcharge. Because of the significant proportion of alloying elements, the raw material cost elements in the purchase price are usually higher than for low or unalloyed steels. However, it is vital to assess the total costs of the manufactured stainless steel component in the context of the higher lightweight potential, the higher component safety, the longer component lifetime and the advantages for recycling at the end of the component lifetime. When all these factors are taken into consideration, then the cost advantages of ultra-high-strength stainless steels become clear.

Applications in automotive engineering

Because of their mechanical-technical properties, ultra-high-strength stainless steels offer additional advantages for the design of structural components in addition to lightweight construction. This includes the possibility for a substantial reduction in material thickness. Especially in the area of tube and profile construction methods, stainless steels can offer thin wall thicknesses combined with a geometrical high stiffness. This capability has been used previously for roll-over bars in passenger vehicles as well as frame construction in commercial vehicles.

Compared to the currently used high-strength cold-formable steels, a weight reduction of 20 to 30 percent is feasible. For complex parts like wheelhouses, up to 50 percent of the weight can be saved with ultra-high-strength stainless steels compared to steels with a similar formability, such as conventional deep-drawing steels.



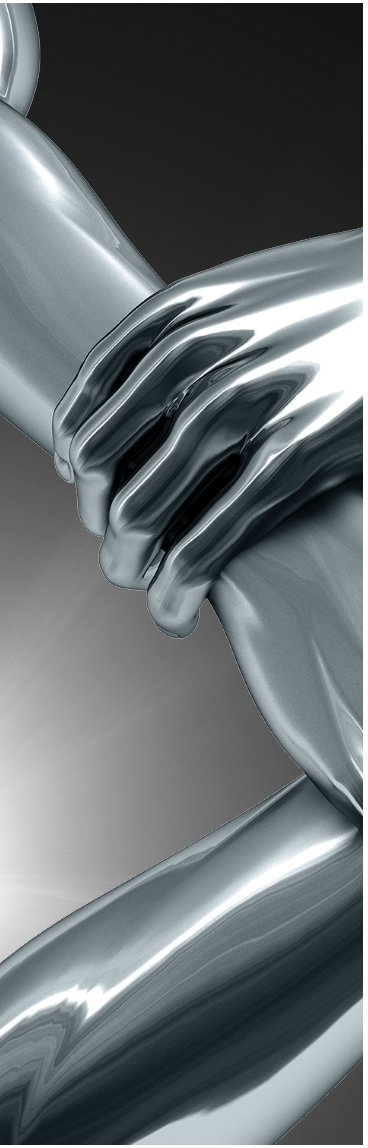


Fig. 7. Chassis carrier of Audi A8 manufactured with Forta H400.

Chassis

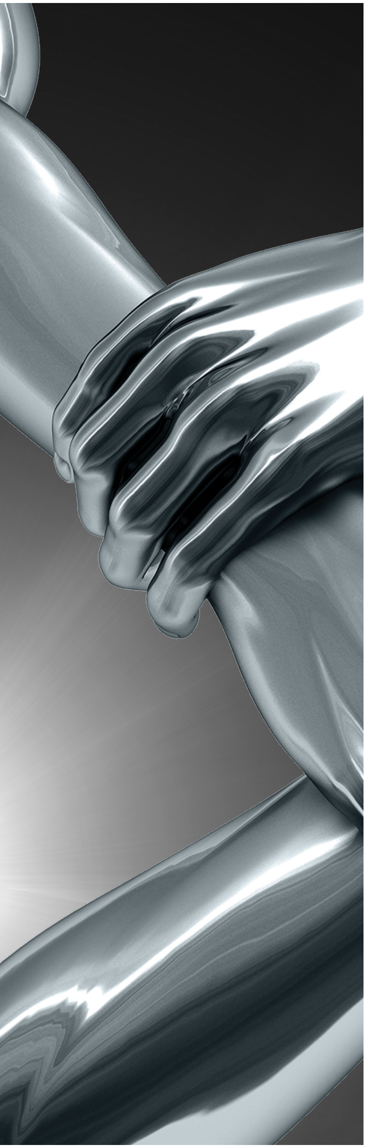
Chassis or undercarriage components must fulfil demanding requirements to bear and support the complete vehicle and its loading weight and make an essential contribution to driving dynamics and safety. In operation, they are exposed to significant forces and vibrations and are also affected by stone chipping and water splashes. This means that as well as being strong, components must be exceedingly corrosion-resistant so that driving safety is ensured even in the event of damage by stone chips or exposure to road salt.

Furthermore, the highest design requirements are related to the fatigue strength of the materials and their joining systems. This is because as well as the permanent load due to the vehicle weight, components are also subjected to vibrations, traction forces, braking and steering forces.

Because of their corrosion resistance in combination with strength and good processability, high-strength stainless steels are suitable for chassis components. Their suitability has already been verified in series applications. The metastable austenitic grade 1.4376 (Forta H400) is especially recommended because it has good fatigue behavior in addition to the previously mentioned properties.

In the undercarriage support of the Audi A8, the beneficial properties of grade 1.4376 were utilized to design the complete component with thicknesses between 1.0 mm and 3.0 mm.

The same material was also used for the control arms of the Bugatti Veyron and Chiron because of its high robustness, corrosion resistance, good formability and weldability.



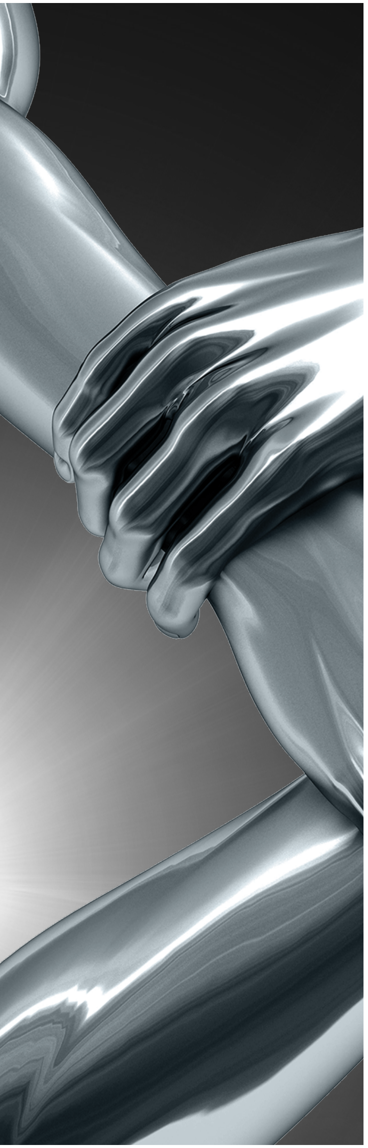
Crash-relevant structural parts

To protect the safety cell during side impacts, vehicle B-pillars are usually executed as multiple shell constructions. Hot-formable steels with a low elongation at fracture are the current state-of-the-art for the outer shell. When reaching the maximum force, fracture of the outer shell can occur which is why highly ductile and strain-hardening stainless steels are the materials of choice in the area of the B-pillar foot and the inner shell.

The crash management system consisting of the bumper and crash boxes must absorb the energy from a crash in the vehicle's longitudinal direction. The highly ductile and strain-hardening austenitic stainless steels can achieve their full energy absorption potential inside crash boxes. One example for such a crash management system is seen inside the Porsche Carrera GT.

For the hydroformed dashboard cowl inside the Porsche Panamera, which is manufactured from laser-beam welded tube, the material 1.4376 (Forta H400) was used (Fig. 29).

Fig. 8. Internal high-pressure formed dashboard cowl of Porsche Panamera manufactured with Forta H400.



Seat structures and interior

For seat structures the safety aspect is paramount, even though specific components like headrest tubes are located within the visible area. As an environmentally friendly alternative to chromium-plated unalloyed steels, the application of high-strength stainless steels is recommended as they provide a visually appealing surface without additional treatment. At the same time, they offer effective protection for the vehicle passengers because of their high energy absorption potential. For safety-critical seat components which are not located in the visible area, the fully austenitic ultra-high-strength stainless steel 1.4678 that provides increased energy absorption compared to other high-strength stainless steels can offer the maximum possible combination of safety and lightweight construction.

Electric mobility

Designers of battery electric vehicles (BEVs) are faced with complex construction requirements. Besides the necessary crash safety in the form of low intrusion, the battery cells must be protected against environmental effects like corrosion, temperature and stone chipping. Any deformation must be absolutely avoided because of the potential danger of spontaneous combustion (self-ignition). Ultra-high strength stainless steels have the necessary spectrum of characteristics to fulfil these requirements.

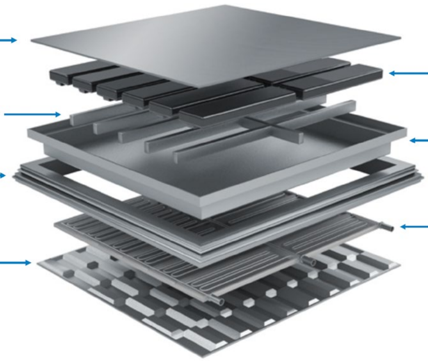


Fig. 9. Battery pack manufactured with ultra-high-strength stainless steel.

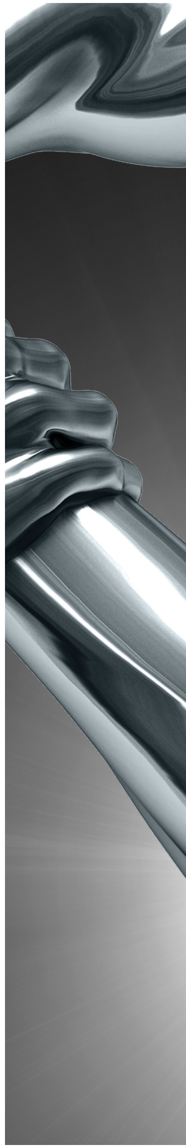
A deep-drawn shell construction manufactured from stainless steel enables the design of a geometrically simple, scalable, production-capable and cost-effective battery compartment. Because of the high tendency for strain hardening, it is possible to manufacture a suitable battery compartment using highly ductile ultra-high-strength stainless steel shell components.

The high heat resistance of stainless steels is already utilized for vehicle exhaust systems as well as heat shielding plates. This characteristic is also crucial for BEVs, as in the case of thermal damage to the battery the compartment must withstand periods of over 10 minutes without structural failure to enable the safe rescue of the occupants. In this way, the use of stainless steel provides a direct contribution to passenger safety.

Fig. 10. Hybrid fuel tank (company TecROI) manufactured with special metastable austenitic steel.

Fuel tanks

Since the 1990s, metastable austenitic stainless steels have been in common use for fuel tanks in both passenger vehicles and commercial vehicles. Their excellent formability enables the creation of complex geometries which can otherwise only be produced with plastics manufactured by an expensive extrusion process.



Summary

Why the automotive industry is driving ahead with ultra-high-strength stainless steels

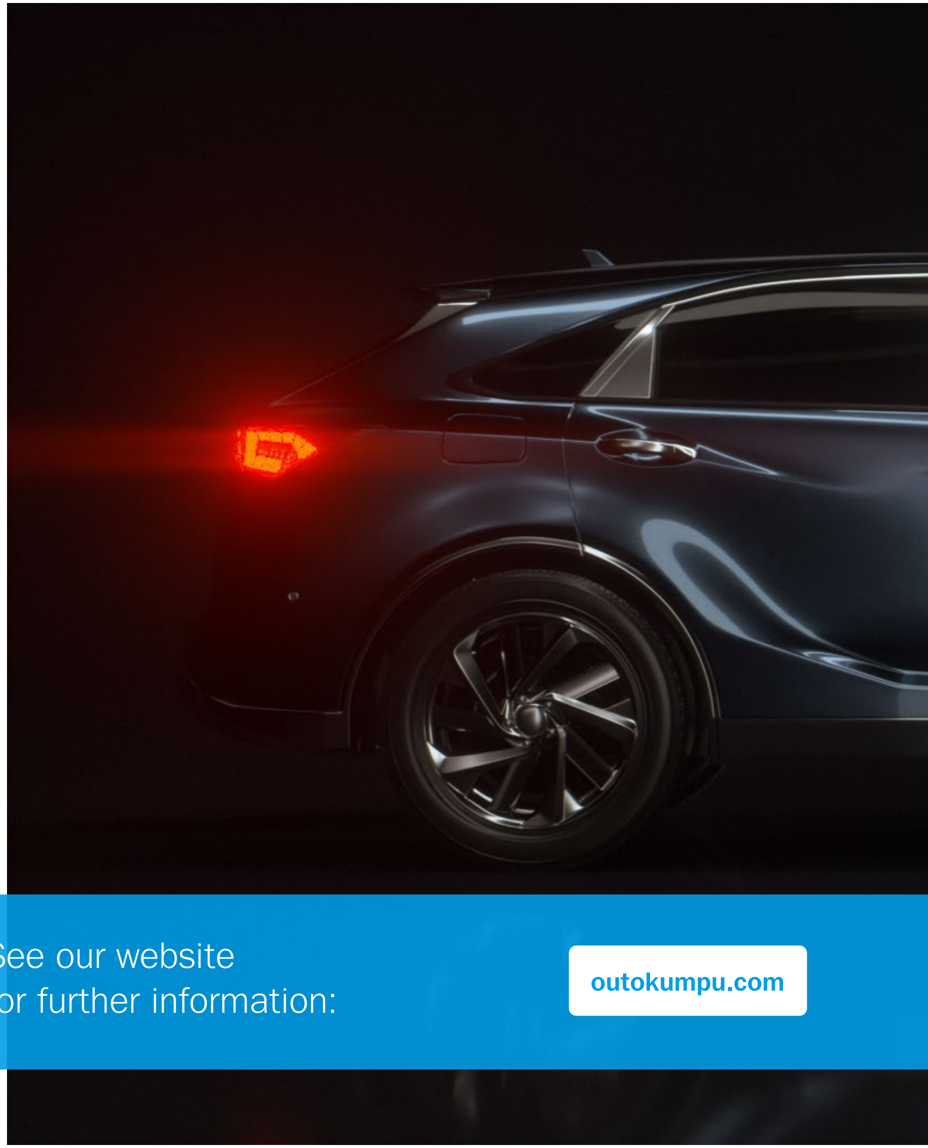
- Good corrosion resistance
- High strength, lightweight material
- Excellent crash resistance
- Full recyclability
- Straightforward switchover from standard steel
- Elimination of hot forming
- Ease of forming and joining

A wide range of potential applications

- Structural parts/body in white
- Battery compartments
- Fuel tanks
- Trim elements
- Seat structures, steering columns and dash cowls
- Channels, pillars and bumpers

Expert support by Outokumpu

- Global supplier for the automotive industry over decades
- Worldwide availability
- Deep understanding of the automotive industry
- State-of-the-art research and development centers



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