STEEL – MATERIAL OF CHOICE FOR AUTOMOTIVE LIGHTWEIGHT APPLICATIONS

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Abstract In recent years, for reasons of improved passenger comfort and safety, the weight of passenger cars has continuously increased, leading to higher fuel consumption and greenhouse gas emissions. Since the early 90s competition for safer, lighter, and more fuel economic ground transportation vehicles, triggered by stringent OEMs and governmental demands, led over the years to the market entry of new materials such as new high-strength steels, polymer composites, aluminium alloys, or also magnesium. In this challenging contest of achieving significant emission reductions and fuel economy across all new generation vehicle platforms, the steel industry is today accelerating the implementation of new innovative steels over other emerging materials. The aim of the present contribution is to review the development of novel high strength steels for automotive applications and to highlight their benefits compared to aluminium alloys, as one of their competitor for the automotive lightweight design.

Keywords:
Advanced high strength steels, press hardening steels, mechanical properties, microstructure, lightweight design

1. INTRODUCTION

When Audi introduced its first A8 model, based on aluminium space frame technology, to the market in 1994, the dominant position of steels as the material for vehicle body construction was put into question. The weight of its all-aluminium body-in-white (BIW) was considerably lower as the competing conventional steel car bodies [1]. The steel grades available at the market at that time, were mostly mild steels and to certain extend conventional high strength steels, which necessitated an increased sheet gage in order to fulfill the same stability and safety requirements as the aluminium alloys.

The world steel industry reacted to the lightweigthing challenge by launching the Ultra-Light Steel Auto Body - Advanced Vehicle Concepts (ULSAB-AVC) project [2] in 1995 with the aim the mass savings of 25 % over the benchmark without almost any cost penalty by using of approximately 10 % of advanced high strength steels (AHSS) in the BIW. This project has triggered an extensive development of novel steel grades with predominantly higher strength at an appropriate formability, which successfully continues up to now.

Today the newly designed automotive structures beneficitates of relevant application of high-strength steel (HSS), advanced high-strength steel (AHSS), and ultra-high-strength steel (UHSS) with a present share of 25 – 40 %, which has continuously been increasing. The application of these modern steel grades allows outstanding mass reductions by lowering sheet gages and/or by reducing the specific density, permitting considerable emission reductions at affordable costs.
The aim of the present contribution is to give a brief overview of the development of novel steel grades for automotive lightweight applications. Furthermore, their critical comparison with the aluminum alloys currently present on the market will be also given for the better understanding how steel industry reacted to make steels to remain the material of choice for automotive lightweight applications.

2. NOVEL STEELS FOR AUTOMOTIVE LIGHTWEIGHT APPLICATIONS

2.1 Advanced high strength steels, first generation:

In the 1990s the development of modern multiphase AHSS for automotive applications with a tensile strength in excess of 450 MPa has been triggered. This has included the development of dual phase (DP) [3], transformation induced plasticity (TRIP) [4] and complex phase (CP) steels [5] with tensile strength which can readily achieve 1000 MPa. Their development was made possible due to new processing lines, designed for integrated steel plant. Nowadays a large range of mechanical properties can be offered by this steel family to automotive customers by an adjustment of different constituents in their complex composite microstructure. The excellent combination of mechanical properties and formability performance predeterminates them to be applied for interior safety related panels. However, their application for exposed panels has lately been also discussed [6].

DP steels have a microstructure consisting of a soft ferrite matrix and a medium C lath-type martensite as the second phase, with a content varying from 5 to 50 vol.-%. The amount of the martensite determines the strength of the steel. For these steels excellent results were obtained in the press shop by making it possible to produce even quite difficult parts such as B-pillars. However, if small radii of curvature are desired appearing in bending and roll forming operations, high strength DP steels often fail. Therefore, these steel grades are mostly recommended for deep drawing applications [7].

TRIP steels have a complex microstructure, composed of different phases: ferrite (~50 vol.-%), bainite (~35 - 40 vol.-%), and retained austenite (~10 - 15 vol.-%). The body-centered cubic (bcc) ferrite phase, exhibiting high stacking fault energy and Peierls lattice friction, is mainly responsible for the ductility. The bainite constituent contributes to a high strength, and has a high dislocation density and complex specific morphology of small size laths microstructure. The retained austenite in these steel grades play a vital role in making use of the transformation induced plasticity (TRIP) effect – its gradual transformation to martensite during straining, which enables high strain hardening of the steel and in turn permits to achieve high ductility with keeping high strength level. In contrary to DP steels with similar strength, TRIP steels have significantly better elongation and strain hardening, which makes them a suitable candidate for deep drawing applications in case that the deep drawability potential of DP steels is exhausted [8].

In contrast to DP and TRIP steels, CP steels are characterized by a more complex microstructure consisting of ferrite, bainite, martensite and tempered martensite. A clear differentiation of matrix becomes in this case quite difficult. They exhibit a high yield ratio, reduced uniform and total elongation by a low work hardening. On the other hand, their bendability is excellent, which originates from more homogeneous microstructure, resulting in lower strain localization among individual microstructural compounds [7]. Therefore, such steel grades are well suited for manufacturing automotive safety related parts, which require bending operations, roll forming and other forming types where high localization of strain occurs [9].

2.2 Advanced high strength steels, second generation:

In order to achieve a superior combination of strength and ductility, which allows engineers to design complex car parts where even parts integration has become possible, Twinning induced plasticity (TWIP) [10], and Duplex/Triplex steels [11] were developed by the steel industry. These steel grades have a medium to high total alloying additions, and they have a manganese concentration comprising from 12 wt.-% to 35 wt.-%. TWIP steels are the mostly developed steel grades in this category.
TWIP steels have a face-centered cubic (fcc) crystal structure of the austenite constituent. The stacking fault energy (SFE) is low and typically ranging from 15 to 50 mJ/m² at room temperature. As the consequence of that, the plastic deformation is characterized by the pronounced dislocation glide and the dissociation of perfect dislocation to Shockley partial dislocations and formation of wide stacking faults. With lowering stability of the austenite, the austenitic microstructure may transform to strain-induced ε-martensite and/or α'-martensite phase during plastic deformation, which is however undesirable. By twinning induced plasticity, these steels achieve outstanding combination of mechanical properties which makes them very attractive for automotive applications, especially where high strength and high ductility is required. These steels are ideally suited to manufacturing complex automotive parts e.g. side members. Their superior formability is ideally adapted to manufacturing components allowing only one or limited number of required forming operations. TWIP steels exhibit typically a tensile strength level ranging from 800 MPa to ~1200 MPa with a product tensile strength – total elongation up to ~70000 %MPa [10]. The first applications of TWIP steels for automotive components such as bumpers are currently being discussed.

The FeCMnAl steels have typically a manganese content varying from 20 to 30 wt.-% and a high aluminium content from ~6 to 12 wt.-%. Increasing Al concentrations results in an overall molar mass reduction of the coexisting bcc Fe(Mn,Al) and fcc solid solution, due to significant effective lattice expansion by larger atomic radii of dissolved atoms compared to smaller iron atoms e.g. Al and Mn. The Duplex and more favored Triplex steels typically exhibit a specific density between 6.4 and 7.1 g/cm³, compared to conventional grades with ~7.85 g/cm³. Triplex steel microstructure consists in an austenitic γ Fe(Mn, Al, C) solid solution matrix, α Fe(Mn, Al, C) ferrite, and a fine dispersion of nano-sized κ carbides (Fe,Mn)3AlC1-X in varying volume fractions, which form during age hardening in a temperature range of ~500 – 650 °C. Triplex steels can offer a tensile strength from 870 MPa up to 1100 MPa by total elongations in a range of 25 % – 70 % [11]. Although Triplex steels offer the automotive industry an interesting combination of mechanical properties and reduced weight, no application in real car bodies has been considered up to now.

2.3 Advanced high strength steels, third generation:

Modern steel candidates for the third generation of advanced high strength steels have often a microstructure containing retained austenite, which undergoes the TRIP and/or TWIP effect during straining or shear-band induced plasticity. These steels are represented by a lean TRIP composition such as TRIP bainitic ferrite (TBF) steels [12] and Quench-and-Partitioning (Q&P) steels [13] or by medium Mn content lower than by above mentioned TWIP and Triplex steels – so called medium Mn TRIP steels [14].

Except medium Mn TRIP steels, in these steel grades is the soft polygonal ferritic matrix generally replaced by a harder one comprised either from bainite (TBF steels) or tempered martensite (Q&P steels), respectively. By using such an approach is the hardness difference between the matrix and inclusions lower. More homogeneous microstructure leads to lower local micro-strains between matrix and inclusions, which extremely improves the bending and hole expansion properties. Moreover, strained induced transformation of retained austenite to martensite during straining significantly improves deep drawability. Therefore, these steels are suited for both bending and deep drawing operations which make them particularly suitable for manufacturing complex components as e.g. seat parts. The tensile strength of TBF and Q&P steels is usually above 1000 MPa with total elongations higher than 10% by superior bendability and hole expansion properties.

Medium Mn TRIP steels contain from 3-12 wt.-% Mn, but more typically from 4-7 wt.-% Mn. Their microstructure consists of ultrafine-grained ferritic matrix with a grain size typically less than 1μm with a high volume fraction of retained austenite usually up to 30 vol.-%. Tensile strength of these steels commonly exceeds 1000 MPa along with total elongations in a range of 25 – 40 %. Besides the production of these steels by continuous annealing lines [15] similarly to all above mentioned steels, their relatively cheap
production via batch annealing also becomes possible [16]. However, medium Mn TRIP steels are recently under development and their mass production for automotive applications is still sound future.

2.4 Press hardening steels:
Press hardening steels offer the automotive industry to manufacture complex components, where good deep drawability is required, by ultra-high strength usually about 1500 MPa. Well formable ferritic-pearlitic steel is formed either by room (the indirect process) or elevated temperature (the direct process) followed by the quenching process in the special tools in order to create a martensitic microstructure with ultra-high strength. Such components are in turn used for anti-intrusion barriers in BIW structures and they recently experience an extreme increase of market share [17].

3. PERFORMANCE - STEELS VS. ALUMINIUM ALLOYS
Fig. 1 represents the microstructure of selected novel multiphase advanced high strength and ultra-high strength steels in comparison with a single phase ferritic ultra-low carbon (ULC) steel, showing how the complexity of microstructure has led to diversification of mechanical properties. Single ferritic microstructures used in case of mild steels allowed to achieve tensile strengths lower than 350 MPa and elongations from 30 – 50 % [18].

![Fig. 1 Microstructure of selected modern steels for automotive applications in comparison with a single phase ultra-low carbon steel, showing the evolution of microstructures over last 25 years](image)

In contrary to aluminium alloys, which can only be strengthened by age hardening, modern steels with a variety of microstructural constituents with completely different strength and ductility levels, starting from weak ferritic phase up to hard martensite, allowed to create "composite materials" with a wide spectrum of mechanical properties. The following step was embedding the metastable retained austenitic islands in weak ferritic or harder bainitic and martensitic matrix. The retained austenite is adjusted by chemical composition
and thermal treatment in such a way that it transforms to strain-induced martensite during straining, which allows the novel steels to achieve even higher strengths by superior ductility. Twinning induced and shear band induced transformation of austenite in modern high Mn steels boosted ductility to such levels that the manufacturing of automotive parts with a high complexity and even an integration of automotive components becomes possible. Finally, single phase martensitic press hardening steels have brought the steels for automotive applications to the level of ultra-high strength materials.

Fig. 2 shows the evolution of tensile strength in modern steels for automotive applications in comparison with aluminium alloys recently available on the market. As already mentioned before, former mild and high strength steels with a tensile strength level from 300 MPa up to 600 MPa and the overall density of ~7.85 g/cm³ could not compete with 5000 and 6000 - series aluminium alloys with a tensile strength up to ~300 MPa and a significantly lower density of ~2.72 g/cm³. However, a decisive increase of tensile strengths in the following generations of modern advanced high strength and press hardening steels has permitted to down-gauge the automotive parts and by a pronounced decrease of component thickness to contribute to the lightweight design of modern automotive platforms. The couple of times higher strength along with better ductility, weldability, crashworthiness, significantly lower CO₂ footprint by their production and mainly reasonable lower price make the modern advanced high strength and press hardening steels the material of choice for automotive lightweight applications in the present times and also in the future.

![Fig. 2 Comparison of strength increase of modern steels for automotive applications compared to aluminium alloys currently available on the market](image)

4. CONCLUSIONS

In challenging contest of achieving significant emission reductions and fuel economy across all new generation of vehicle platforms, the steel industry has been putting efforts in accelerating the development and implementation of new innovative steel grades over the other emerging materials. In the present paper the development of these steels has been briefly reviewed. The benefits of modern steels have been highlighted in comparison with their strongest competitor among emerging materials, i.e. aluminium alloys, with the scope that steel remains an essential material of choice for recent and future lightweight design by automotive applications.
LITERATURE


