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Dušan Arsić[1]*
Djordje Ivković[2]
Dragan Adamović[3]
Vesna Mandić[4]
Marko Delić[5]
Andjela Mitrović[6]
Nada Ratković[7]

APPLICATION OF HIGH STRENGTH STEELS IN AUTOMOTIVE INDUSTRY

ABSTRACT: The aim of this paper was to present possibilities for application of the Advanced High-Strength Steels (AHSS) in the automotive industry. Besides, paper analyses their manufacturing processes and properties. Nowadays, there is constant need in the automotive industry to reduce weight of the vehicle in order to lower the gas consumption as well as to increase the ability to carry more weight. This goal can be achieved by using the materials with better mechanical properties or to use materials with lower density, such as aluminium or titanium. The AHSSs were created as a solution to reduce the weight of parts and structures in various transportation industries by increasing the mechanical properties. The AHSS steels are developed in three generation. Each generation has better mechanical properties than the previous. The increase of the steels properties is achieved by implementing the selected heat treatment procedures and precise micro alloying. In this paper authors tried to emphasize the advantages of using the AHSS in automotive industry and that the application of these materials directly results in lowering the structures' mass and it positively affects energy efficiency, preservation of the environment and lowering the pollution levels.

KEYWORDS: Advanced High-Strength Steels, automotive industry, vehicle, mechanical properties.

INTRODUCTION

In today's world of transportation, the focus is on environmental preservation, primarily by aiming to reduce greenhouse gas emissions. The current emphasis is on the development of electric vehicles; however, this approach will only be meaningful when electricity is produced from renewable energy sources. Therefore, the authors of this paper wish to highlight the importance of vehicle manufacturing materials in reducing harmful gas emissions. European Union (EU) environment in 2023 reports the transportation sector's 25% share of greenhouse gas emissions [1]. The EU plan is to reduce the transport emission for a 23% by 2030 compared to 2005. In vehicles, a 10% weight reduction corresponds to a fuel consumption saving of 6.5% [1] so the automotive industry prioritize lightweight construction to reduce CO_2 emissions and fossil fuel use in vehicles. New car emissions have decreased

[1] Dušan Arsić, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, dusan.arsic@fink.rs
[2] Djordje Ivković, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, djordje.ivkovic@fink.rs
[3] Dragan Adamović, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, adam@kg.ac.rs
[4] Vesna Mandić, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, mandic@kg.ac.rs
[5] Marko Delić, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, marko.delic@kg.ac.rs
[6] Andjela Mitrović, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, andjamit99@gmail.com
[7] Nada Ratković, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, nratkovic@kg.ac.rs

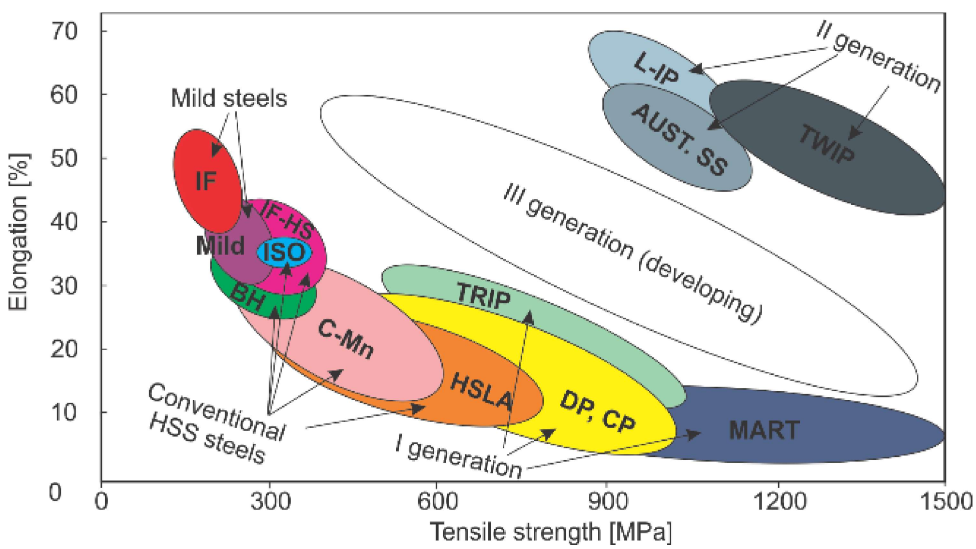
notably, with 12% declines for both 2020 and 2021. This trend is partially attributed to the reduction of Body in White (BiW) components' overall weight, which are the main contributors to the overall weight of vehicles [6].

Initially, vehicles were made from steel of a certain thickness. With the advancement of steel, the material's thickness has decreased, and today, very thin sheets (sometimes as thin as 0.5 mm) are used in car body manufacturing. Additionally, many steel parts are being replaced with parts made from lighter materials, reducing the vehicle's unladen weight and increasing its payload capacity. Moreover, the reduced vehicle mass leads to lower fuel consumption, which directly contributes to environmental protection. Importantly, replacing materials and reducing thickness do not compromise passenger safety.

The group of materials that stands out the most in these tasks is high-strength steel. High-strength steels were developed in the late 19th century and are now widely used across all branches of mechanical engineering. They are characterized by favourable mechanical properties (strength and ductility) while maintaining good workability (forming, welding, etc.) [1-3]. Today, even the processes for producing these steels are so advanced that their cost is often comparable to that of conventional low-carbon steels, yet with significantly better mechanical properties. The high strength of these steels results from the application of complex thermal, thermo-mechanical, and mechanical processing procedures. Consequently, the high strength allows for smaller cross-sectional dimensions of parts, reducing the amount of material used and the weight of structures. Regarding the vehicle production industry, the amount of advanced high-strength steel (AHSS) used in vehicle body production increases each year (Figure 1). Nowadays, high-strength steels are used in vehicles not only for body parts but also for more critical components of cars [4, 5].

REVIEW OF THE GENERAL CHARACTERISTICS OF THE AHSS

As already mentioned, the advantages of advanced high-strength steels (AHSS) are numerous. These advantages often include high strength and good ductility while maintaining favourable technological properties. Today, a wide variety of high-strength steels are in use, and they can be classified based on several criteria. A general classification divides them into generations according to their development time and the characteristics they possess (mostly referred to tensile strength and elongation). According to this classification, there are three generations of AHSS (Fig. 1). This paper will focus on the second and third generations of AHSS, as the first generation has been thoroughly examined in [6].



IF – interstitial free, IF-HS – interstitial free high strength, BH – bake hardened, HSLA – high strength low alloy, TRIP – transformation induced plasticity, DP – dual phase, CP – complex phase, MART – martensitic, L-IP - Al-added lightweight steels with induced plasticity, TWIP – twinning induced plasticity, AUST, SS – austenitic stainless steel

Figure 1 Mechanical characteristics of the advanced high strength steels [3]

AHSS are produced through a complex thermo-mechanical production cycle characterized by intense hot rolling followed by rapid cooling to achieve a specific microstructure. Depending on the type of steel, the rolling temperatures, cooling rates, and any subsequent heat treatments vary. For example, the production of cold-rolled dual-phase (DP) steels primarily involves heating previously cold-rolled steel strips of appropriate chemical composition to a temperature between A_{C1} and A_{C3}. In this temperature range, the microstructure of the steel consists of ferrite and austenite. With an increase in the heating temperature (approaching the critical temperature Ac3), the proportion of austenite increases, as does the amount of carbon that can be dissolved in the austenite [4]. On the other hand, the production of transformation-induced plasticity (TRIP) steels starts with rolling in the austenitic region, followed by cooling to 800 °C. At this temperature, the steel is soaked for 60 seconds, followed by rapid cooling to 450 °C, where the steel is held isothermally for 90 seconds. This isothermal holding results in the formation of a certain amount of bainite in the ferrite matrix. After holding at 450 °C, the steel is coiled and cooled to ambient temperature. The microstructure of these steels is also interphase, consisting of a ferrite matrix with residual austenite and bainite [4].

The second generation AHSS

As it was shown in paper [5] and in diagram 1, the first generation AHSS possesses great strength, but elongation and plasticity are low, especially for martensitic steels. Due to the lower plasticity, deformation rates during forming procedures such as bending and deep drawing are reduced and the risk of crack appearance is increased. In automotive industries, parts often have complex design and to produce such parts, greater plasticity is required, and researchers began developing the second generation AHSS. Design of the second generation of AHSS is based on austenitic microstructure, which offers greater plasticity and formability in comparison to the first generation, but strength levels are not drastically reduced [4]. The second generation of the AHSS includes the TWIP (TWinning Induced Plasticity) steels, L-IP (Lightweight Induced Plasticity) steels and austenitic stainless steels.

<u>The TWIP (TWinning Induced Plasticity) steels</u>

The TWIP steels have austenitic microstructure, which is retained at room temperatures due to high Mn content (22 % to 30 %). Besides Mn, the TWIP steels also contain fair amount of Al (maximum 10 %), as well as Si (maximum 3 %). Tendency to create twins in microstructure allows for the great strength to be achieved. Austenitic microstructure allows for elongation values to range from 60 to 90 % and their tensile strength exceeds 1000 MPa. The high strength results from austenitic microstructure ability to form twins, which are blocking movement of dislocation, thus increasing strength.

The chemical composition and mechanical properties of some TWIP steels are shown in tables 9 and 10, respectively, and a microstructure example is given in Figure 2.

Table 1 Chemical composition of some TWIP steels, wt% [1]

Designation according to BS*	Mn	Si	Al	C
Fe -15Mn-4Si-2Al	16.2	4.0	1.8	0.2
Fe-20Mn-3Si-3Al	20.1	2.8	2.9	0.4
Fe-25-Mn-4Si-2Al	25.5	3.9	1.8	0.3
Fe-30Mn-4Si-2Al	28.7	4.0	2.0	0.2
Fe-30Mn-2Si-4Al	30.6	2.0	3.9	0.1

**** BS – British standard***

Table 2 Mechanical properties of some TRIP steels [1]

Designation according to BS	$R_{p0.2}$, *MPa*	R_m, *MPa*	A, %
Fe -15Mn-4Si-2Al	190	1080	39
Fe-20Mn-3Si-3Al	300	840	82
Fe-25-Mn-4Si-2Al	280	770	69
Fe-30Mn-4Si-2Al	220	770	75
Fe-30Mn-2Si-4Al	210	570	83

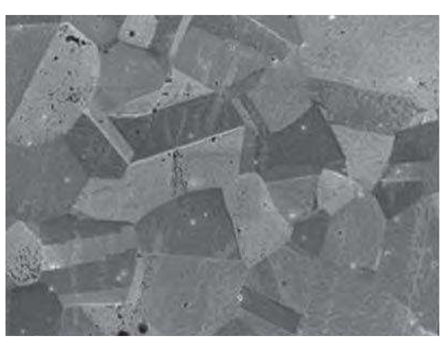


Figure 2 Microstructure of annealed Fe-30Mn steel [3]

The L-IP (Lightweight Induced Plasticity) steels

This steel group is still in development. Up to now, it is known that their strength ranges between 1000 to 1100 MPa, and elongation values reach up to 80 %. Application of this steel group could be found in automotive industry for producing parts with complex geometry, due to their good plasticity values [7].

Austenitic stainless steels

Austenitic stainless steels contain more than 12 % of Cr dissolved in solid solution, thus they are resistant to corrosion. This steel group besides Cr contains high values of Ni (max 35 %), which allows austenite to be stable at room temperatures. Addition of Ni drastically increases production costs due to its high price. Yield stress values range from 200 to 400 MPa, tensile strength values from 900 to 1200 MPa, and elongation values from 40 to 45 %. In comparison to other steels, they have good strength and formability with addition of corrosion resistance, so they can be used in more aggressive environment [7]. The chemical composition and mechanical properties of some austenitic stainless steels are shown in tables 3 and 4, respectively, and microstructure example is given in figure 3.

Table 3 Chemical composition of some austenitic stainless steels, wt% [1]

Designation according to EN 10088.2	max C	maxN	max Mn	max Si	Cr	max Ni
X8CrNiS18-9	0.15	-	2.0	1.0	17-19	8-10
X5CrNi18-10	0.07	0.1	2.0	0.75	17.5-19.5	8-10.5
X8CrNi25-21	0.25	-	2.0	1.5	24-26	19.22
X5CrNiMo17-12-2	0.08	0.1	2.0	0.75	16-18	10-14

Table 4 Mechanical properties of some austenitic stainless steels [1]

Designation according to EN 10088.2	$R_{p0.2}$, *MPa*	R_m, *MPa*	A_{50}, %
X8CrNiS18-9	300	650	45
X5CrNi18-10	205	515	40
X8CrNi25-21	205	515	40
X5CrNiMo17-12-2	205	515	40

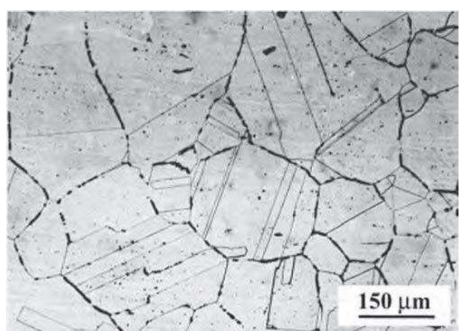


Figure 3 Microstructure example of austenite stainless steel [3]

The third generation AHSS

As the second generation AHSS is based on austenite microstructure, those steels contain high values of Cr and Ni to allow austenite to be stable at room temperature. The addition of mentioned components drastically increases price of steel, thus greatest disadvantage of second generation AHSS is their high price. Developing cheaper steels with similar properties represents the key for wider application of AHSS [1].

Development of third generation AHSS is based on the goal to achieve similar plasticity of second generation AHSS, but with significantly lower price. The third generation AHSS includes Q&P (Quenching and Partitioning) steels, Medium Mn steels and Trip Aided Bainitic Ferrite (TBF) steels.

The Q&P (Quenching and Partitioning) steels

These steels typically contain C (0.1 - 0.3 %), Si and/or Al (1 - 2 %) as well as Mn (1.5 - 3 %). The yield stress values range from 600 to 1150 MPa, tensile strength from 980 to 1300 MPa and elongation from 8 - 22 %. One can conclude that strength values are higher than of the second-generation steels, with reduced formability. However, it needs to be emphasized that the price of the third-generation steels is significantly lower. Mechanical properties of some Q&P steels are given in table 3. Steels from this group are often used to produce parts of vehicle chassis such as B-pillars [7].

Table 5 Mechanical properties of some Q&P steels

Designation of steel	$R_{p0.2}$, *MPa*	R_m, *MPa*	A, %
QP980	698	1057	20
QP1180	990	1188	16

The microstructure of these steels is composed of austenite (5 - 12 %), ferrite (20 - 40 %) and martensite (50 - 80 %). As the ratio of mentioned phases changes, the steel's properties vary accordingly. Example of a microstructure is presented in figure 4.

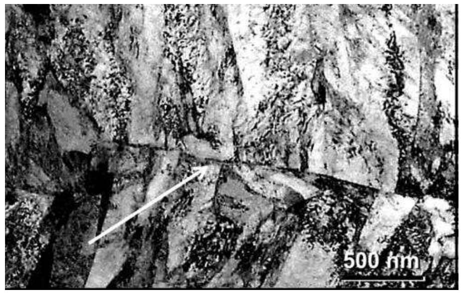


Figure 4 Microstructure of Q&P steel

The medium Mn steels

This steel group has fine grain ferritic-austenitic microstructure. Percentage of austenite in microstructure can vary from 20 to 40 %, based on required properties and chemical composition. Typical for this steel group is that they contain C (0.05 - 0.4 %), Si (1- 3 %) and Mn (3 - 12 %). The yield stress values range from 400 to 1150 MPa, tensile strength from 780 to 1350 MPa and elongation ranges from 15 to 60 %. A microstructure example is given in figure 5.

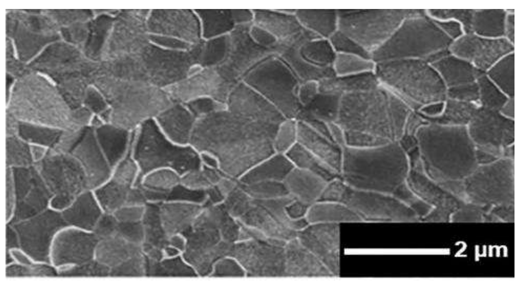


Figure 5 Microstructure of Medium Mn steel

The TBF (Trip Aided Bainitic Ferrite) steels

The TBF steels are similar to Q&P steels and the first grades of this group were produced in Japan. The yield stress value is around 790 MPa, tensile strength around 1240 MPa, and elongation 16.5 %. These steels are alloyed with Mn, Al, Nb and Cr and their microstructure is composed of bainite, ferrite and austenite. The share of austenite has the great effect on plasticity and can be controlled through the carbon content [4]. The chemical composition and mechanical properties of some TBF steels are given in tables 6 and 7, respectively. The microstructure of TBF steels is shown on figure 6.

Table 6 Chemical composition of some TBF steels, wt%

Designation according to VDA 239-100	max C	max Si	max Mn	max P	max S	Al	max Cu	max B	mac Ti + Nb	max Cr+ Mo
CR330Y590T-DH	0.15	0.8	2.5	0.05	0.01	0.015-1.0	0.2	0.005	0.15	1.4
CR440Y780T-DH	0.18	0.8	2.5	0.05	0.01	0.015-1.0	0.2	0.005	0.15	1.4
CR700Y980T-DH	0.23	1.8	2.9	0.05	0.01	0.015-1.0	0.2	0.005	0.15	1.4

Table 7 Mechanical properties of some TBF steels

Designation according to VDA 239-100	$R_{p0.2}$, *MPa*	R_m, *MPa*	A_{80}, %
CR330Y590T-DH	330-440	590-700	26
CR440Y780T-DH	440-550	780-900	18
CR700Y980T-DH	700-850	980-1130	13

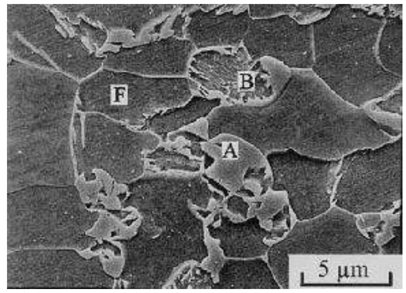


Figure 6 Microstructure example of TBF steel

CONCLUSIONS

The industrial development of humanity has inevitably led to increased environmental pollution. Today, the transportation sector is one of the most important in all branches of industry. Successful, fast, and efficient transportation requires the consumption of fossil fuels, the combustion of which results in the emission of harmful gases into the environment. To reduce these emissions, many options are being considered today, one of which has already been adopted and shown results: reducing vehicle weight. This weight reduction is most often achieved by replacing steel parts with parts made from lighter materials (Al, Ti, polymers, etc.). However, key vehicle components, for safety reasons, cannot be made from materials that do not offer high reliability. Therefore, advanced high-strength steels (AHSS) are currently emerging as the most suitable materials.

In this paper, the authors aimed to highlight the importance of materials used in the automotive industry, particularly high-strength steels. Knowing that by doubling the yield strength of a material, the thickness of the material used can be halved (provided there is no risk of buckling), and consequently fuel consumption for vehicle operation can be reduced, it is clear that progress can be made in this direction.

This paper analyzes the second and third generations of AHSS in detail, while the first generation is only mentioned as it is covered in another publication. The first generation of advanced high-strength steels has the greatest strength but the worst deformability among the three generations of mentioned steels. The advanced high-strength steels of the second generation are characterized by slightly lower strength than the first-generation steels; however, they possess significantly better deformability. Their greatest disadvantage is the very high price due to large amounts of alloying elements, especially Cr and Ni. The third-generation steels represent a balance between the first two generations. Steels that belong to the third generation of advanced high-strength steel have good strength values (slightly below the first generation) and good deformability (slightly worse than the second generation). Their greatest advantage is the lower price as compared to the second generation, with the formability being good enough for producing vehicle chassis parts.

All the above indicates that AHSS should be used in the automotive industry due to the numerous advantages they offer.

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