Stainless Steel: a new structural automotive material

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High strength mechanical characteristics, energy absorption capability, ductility which means ease of fabrication, fatigue resistance, and corrosion resistance are some of the properties held by most of stainless steels which enable them to meet the specific requirements of various passenger car structural sub-assemblies.
The aim of this paper is to show the structural applications of the stainless steel in the automotive sector, starting from the first experience for the buses' frames (beginning of the '90s) to the last experiences for the frames of the so called "microcar" and for some "critical" safety components.
The cold forming technique combined with the high formability of austenitic stainless steel allows the optimisation of structural members. In the case of a crash this shape optimisation associated with the strain-rate sensitivity of the material promotes the crushing of side members instead of buckling and therefore improves the energy absorption capability.

AUSTENITIC STAINLESS STEELS: MECHANICAL PROPERTIES AND CORROSION RESISTANCE

It is a fact that the **work-hardening properties** of austenitic stainless steels occurring during the forming processes and the **stress-strain rate sensitivity** of these alloys have a pronounced and aggregated effect on the mechanical behaviour of these metallic materials. That means that the mechanical behaviour of austenitic stainless steels is highly influenced by those two effects.

Work-hardening has two main effects:
- an increase of the yield strength (σ_y) function of the cold work (%)
- only a moderate decrease of the ductility (ε)

while an increase in strain rate has two main effects:
- an increase of the stress value (σ) function of strain rate ($\varepsilon'=d\varepsilon/dt$)
- only a slight decrease of the ductility (ε)

In table 1 are summarized the main mechanical and physical properties of a Cr-Ni-(N) stainless steel (EN 1.4318 – X2CrNiN18-7) that in the last years has been variously investigated for structural automotive applications; other grades properly thought for this kind of use, have similar or even better "performances":

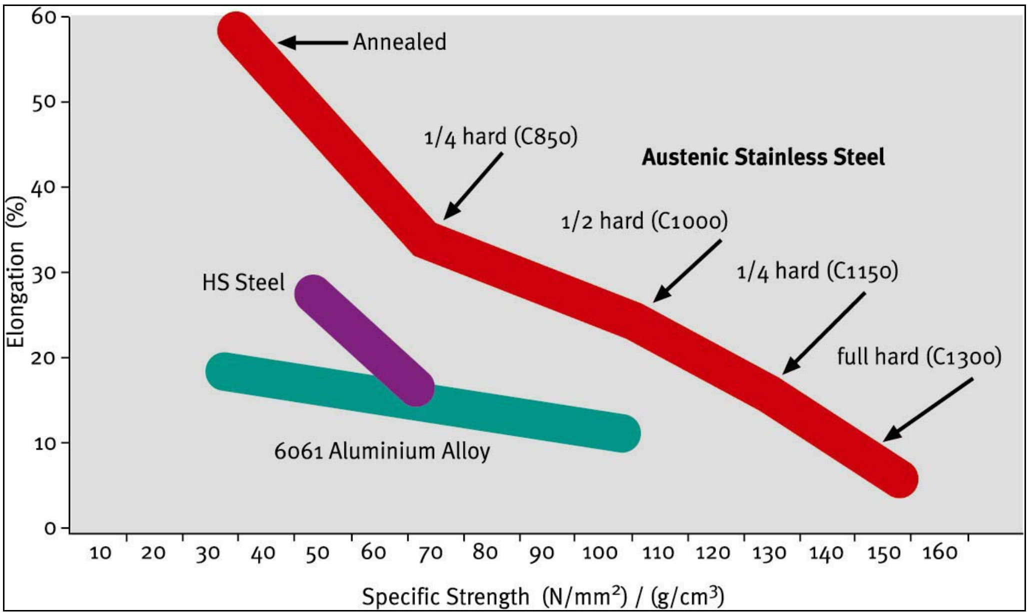
Tab. 1 Mechanical and phisical properties of various metallic materials

Property	Austenitic Stainless Steel EN 1.4318 - X2CrNiN 18-7					Aluminium Alloy 6061		High Strength Steel (HSS)
	Annealed	C850 (1)	C1000 (2)	C1150 (3)	C1300 (4)	T4 (5)	T6 (6)	
Density ρ (g/cm^2)	7,9	7,9	7,9	7,9	7,9	2,7	2,7	7,83
Density relative to steel	1	1	1	1	1	0,35	0,35	1
Yeld strength σ_y (N/mm^2)	370	600	880	1100	1200	130	275	410
Tensile strength σ_t (N/mm^2)	800	900	1160	1300	1400	225	310	480
Specific strength $\sigma_{y/}\ \rho$	46,8	76,0	111,4	139,2	151,9	48,1	101,8	52,4
Specific strength relative to HSS	0,9	1,45	2,12	2,66	2,9	0,92	1,90	1,0
Elongation El(%)	53	35	20	15	10	15	8	22
Specific Elongation relative to HSS	2,41	1,59	0,91	0,68	0,45	0,68	0,36	1,0
Young's modulus (E) (kN/mm^2)	200	200	190	190	190	69	69	200
Specific Stiffness E/ρ	25	25	24	24	24	25,5	25,5	25

(1) work hardened C850 (1/4 hard); (2) work hardened C1000 (1/2 hard); (3) work hardened C1150 (3/4 hard); (4) work hardened C1300 (4/4 hard); (5) T4:annealed; (6) T6: after ageing treatment

As it can be seen, the specific stiffness (E/ρ, ratio between Young modulus and density) of stainless steel is very similar to the aluminium alloy and the high strength steel (HSS), while the specific strength (σ_y/ρ) of austenitic stainless steel in the cold worked condition is much higher that one for others materials.
Another important factor is formability: figure 1 gives elongation (El%) as a function of specific strength (σ_y/ρ), demonstrating the very good suitability of austenitic stainless steels for cold working operations such as stretching, deep drawing and hydroforming.

Fig. 1 Elongation as a function of specific strength



In terms of energy absorption capability, remembering that it can be evaluated by integrating the area under the stress strain curve, in table 2 absorbed energy for the different materials within the scope of this survey are given.

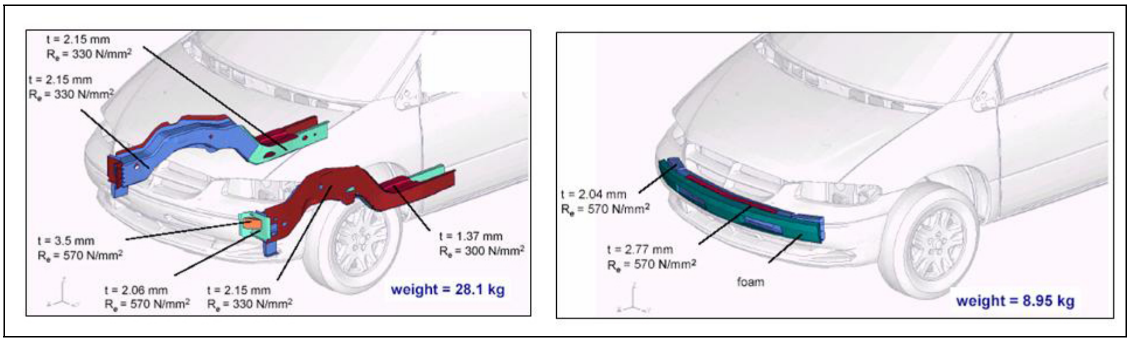
Tab. 2 Absorbed energy for the different materials

Material	σ_y (N/mm^2)	σ_t (N/mm^2)	n (1)	Density ρ (g/cm^2)	Absorbed Energy W_2 (J/g)
Stainless Steel X2CrNiN18-7/1.4318					
Annealed	370	800	0,60	7,9	38,0
C 850 (2)	600	900		7,9	33,5
C 1000 (3)	880	1160		7,9	25,9
Aluminium alloy 6061 – T4	145	240	0,22	2,7	20,4
High Strength Steel (HSS)	410	480	0,15	7,83	12,5

(1) Strain-hardening coefficient
(2) In the cold-worked condition: C850 ($850<\sigma_t$(N/mm^2)<1000)
(3) In the cold worked condition: C1000 ($1000<\sigma_t$(N/mm^2)<1150)

Various experiences about this theme, some of which will be shortly illustrated in this paper, have confirmed the good behaviour of stainless steels in terms of safety and weight reduction potential; recently Euro Inox (The European Stainless Steel Development Association) commissioned a study that was carried out by FKA, an Automotive Research Institute closely linked to the University of Achen.
The aim of this investigation was to determine weight-reduction potential for the side member and bumper beam of a car body using stainless steel material substitution. The limiting factor in weight reduction of these parts was crash safety requirements, since these members are part of the front body structure. In addition to material substitution, redesign of these parts was undertaken. Pedestrian protection requirements were taken into account in the bumper beam's design. The first part of the investigation dealt with the side member. Two crash configurations were considered: high-speed crash and low-speed crash. Possible weight reduction with stainless steel in high-speed crash was 9% (2B condition) to 28% (cold worked).

Fig. 2 The side member and the bumper beam studied



Possible weight reduction in low-speed crash was 12% (2B condition) to 49% (cold worked). The strain rate dependency factor did not bring further benefits in comparison with high-strength carbon steels. The analysis showed weight-reduction potential in low-speed crash to be much higher than in high-speed crash. For this reason, high-speed crash is the limiting load case for weight reduction. Another aspect of the side-member investigation was redesigning the multi-part side-member into a single-part hydroformed beam. Possible weight reduction with stainless steel in high-speed crash was 19% (2B condition) to 34% (cold worked). Possible weight reduction in the low-speed crash with stainless steel was 41% (2B condition) to 50% (cold worked). Once again, high-speed crash was the limiting load case for weight reduction. In the second part of the study, the bumper beam is analysed. Firstly, weight-reduction potential without consideration of pedestrian protection requirements was determined. A parameter study was carried out to establish the most efficient design. The last step was a pedestrian-friendly bumper beam designed with reduced bumper beam width. Even taking pedestrian protection into account, weight reduction of 38.8% was possible. This was achieved by redesign and stainless steel material substitution. This investigation showed high weight-reduction potential, up to 34%, for the side member and 38.8% for the pedestrian-friendly bumper beam. It should therefore be worthwhile to undertake further investigations into the formability and manufacturing of stainless steel parts. (For further details about this study please contact Euro Inox: www.euro-inox.org).

By a corrosion resistance point of view, stainless steels are very well known for their suitability in a great variety of environments. Their self-passivating behaviour gives them the capability to resist to uniform corrosion, affecting non protected carbon steels, and, if properly selected, localized corrosion too. In the field of transport sector there are various experiences assessing the great performances of these alloys in various conditions:

- high temperature: valves, exhaust systems, manifolds, fasteners, cylinder head gaskets,…
- atmospheres: exhaust systems, braking systems, bus structures, decorative parts, …

It can be estimated that in an average European vehicle for these kinds of applications stainless steel accounts for some 20 kg of the total weight.

In figure 3 the aspect of a EN 1.4301 (AISI 304) structures of an off-road car used by three years for ordinary service and exposed to de-iceing salts environments too:

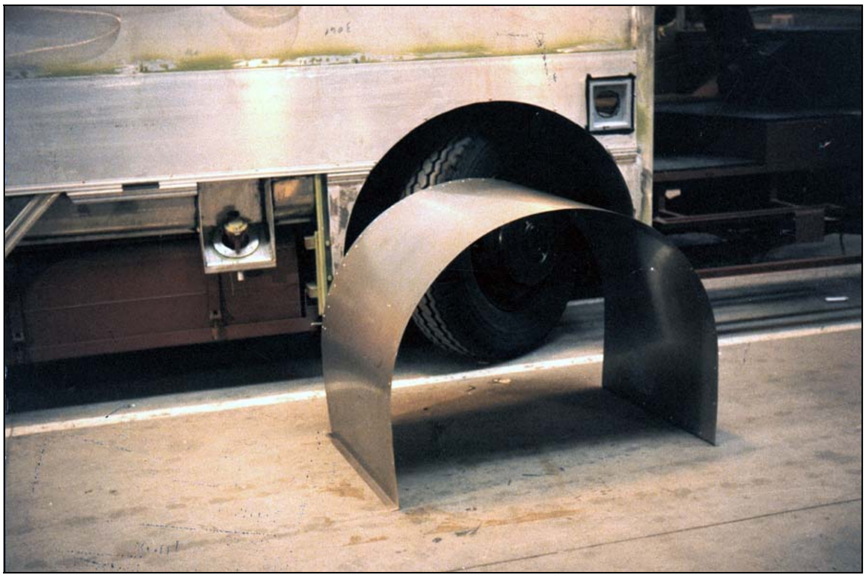
Fig. 3 The aspect of a stainless steel structure after three years exposure to road environment

The possibility to avoid protective surface treatments is an aspect involving economical and environmental considerations, that has been investigated by the stainless steel industry in terms of LCC and LCA, remembering the 100% reciclability of stainless steels too.

THE BUS SECTOR EXPERIENCE

Concerning buses, for instance, about 12 years ago a company located in the north east of Italy, near Udine, applied to Centro Inox for a tailor made technical course on stainless steel. Their purpose was the realisation of a stainless steel bus frame. This was the first "development point" which, as a chain reaction, produced a cluster of other bus manufacturers who began to use stainless steel. In this case we took advantage from a first, already sensitive company.
The result is that 20 years ago stainless steel was not used for the bus construction. Now the 80% of buses produced in Italy have the frame made for the most part in stainless steel.
In Italy, the use of stainless steel to make both the outer panelling and the actual structural parts of the body of motor buses in general has increased enormously.
Originally, flat rolled sections (sheet metal and strip) were mainly used in the "below-waist" panelling areas and the wheelhouses, i.e. the parts most liable to corrosion. These parts are in any event treated with primer and epoxy paint (Fig. 4)

Fig. 4 The wheel-lodging covers in EN 1.4301 (AISI 304) sheet, 1.5 mm thick



As regards the structural part of the body, some tentative experiments began with the use of square and rectangular stainless steel pipes about 20 years ago.
Some companies manufactured prototypes (above all in the Touring series) with part of the body made of stainless steel, and they were sent out onto the Italian roads on an experimental basis.
The results were highly satisfactory as regards mechanical performance and corrosion-resistance of the parts, even in extremely aggressive environments.
As a result of these successful experiments the technique began to be used quite widely, and nowadays the major Italian bus manufacturers regularly use stainless steel for the structural parts and panelling most liable to corrosion.
The exterior panelling parts, which are generally made of stainless steel, are as follows:

Below the waist

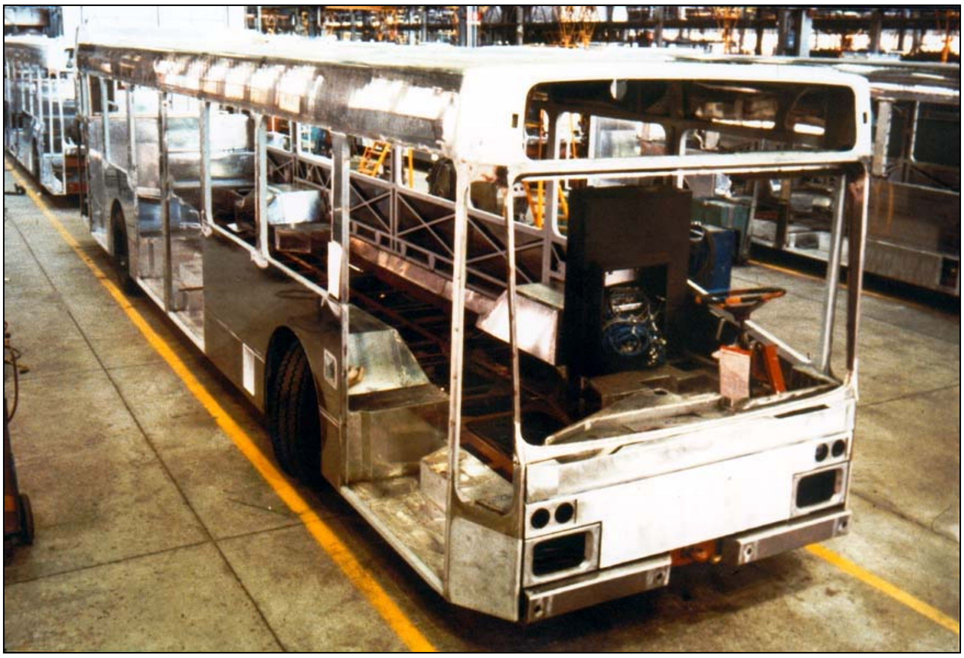
- inner and outer wheelhouses
- exterior panelling and sides
- rear band
- luggage compartment
- panelling of service housing

Above the waist

- exterior panelling and sides
- front head
- rear head
- part of top

The most interesting application of stainless steel, as stated above, is for structural work. It is used for two types of structure: those with a body which "collaborates" with the load-bearing chassis (flooring) and those having a self-supporting body.
Most vehicles are made by the first method, using a frame to which a lattice of square or rectangular stainless tubes is welded (Fig. 5)

Fig. 5 Example of stainless steel structural application



Some companies make vehicles with a self-supporting body (Fig. 6).

Fig. 6 Self-supporting bodies made with square section EN 1.4301 (AISI 304) stainless tube

Some companies have entirely redesigned the body around the "new" material, sometimes using the finite-element method for the structural calculation.
Others have transferred all the construction criteria used for carbon steel structures to stainless steel, merely reducing the thickness of the tubular shapes in some parts.

There is no doubt that the use of stainless steel involves technical advantages in the vehicle, which are greatest, when the structure is designed from scratch.
These advantages can be summed up as follows:

- overall weight of structure lower than that of conventional structures
- no corrosion under normal operating conditions
- stronger structure
- more usable interior space
- virtually no maintenance.

The safety aspect associated with the greater strength obtained is particularly important.
In some cases, the resistance to deformation of the entire structure in the passenger area has been increased from 10 to15 % over the conventional carbon steel structure.
In addition, the reduction in thickness of the tubular sections and consequent overall lightening of the structure (ranging from 12 to 14 %) produces a considerable fuel saving in operation and lower stresses of all mechanical parts.
It has also been possible a coast analysis on the base of the experience of a bus manufacturer. As it can be seen by the LCC calculation below, even the initial cost and not only the cost after 20 years is lower for the stainless steel structure (Tab. 3):

Tab. 3 LCC calculation for a bus structure

Cost of Capital		10.00%
Inflation Rate		5.00%
Real interest rate		4.76%
Desired LCC duration		20.0 years
Downtime per maintenance/replacement event		1.0 day
Monetary unit		US $
Value of lost production		101 US $ / day
	STAINLESS STEEL	**CARBON STEEL**
Material costs	3.331	1.391
Fabrication costs	25.322	26.582
Other installation costs	2.185	4.050
TOTAL INITIAL COSTS	**30.838**	**32.023**
Maintenance costs	0	1.448
Replacement costs	0	2.897
Lost production	0	57
Material-related costs	0	0
TOTAL OPERATING COST	0	4.402
TOTAL LCC COST	**30.838**	**36.425**

THE AUTOMOTIVE SECTOR: FROM MICROCARS TO …..

Microcars

Microcars have become increasingly widespread throughout Italy and Europe over the past few years. In Italy they are classified as "light weight- quadric cycles". They can be driven as from the age of 14 years, their maximum speed may not exceed 45 km/h, their engine power may not be higher than 4.0 kW and their mass may not be greater than 350 kg. This latter limitations seems to be particularly binding during the design phase in that the lightness of the vehicle needs to be combined with the safety in the case of a collision. For this reason EN 1.4301 (304) stainless steel has made it possible to fulfil the pre-established objectives of safety and lightness. Mechanical properties (strength and energy absorption capacity), workability (eg. formability and weldability) with the corrosion properties typical of stainless steels (no surface protective coating is necessary) make it an ideal material for the "skeleton" of these microcars:

Fig. 7 Isigò, one of the first examples of stainless steel frame on a micro-car

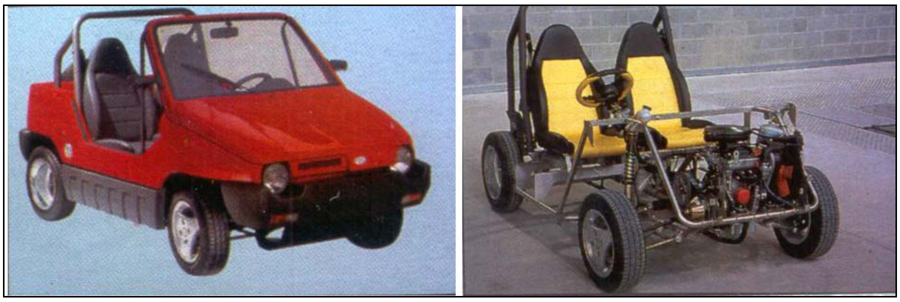
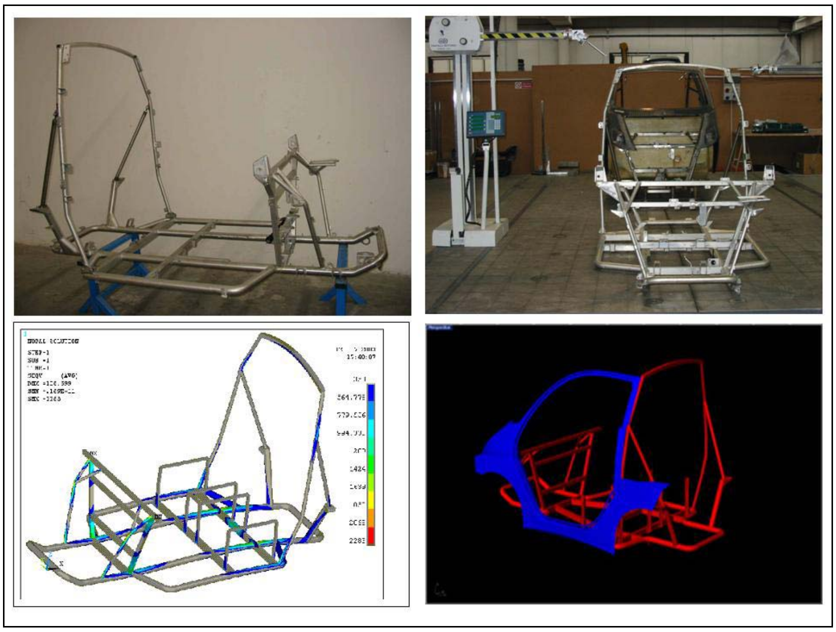


Fig. 8 The Ginevra model by Townlife

Fig. 9 Some pictures of a brand new microcar produced by Effedi, presented in Italy last April



Nido

The car prototype "NIDO" produced by Pininfarina, has been exhibited for the first time at the world car exhibition in Paris (Mondiel de l'Automobile – Paris 2004). For this prototype stainless steel type EN 1.4301 (AISI 304) has been used to manufacture the whole frame, by using sheet, tubes and bars. The project, which had the aim to have the maximum safety in a car of small dimensions, has seen the participation of various partners, among which Centro Inox of Milan (the Italian Stainless Steel Development Association) for the know-how on stainless steel.

Fig. 10 The car prototype Nido with some details of the stainless steel structure

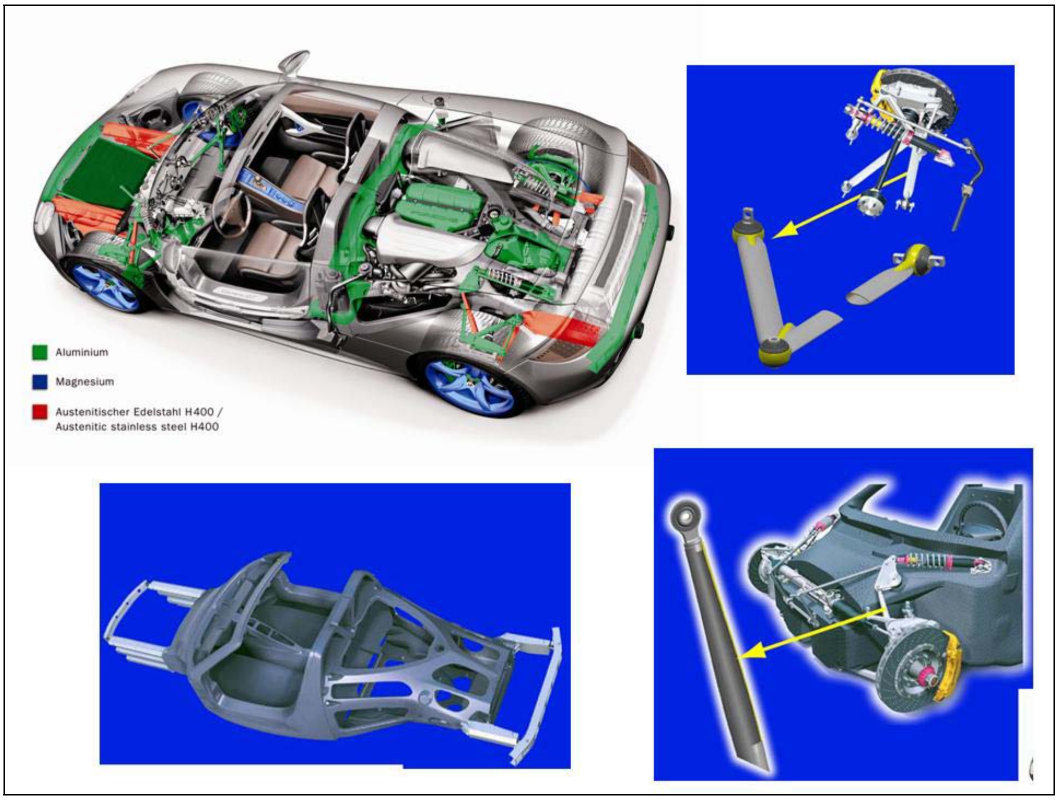
The decision to use stainless steel for the structure was taken because of the specific characteristics of this material, which has an excellent energy-absorbing capacity in the event of a collision and which increases in mechanical strength in relation to the degree of deformation (strain hardening). As it requires no anti-corrosion surface treatment, stainless steel also makes the industrial process more flexible, and means that the cataphoresis treatment can be completely omitted. A new concept of chassis construction has also been developed, replacing the traditional floor tray, tunnel and firewall configurations with a structure in cellular stainless steel sheet. The advantages of this technology lie in its improved energy absorption capacity in collisions and excellent torsional stiffness. Cellular stainless steel sheet technology consists of a sandwich made up of four or more thin layers: flat sheets are used for outside sections, whereas for internal parts, two or more ribbed sheets were assembled together with their respective corrugations opposed.
Lastly, the use of solid coloured plastics for the external body panels means that the painting process can be eliminated completely and gives the NIDO project a high environmental value.

Porsche

H400 stainless steel has been used in Porsche GT for some structural components:

- front and rear side members (crash structures)
- internal high-pressure formed push rod on front and rear axles
- lower rear axle wishbone in the aerodynamic air flow of the diffuser

Fig. 11 H400 Stainless steel has been used for some structural components of Prsche Carrera GT



One of the important aspect for Carrera GT was the need to achieve high safety potential despite the low weight. Properties of this austenitic stainless steel (H400) considered were:

- increased operating strength with possible reduction in weight;
- high energy absorption capacity;
- very good strength/formability ratio
- high permanent elongation capacity;
- weldable with all the commonly used techniques;
- corrosion resistant

Thanks to these characteristics lower gauge was possible to have thin gauges absorbing high energy and the overall weight was lowered.

Volvo

Components linked to crash safety in automotive vehicles are required to transmit or absorb energy. The energy absorbing capability of a given component depends on a combination of geometry, material properties and loading conditions. Increased crash performance can be obtained by using materials with higher yield strength and relatively high elongation to fracture These demands have led to increasing interest in the use of high strength stainless steels due to their relatively high elongation to fracture and good formability. To increase knowledge of the formability and forming behaviour of these materials, several components from current and prototype vehicles have been made using high strength stainless steels at Volvo Cars Body Components, Olofström, Sweden. These were subsequently analysed in close collaboration with the Division of Manufacturing Systems Engineering at Luleå University of Technology, Sweden.

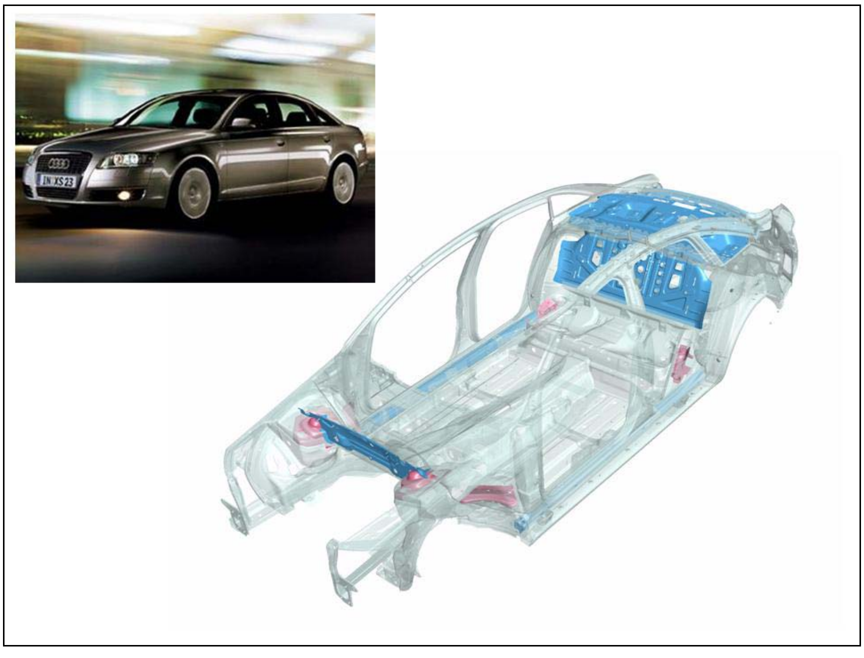
Fig. 12 The stainless steel bumper studied by volvo

These studies have shown that stainless steels can be successfully used to manufacture crash-absorbing components for automotive vehicles. High strength combined with good formability makes these materials ideal for making high strength and stiff components. Combined with component designs optimised for these materials, the use of stainless steels in automotive vehicles could significantly increase the crash safety compared to using components manufactured from carbon steels.

Audi

Stainless steel has been used in body manufacturing for the first time on the A6. 31 robots arranged in nine production cells apply a total of 223 stainless steel weld points. The method of inline testing has been introduced to verify the effectiveness of the stainless steel weld points. The use of aluminium (for the front lid, wings and various interior components) and high-strength steels including stainless steel, coupled with increased use of tailored blanks, has led to a reduction in the body weight of around 30 kilograms.

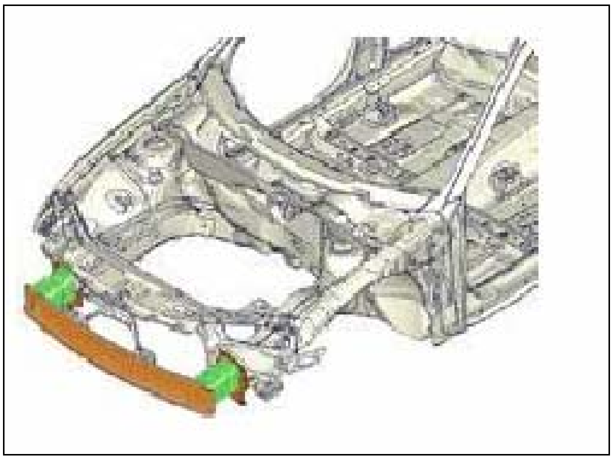
Fig. 13 Stainless steel has been used for the first time in the body manufacturing of Audi A6



Saab

Increasingly stringent environmental demands are encouraging the automotive industry to look for ways of producing lighter and more fuel-efficient cars. Higher fuel prices and requirements for reduced carbon dioxide emissions have put automotive manufacturers under increasing pressure to produce lighter, more fuel-efficient cars. Using a high-performance stainless steel, the VEK Project has succeeded in developing a bumper system for Saab 9-3 Sport Sedan that at no extra cost and without sacrificing performance is 26 percent lighter than existing bumpers.

Fig. 14 The bumper system developed for Saab 9-3 in the VEK project

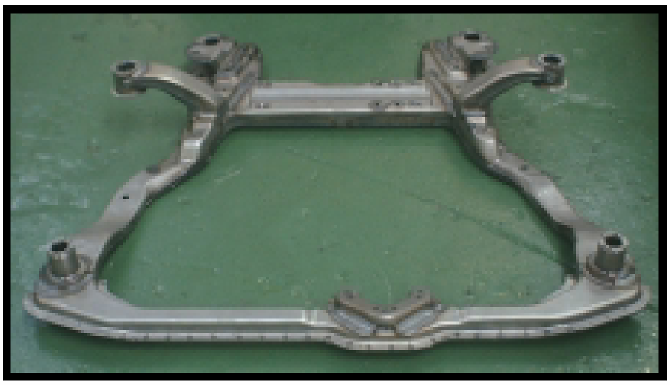


The greatest weight reduction has been achieved in the collision boxes. An interactive network including Saab Automobile together with a further 19 parties, has been involved in the project, which has been financed in part by the 2nd EU frame program and Vinnova, the Swedish Agency for Innovation Systems, as part of the "GreenCar" initiative for environmentally-friendly cars. A ultra high-strength stainless steel grade has been used in the prototypes; the properties and weight of the components can be optimized by interactively controlling the strength when the component is shaped. The potential environmental benefits of manufacturing cars using a lightweight design that involves high-performance steel are enormous. A preliminary study suggests a potential overall weight saving of 35-40 kg per car. If Saab produces 70 000 cars/year, the weight reduction corresponds to a saving of 2 500 tons a year. A rule of thumb is that a weight reduction of 10 percent can result in a 2.5 percent reduction in fuel consumption. This would correspond to a reduction in fuel consumption of 1.5 million liters per year, assuming mileage of 20 000 km/car/year. In five years, that amounts to some 7.5 million liters. This method also means that the components do not need to undergo surface treatment.

Hyundai Mobis

In a study conducted by Hyundai Mobis, tensile properties, strain hardening characteristics and sheet formability of an austenitic stainless steel (HSA) containing Nitrogen in the range from 0.2 to 0.27 wt.% have been investigated. An excellent combination of yield strength, strain hardening and ductility was obtained in both annealed and work-hardened conditions by optimising austenite stability as well as nitrogen content.

Fig. 15 The frame studied by Hyunday Mobis



In order to predict potential improvement of structural performance and weight saving of automotive component by using the HSA steel, finite element structural analysis was conducted for the front subframe of passenger car, which is shown in figure 15. The function of this component is to support suspension, steering system and power train, thus providing the suspension stiffness. Based on the measured mechanical properties, the front-sub frame was designed with HSA steel sheet in two ways, i.e., Case 1 by using 1.6 mm thick sheets for all the subparts and Case 2 with various sheet gauges from 1.6 to 2.0 mm for each different subpart. A front-sub frame designed with a mild carbon steel sheet of 2.0 to 2.3 mm thickness was also analysed for comparison purpose. By means of finite element structural analysis for front sub-frame application, it was predicted that a remarkable improvement in structural safety and at the same time a large weight saving of the component could be attained by using this steel in automotive structural parts.

Volkswagen

In response to increasingly stringent emission standards in the United States, several European car manufacturers are fitting certain models bound for U.S. markets (e.g. Volkswagen Beetle) with stainless steel tanks.

Fig. 16 The Stainless steel tank of Beetle for the U.S market

The tanks will help car manufacturers conform to environmental laws designed to control smog. The state of California, for instance, has introduced legislation that limits hydrocarbon emissions to two grams per day per vehicle. According to the Environmental Protection Agency (EPA) in the U.S., vehicles account for about 60% of the country's total emissions of carbon monoxide, 31% of nitrogen oxides, 30% of volatile organic compounds, and eight percent of particulate matter. One source of these emissions is fuel vapour that permeates the walls of conventional plastic tanks at a rate of about two grams per day. Both carbon steel and stainless steel prevent this leakage, but stainless steel has the added advantage of longevity because of its resistance to corrosion -- and since the California legislation requires car manufactures to guarantee zero emissions for at least 15 years or 240,000 kilometres, longevity is a crucial feature. Stainless steel tanks are 100% recyclable.

CONCLUSIONS

Stainless Steels, which are well known for their excellent corrosion resistance, also exhibit a combination of outstanding characteristic which make them particularly attractive in the automotive field. In the intense competition between different materials, stainless steel products have significant advantages with respect to corrosion resistance, fatigue resistance and crashworthiness over aluminium alloys and high-strength low-alloy steels.

As it is shown and illustrated by examples, stainless steels exhibit properties that meet the very stringent requirements of crash energy management. These requirements based on large elongation percentages linked to high strain rate sensitivities and high strength properties are typical of high strength stainless steels It is these characteristics along with the other usual benefit which make stainless steels ideal candidates for application in the field of car structures.

Stainless steel is also an ecological, long lasting and recyclable material that matches the efforts to protect environment.

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