

# Development of Advanced High Strength Automotive Steels

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## Abstract

In recent decades, the automotive industry has faced ever-increasing demands. Increasing requirements can be observed in terms of both consumer expectations and legal requirements. On the consumer side, there is a demand for cars that are as economical as possible with lower fuel consumption, but providing also greater comfort and safety. These requirements are accompanied, from a legal point of view by more rigorous environmental regulations and requirements concerning the reduction of harmful emissions. Meeting these often-contradictory requirements is a growing challenge for car manufacturers and raw material suppliers, as well. Meeting the requirements in the most versatile way has resulted in tremendous progress over the last 40-50 years, both in the automotive industry and in the production and development of raw materials. The first part of this series of papers summarizes the main requirements in the automotive industry, as the main driving forces for material developments. Furthermore, the main types and properties of traditional high-strength steels, as well as the so-called first-generation Advanced High-Strength Steels will be introduced. In the second part, the main types and manufacturing processes of second generation advanced high-strength steels will be analyzed and some of the current steel developments will be presented through the results of the three generations of Advanced High-Strength Steels.

**Keywords:** *Advanced High Strength Steels, AHSS, automotive industry applications.*

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## 1. Introduction

Due to the increasing global competition in the automotive industry, reducing the manufacturing costs is a key objective: this is closely linked to reducing the weight of vehicles for a number of reasons.

Mass reduction in car manufacturing is also at the heart of research activities internationally. This can be explained by a number of factors, some of which are highlighted here: due to the ever increasing strict emission standards and environmental restrictions, vehicle weight reduction plays a key role in meeting consumer demands for cars that can be operated as economically as possible.

Regarding the total weight of a car, the car body plays a crucial role. The body parts – the so-called Body-in-White – in the manufacture of sheet metal forming is one of the most important manufacturing processes. This also justifies the development of new, innovative, low-cost manufacturing

processes in sheet metal forming as well. The two main directions in the production of lightweight automotive components are the use of high-strength steels and light metals, with a particular emphasis on various high-strength aluminium alloys [1].

In this paper, we focus on the development of high-strength steel materials and the results of these developments. This several decades-long development activity is best characterized by the development results of advanced high-strength steels, which appear in the international literature as AHSS, so we will often use the commonly accepted short designation in this work.

Developments in this area can be clearly defined into three major groups, namely the so-called first, second and third generation advanced high-strength steels. These developments are also closely related to the requirements of the automotive industry, which are also the driving forces behind material developments.

## 2. Driving forces in car manufacturing

The main driving forces of material development in the automotive industry are from the one hand the consumer expectations (more economical, safer, more comfortable cars, with better performance); on the other hand, it is supplemented by several legal requirements (more rigorous environmental standards, lower emissions, increased crash test standards).

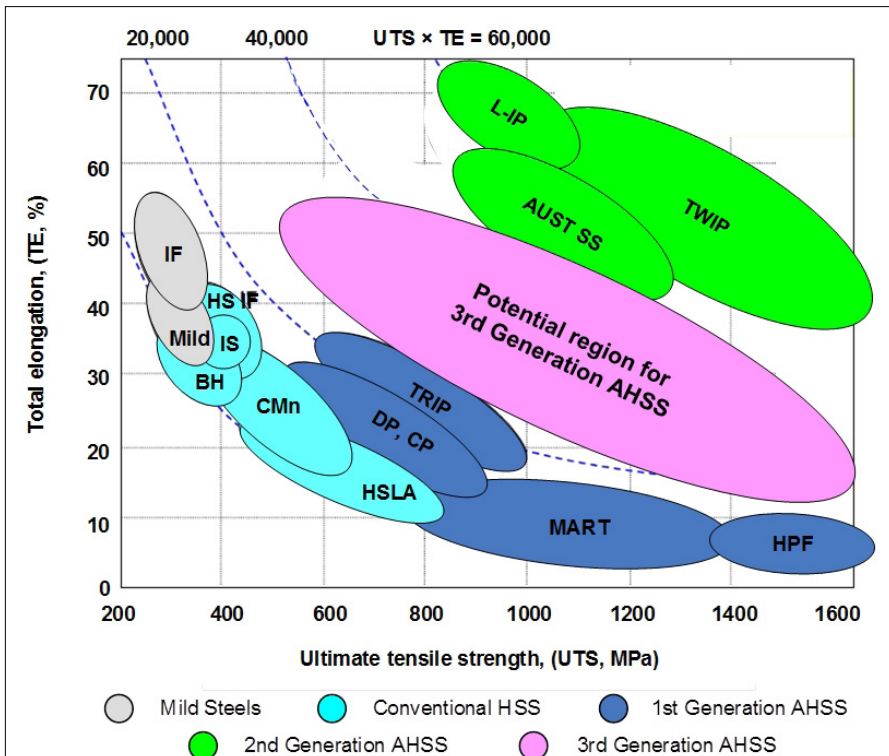
These two large groups represent partly similar and partly contradictory requirements. Due to global competition, the automotive industry needs to find appropriate responses for these challenges. Developments in recent decades have clearly shown that weight reduction plays a key role in meeting this diverse set of requirements.

Considering the proportion of different structural elements in the total weight of cars, it can be concluded that the reduction of the weight of Body-in-White elements, the various chassis and suspensions – i.e. the sheet parts – plays a key role. Reducing the weight of the sheet metal components requires the reduction in the thickness of the sheet materials and thus an increase in strength.

However, an increase in strength is usually accompanied by a decrease in formability, which in turn raises fundamental technological problems. Steel developments in recent decades have sought to balance these contradictory requirements, i.e. to develop high-strength steels that also meet the needs of the automotive industry in terms of formability.

### 2.1. Classification of automotive steel developments

The most commonly used classification in steel development in recent decades – the so-called Advanced High Strength Steels (AHSS) grouping – distinguishes three main groups, namely, first, second and third generation high strength steels. This classification is illustrated graphically in **Figure 1**. This figure also shows the well-known regularity of metallic materials, according to which, as the strength increases, the deformability decreases following a hyperbolic relationship. This is illustrated by the  $R_m \times A_{80} = C$  (constant) curves showing the product of tensile strength and total elongation, which play an important role in the classification of advanced high-strength steels.



**Figure 1.** Ultimate Tensile Test vs Total Elongation including the classification of Advanced High Strength Steels. [2]

**Figure 1.** shows the mild steels (IF, Mild) that have played a key role in the automotive industry for several decades, the traditional high-strength steels (HS-High Strength Interstitial Free, BH-Bake Hardening, CMn-Carbon Manganese), which also have significant automotive applications, and finally HSLA, i.e. High Strength Low Alloyed steels, which is the main representative of this group).

The next group is the 1<sup>st</sup> generation of advanced high-strength steels (1G-AHSS). This group includes dual-phase DP steels, phase transformation induced plasticity TRIP steels, complex phase CP steels, and martensitic, MS steels. These steels are in the range of  $C = 10,000\text{--}25,000$  (MPa %) with respect to the previously introduced  $R_m \times A_{80} = \text{Constant}$  curves.

The 2<sup>nd</sup> generation of advanced high-strength steels is represented by steel developments in the range  $R_m \times A_{80} = 40,000\text{--}65,000$  (MPa %) (2G-AHSS). The most characteristic members of this group are the Twinning Induced Plasticity (TWIP) steels with twin-induced plasticity behaviour, but this group also includes corrosion-resistant austenitic steels with high-Mn content (e.g. AUST SS) and L-IP steels called Lightweight Induced Plasticity. These steels provide an excellent combination of strength and formability, however, despite their excellent properties, this group has not achieved a real breakthrough in automotive applications, mainly due to low productivity and high production costs.

The next stage of development of advanced high-strength steels (AHSS) led to the development of so-called 3<sup>rd</sup> generation high-strength steels (3G-AHSS), which is still in the development and first industrial implementations stage, however, steelmakers have already achieved a number of remarkable achievements in this field, too.

The basic idea behind these developments is to provide properties in the range between the 1<sup>st</sup> and 2<sup>nd</sup> generation high-strength steels, which can be interpreted on the basis of **Figure 1.**

In the development of this group, it is of paramount importance that excellent mechanical properties are achieved with less alloying elements and thus at a lower cost, especially compared to 2<sup>nd</sup> generation steels.

The microstructure of these steels typically consists of multiple phases (e.g., nano / ultra-fine-grained ferrite, martensite, or bainite) and, when combined with an additional phase (e.g., austenite), provides increased formability and higher strain hardening. With this development concept,

high-strength steels in the GPa range can be produced with remarkable formability at the same time [3].

In the following, we analyse the recent major steel development efforts and achievements through the presentation of some representatives of these three generations.

### 3. Main types of Advanced High Strength Steels

The most important feature of the different generations of advanced high-strength (AHSS) steels is that they have a complex, carefully selected chemical composition and a multiphase microstructure that can be produced as a result of precisely controlled heating and cooling processes. Various strength-enhancing mechanisms are used to achieve significantly increased strength, better formability, increased toughness and fatigue properties to meet, as far as possible, the complex requirements for car components.

#### 3.1. First Generation Advanced High Strength Steels

The most characteristic and already widely used types of this group are the DP and TRIP steels, but in this group it is definitely worth mentioning the martensitic steels recently with growing application developed specifically for hot sheet forming in the automotive industry. These steels are referred to as Press Hardening Steels (PHS) in the international literature. In order to utilize their excellent properties, special new technological processes have been developed particularly for the processing of this type of steel.

##### 3.1.1. Dual Phase (DP) steels

Dual-Phase (DP) steels play an important role in both first-generation high-strength steel developments and in automotive applications. DP steels evolved from early research on dual phase steels in the late 1970s and early 1980s. Their widespread application is mainly due to the fact that their favourable strength and formability parameters result in a significantly more favourable property combination compared to conventional high-strength steels, such as HSLA.

DP steels have high specific strength, good initial deformation hardening together with excellent formability. These properties make it particularly suitable for the production of vehicle body parts, various enclosures and fuel tanks by forming [4].

**Figure 2.** shows temperature-time diagrams of different production possibilities of DP steels (processes A, B and C). In each procedure, the

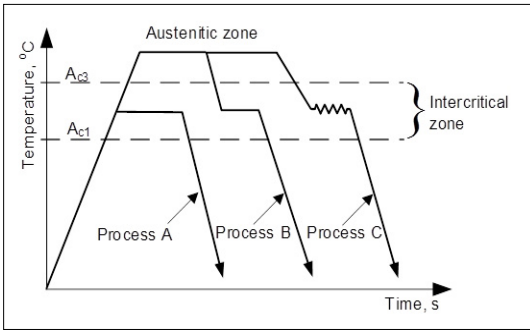


Figure 2. Processing routes of DP-steels.

so-called intercritical temperature is of paramount importance.

Dual Phase (DP) steels contain mainly martensite islands (in some cases bainite) embedded in a ferrite matrix as the second phase. It is characteristic that the continuous ferrite particles provide excellent formability. During forming, the deformation is concentrated on the low-strength ferrite phase surrounding the martensite islands; in addition to the excellent formability, this microstructural feature is also the basis for the significant deformation hardening experienced in DP steels [5].

### 3.1.2. TRIP steels

These steels utilize the phenomenon of transformation-induced plasticity. (The abbreviation TRIP is formed from the initials of the English words Transformation Induced Plasticity). These steels are also excellent for the production of body elements / structures that focus on weight reduction, and at the same time provide additional benefits in terms of increased safety.

One of the main characteristics of TRIP steels is that the transformation of residual austenite present in the microstructure, during processing due to deformation, results in a significant increase in strength, while also having a relatively significant formability depending on the manufacturing process [6].

The microstructure of TRIP steels contains martensite, bainite and residual austenite embedded in a ferrite matrix. Their excellent formability and high strength can be explained by the transformation of residual austenite to martensite due to deformation. This transformation of the phases due to deformation is called the TRIP effect, and results in an excellent combination of strength and deformation, as well as good resistance to dynamic effects.

The typical manufacturing process for TRIP steels is as follows: the steel is heated up to the austenitic zone and kept for the time required to achieve a homogeneous austenitic state. This is followed by cooling to the intercritical temperature and then hot forming the sheet at that temperature. The next step is rapid cooling to the bainite zone and keeping in the bainite range to get bainite in the required amount.

TRIP steels are characterized by a relatively low alloy content. For example, in TRIP 790 steel ( $R_m \approx 790$  MPa), the total amount of alloying elements is about 3.5 weight percent. The selection of the appropriate alloying elements and the amount required to achieve the desired properties are critical to the intended mechanical properties of the alloy. TRIP steels generally have a higher carbon content than DP steels [7].

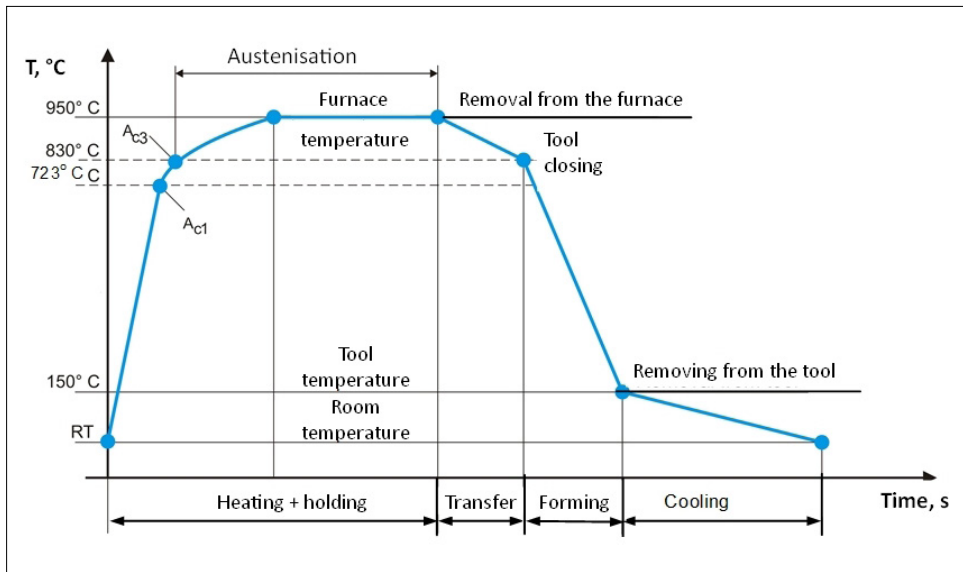
### 3.1.3. Press Hardening Steels – PHS

Among advanced high-strength steels, the application of Press Hardening Steels and Hot Press Forming (HPF) technology is a very special, unique group of advanced high-strength steels. These are mostly manganese steels with different boron content and a wide range of high-strength structural elements (e.g. A-pillars and B-pillars for passenger cars) can be produced from them. Several types are known, of which 22MnB5 is considered the basic type of PHS steels.

A typical temperature-time diagram of the hot press forming + hardening in the tool process is shown in Figure 3.

With the appropriate combination of heating, holding, forming and rapid cooling, complex components with excellent strength properties can be produced by the process shown in Figure 3. [8]. There are various technological variants of the process, including so-called direct and indirect hot forming.

In addition to these two basic processes, there are other process variants: the final microstructure and the mechanical properties of the component can be controlled very effectively depending on the holding temperature and the cooling process. Depending on the holding temperature, two further process variants can be derived: complete austenitisation can be considered as the basic variant, i.e. when the holding temperature is chosen in the homogeneous  $\gamma$ -zone. Depending on the holding temperature, a further process variant can be used if the holding temperature is chosen in the intercritical range (i.e. between  $A_1$  and  $A_3$  temperatures), which means that there



**Figure 3.** Time-temperature diagram of Hot Press Forming.

is no complete austenitisation. The initial microstructure at this holding temperature contains ferrite and austenite, in quantities depending on the position of the actual holding temperature between the critical temperatures  $A_1$  and  $A_3$ . In this case only the austenite content can be converted to martensite and the final microstructure will contain a certain amount of ferrite after forming and rapid cooling. Obviously, this variant results in lower strength compared to total austenitisation, while also providing better formability and better toughness characteristics.

Additional process variants can also be derived by varying the cooling rate after forming. If the cooling rate is lower than the upper critical one, the final microstructure contains bainite in addition to martensite. This results in lower strength depending on the amount of bainite, but together with increased toughness; bainite may be advantageous due to its better energy absorption properties in parts where impact resistance and fracture safety play a key role, increasing the fracture toughness of the part.

It is important that the forming should be completed above the  $M_s$  line (i.e. above the initial temperature of martensitic transformation): these material qualities still have sufficient formability at this stage. After forming, the part is cooled together with the tool: this cooling must provide the critical cooling rate in order to obtain the required amount of martensitic microstructure. With this process, post-forming springback can

be reduced significantly and parts with excellent strength properties can be transformed into complex geometries.

Typical hot-pressed steels (PHS) also have a tensile strength of  $R_m = 1500\text{--}2000$  MPa. In recent decades, these process variants have been widely used in various safety and impact-resistant body parts. The new generation PHS steels even reach strengths above 2000 MPa. These PHS steels and the process variants analysed above are mainly used in the production of elements where, in addition to increased fracture safety, small deformations are typically allowed (e.g. A- and B-column reinforcements, various sill elements, floor panels, etc.).

### 3.2. Second Generation Advanced High Strength Steels

The 2<sup>nd</sup> generation of advanced high-strength steels (2G-AHSS) are represented by steel developments in the range  $R_m \times A_{80} = 40,000\text{--}65,000$  (MPa·%). The most characteristic representatives of this group are the TWIP steels with twin-induced plasticity, but also some corrosion-resistant austenitic steels (AUST SS) with high Mn-content and L-IP steels called Lightweight Induced Plasticity steels belong to this group. These steels provide an excellent combination of strength and formability, however, despite their excellent properties, this group has not yet achieved a real breakthrough in automotive applications, mainly due to low production productivity and high production costs.

### 3.2.1. TWIP steels

TWIP steels are based on the special mechanism by which an outstanding balance between strength and formability characteristics can be achieved by utilizing the deformation twin mechanism. The name of the steel group is also derived from this characteristic mode of deformation, i.e. the acronym abbreviation for the English name for twin-induced plasticity (TWIP). Twin formation results in a significant increase in the hardening exponent, the  $n$ -value, due to the increasingly fine microstructure associated with the twin formation mechanism.

TWIP steels typically have a high manganese content ( $Mn=17\text{--}24\%$ ), as a result of which the steel is completely austenitic even at room temperature. These steels have an outstanding strength-formability combination (for example, even with a tensile strength above  $R_m > 1000$  MPa, a total elongation of up to 50% can be achieved), i.e. TWIP steels also show extremely high formability in addition to very high strength [9].

Another feature of TWIP steels is the high hardening exponent, which can reach  $n \geq 0.4$ . For TWIP steels, the stability of the strain hardening is closely related to the Stacking Fault Energy (SFE). This parameter basically determines the deformation behaviour of TWIP steels.

The characteristics outlined above result in a very exceptional combination of strength and formability, which places the constant value of  $R_m \times A_{80} = \text{Constant}$  in the range  $C = 40,000\text{--}65,000$  MPa% outlined in Figure 1. Despite these outstanding mechanical properties, TWIP steels have not achieved breakthrough application success in the automotive industry, mainly due to low productivity and high costs.

### 3.2.2. Austenitic corrosion-resistant steels

The excellent properties of austenitic stainless steels are well known and are used in many fields. Their use in the automotive industry came to the forefront of research during the development of 2<sup>nd</sup> generation high-strength steels.

Austenitic stainless steels typically have a high chromium and nickel content. Their most typical representatives are the classic 18/8 stainless steel with 18% Cr and 8% Ni, which, in addition to its excellent corrosion resistance, also has excellent mechanical properties. In this respect, their significant cold strain hardening capacity is particularly remarkable. These steels are characterized by low yield strength, high ductility, high tensile

strength and excellent toughness properties.

The excellent formability characteristics of such steels are due to the 12 sliding system resulting from the face centred cubic crystal system. In addition, the minimum amount of interstitial elements should be mentioned, as this also contributes to the operation of the barrier-free dislocation sliding mechanism and thus to the excellent plasticity characteristics.

AUST SS steels are typically produced by continuous strip casting and hot sheet rolling. The sheets thus produced are cold-rolled to the desired thickness and the resulting hardening is achieved in a hydrogen / nitrogen protective atmosphere. During the recrystallization, a sufficiently fine particle structure and the dissolution of any carbide precipitates are ensured by an appropriate thermal program. After annealing, cooling should be performed at a sufficient rate to avoid precipitation of carbides.

### 3.2.3. Lightweight Induced Plasticity – L – IP steels

Special types of weight reduction induced plasticity steel developments are Lightweight Induced Plasticity steels, which are referred to as L-IP steels. This designation is mainly used for the Fe-Mn-Al-C alloy type, for which the Al content is a special feature: Al is the key alloying element in providing mass reduction [10].

In terms of alloying elements, Mn and C are austenite forming and Al are ferrite-stabilizing and increase the metastable dissolution of C by reducing the diffusion capacity. L-IP steels with a suitable chemical composition result in a triplex microstructure containing austenite, ferrite and  $\kappa$ -carbides – (Fe, Mn)<sub>3</sub>AlC.

## 3.3. Third generation advanced high strength steels

The main goal of the development of 3<sup>rd</sup> generation high strength steels (3G-AHSS) is to achieve mechanical property combinations in the range of 1<sup>st</sup> and 2<sup>nd</sup> generation AHSS steels with less alloying quantities and consequently more economical, lower cost production with a wide range of applications achieved in a short time. We present some recent development results from this group.

### 3.3.1. Quenching & Partitioning – Q&P steels

Steels produced by rapid cooling (quenching) and partitioning are the result of the latest developments in third generation AHSS steels: they are

referred as Q&P steels, i.e. Quenched and Partitioned steels. Q&P steels typically contain alloys of carbon, manganese, silicon, nickel and molybdenum. Depending on the strength requirements, they contain around 4% alloying elements, which is much less than for second-generation AHSS steels, making it a less expensive manufacturing process [11].

During the heat treatment of Q&P steel, rapid cooling, i.e. quenching is interrupted and the steel is reheated for partitioning. This results in 5–12% stable residual austenite, 20–40% ferrite and 50–80% martensite. The Q&P process can produce steels with a tensile strength above 2100 MPa with a uniform elongation of 9% and a total elongation of about 13%. The deformation behaviour of this steel is comparable to that of DP 980 steel, which can be considered cold-formable.

Q&P steels are a series of C-Si-Mn, C-Si-Mn-Al, or other similar compositions produced by the quenching and partitioning (Q&P) heat treatment process. The microstructure of Q&P steels is ferrite (in the case of partial austenitisation), martensite and residual austenite, which results in excellent strength and deformation characteristics. These properties allow them to be used as automotive parts. Q&P steels are suitable for the cold-forming production of relatively complex automotive components, while increasing fuel economy and passenger safety.

Two basic versions of the Quenching & Partitioning procedure have been developed. The basic version includes a quenching followed by partitioning. The newer version uses the so-called Double-Stabilization Thermal Cycle (DSTC) [12].

The Double Stabilization Thermal Cycle (DSTC), aims to provide a high volume of residual austenite and martensite with sufficient carbon content to provide high strength. Similar to the basic variant analysed above, the aim is also to prevent carbide formation in order to allow as much carbon diffusion from martensite into austenite as possible during the partitioning process. The temperature-time cycle of this process is shown in Figure 4.

The production steps for Q&P steels produced with a double stabilization thermal cycle (DSTC) can be summarized as follows:

1. *Austenitisation.* The first step in the Double Stabilization Thermal Cycle is a full austenitisation process.
2. *Initial rapid cooling.* Austenitisation is followed by a sufficiently rapid, first cooling to prevent possible bainite transformation. This

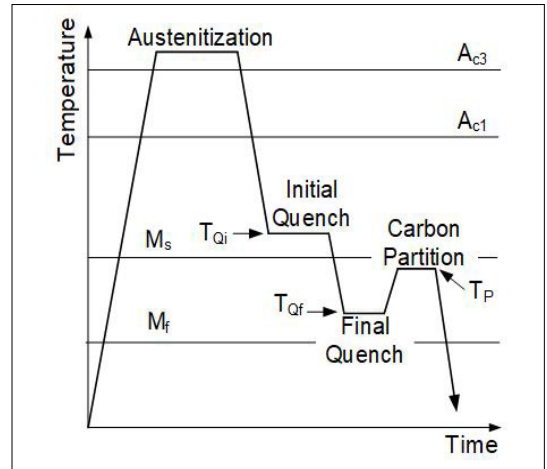


Figure 4. Q&P with Double Stabilization Thermal Cycle).

cooling is continued down to slightly above the initial temperature ( $M_s$ ) of the martensitic transformation. At this temperature, austenite is primarily stabilized.

3. *Finishing fast cooling.* The initial rapid cooling is then followed by rapid cooling to a temperature above  $M_f$ , where the austenite / martensite ratio is adjusted by the appropriate holding time.
4. *Carbon partitioning.* Partitioning is carried out below the temperature  $M_s$ : the purpose of this is a secondary stabilization in which carbon diffuses from the martensite into the austenite, increasing the carbon content of the austenite and thus increasing its stability. As a result, the resistance of austenite to martensite is further increased.
5. *Air cooling.* The steel containing about 30% austenite, 23% ferrite and 47% martensite is then cooled down to room temperature in air. Additional Si and Al alloys are added to prevent carbide formation.

### 3.3.2. Bainite-ferrite steels utilizing the TRIP effect

Third-generation high-strength steels represent a further remarkable development of low-alloy bainite-ferrite (TBF) steels utilizing the TRIP effect. Various literature refers to TBF steels utilizing the TRIP effect, some literature refers it as  $\delta$ -TRIP steels, referring to lower density based on aluminium content.

The microstructure of TBF steels consists of a bainite-ferrite matrix with residual austenite

particles. The typical chemical composition of TBF steels contains as main alloying elements C, Si and Mn. Other common alloys are Al, Nb and Cr in various composition combinations [13]. Si inhibits carbide formation during bainite phase transition, which increases the C content of residual austenite and thus allows stabilization of residual austenite with carbon.

One of the major advantages of these steels over Q&P steels is that they can be produced in conventional heat treatment facilities, while the production of Q&P steels has required significant conversion of heat treatment facilities. They are produced from the fully austenitic microstructure by isothermal heat transfer in the bainite range after rapid cooling.

### 3.3.2. Nano Steels

Another group of third-generation, high-strength steels, is the so-called Nano-steel®, which is still mostly in the development stage, and is not commercially available yet. This type is characterized by a nano-crystalline structure created by a special chemical composition and heat treatment. After casting, the steel has a predominantly austenitic microstructure with some boride. After heat treatment, the austenite is refined to a nanometer scale. During plastic deformation, stress-induced nano-scale phase formation increases the ability of the deformation to harden, i.e. the strain hardening ability [14].

## 4. Conclusions

The automotive industry is facing increasing demands in recent decades. Growing demands can be observed in terms of both users and legal requirements. On the consumer side, there is a need for passenger cars that are increasingly economical, lower in consumption, but at the same time offer a higher level of comfort and safety. This is complemented on the legal side by increased environmental standards aimed at achieving the lowest possible emissions. In meeting these requirements, weight reduction plays a key role in the automotive industry. Weight reduction needs increasingly necessitate the use of high strength sheet materials.

The development of high-strength steels is of paramount importance for mass reduction needs. In recent decades, three generations of the development of high-strength steels - first, second and third generation, have been observed in the development of advanced high-strength steels.

In this paper, we have reviewed three generations of steel developments, presenting the key representatives of each generation, analysing the key characteristics of each high-strength steel, their manufacturing processes and their applications in the automotive industry.

Some of these developments (eg DP and TRIP steels) have already been widely used in the automotive industry, while some types (mainly the second generation developments such as TWIP steels) have not yet been used due to lower production productivity and higher production costs.

The latest, promising phase of the developments is the elaboration of third-generation high-strength steels, which aims to bridge the gap between first- and second-generation developments. In the development of this group, it is of paramount importance that the designed excellent mechanical properties are achieved with fewer alloys and thus at a lower cost, especially compared to 2<sup>nd</sup> generation steels.

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