Three Generations of Advanced High Strength Steels in the Automotive Industry

Miklós Tisza(✉)

University of Miskolc, Miskolc 3515, Hungary
tisza.miklos@uni-miskolc.hu

Abstract. Sheet metal forming is one in all the foremost important production processes in car manufacturing; therefore its developments are significantly determined by the demands of the automotive industry. Recent trends in car production are also characterized by applying lightweight principles. Its main priority is to fulfil both the customers' demands and also the increased legal requirements. Applying high strength steels could also be thought to be one in all the potential possibilities. Applying high strength steels have a positive response for several of the requirements: increasing the strength may result in the appliance of thinner sheets leading to significant mass reduction. Mass reduction ends up in lower consumption and increased environmental protection. Increasing strength often leads to a decrease in formability. In this paper, an outline of recent material developments within the automotive industry concerning the employment of recent generation advanced high strength steels are going to be given.

Keywords: Advanced High Strength Steels - AHSS · Automotive industry · Lightweight manufacturing

1 Introduction

Increasing global competition in car-making requires low-cost production, which is strongly connected with lightweight manufacturing. The need for lightweight manufacturing within the vehicle industry may be explained by several reasons: the continuously increasing environmental restrictions, the requirement for the reduction of harmful emissions, and the higher safety requirements should be mentioned. Fulfilling these requirements, weight reduction has a decisive role. Within the total weight of an automobile, the car body incorporates a determinant role. Sheet metal forming thought to be one in all the foremost important manufacturing processes in the production of car body elements. This is why the elaboration of new, low-cost manufacturing processes is one of the main objectives in sheet metal forming: in this respect, the lightweight production principles are of utmost significance. The two main possibilities for producing lightweight automotive parts are the applying of high strength steels or lightweight materials – especially various high strength aluminum alloys [1]. In this paper, I mainly concentrate on Advanced High Strength Steel materials. First, the main requirements

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and the driving forces for car manufacturing will be overviewed. It will be followed by the classification of Advanced High Strength Steels (AHSS) steels introducing some important representatives of 1st, 2nd and 3rd generation AHSS materials.

2 Main Requirements in the Automotive Industry as the Driving Forces of Car Manufacturing and Sheet Metal Development

Considering the main requirements for the automotive industry in recent decades, the main driving forces of material developments can be clearly defined, too.

The global competition in car manufacturing is very strong and furthermore, the requirements are often contradictory: for example, from the customers' side more economical, more safe and higher comfort together with better performance are the most important issues. These are further increased by legal requirements as the ever-increasing environment restrictions including the reduction of harmful emissions and also higher safety requirements. Some of these legal requirements are in accordance with the customers' demands, however, some impose further requirements. Due to the worldwide competition in car manufacturing, the automotive industry has to find the best answers to these challenges. To meet these requirements is hardly possible with conventional materials and manufacturing methods. This is often one of the most reasons that the development trends in the automotive industry are the most driving forces in material development and sheet metal forming, too.

In the fulfillment of these manifold requirements, the weight reduction has an important role: reducing the overall weight of vehicles results in lower consumption, and thus less harmful emissions together with more economical vehicles and increased environmental protection. If we analyze the potential weight reduction in various parts of a regular automobile, it can be stated that about 45% of the total weight is covered by the body parts, chassis and suspension elements [2], thus, the main focus should be placed on these components. These parts are mostly produced by sheet metal forming, therefore sheet metal forming as a key technology has a critical role in the weight reduction of automobiles.

3 Material Development Tendencies in Sheet Metal Forming Concerning the Lightweight Production Principles in Car Manufacturing

Lightweight production principles led to the intensive development of recent, new materials. Concerning steel materials, these developments resulted in the widespread application of assorted grades of high strength steels. The origin of those developments may be traced back to the mid-seventieth when the first examples of micro-alloyed steels arrived in the economic, industrial application. Since then, thanks to the continual pressure on material development several new high strength steel grades appeared and reached already the everyday industrial application. Systematic analysis of those developments may be found in several papers from various authors in the literature [3–7]. In the following sections, a systematic scientific classification of those developments will be summarized.

3.1 Classification of Steel Developments

Steel developments are classified in several alternative ways. One usual way of classification is completed per the metallurgical designation. In step with this, steels can be grouped into the subsequent types: low strength steels (including mild steels, interstitial free IF-steels), conventional high strength steels like Carbon-Manganese (C-Mn) steels, Bake-Hardenable (BH) steels, High Strength Low Alloyed (HSLA) steels, and also the newer varieties of Advanced High Strength Steels (AHSS), e.g. Dual Phase (DP) steels, Transformation Induced Plasticity (TRIP) steels), Twinning Induced Plasticity (TWIP) steels, Complex Phase (CP) steels, Martensitic (MS) steels. In recent years, several new AHSS grades have been developed, e.g. TRIP-aided Bainitic Ferrite (TBF), Quenching & Partitioning (Q&P), or different kinds of NanoSteels: of these with the primary aim supplying even higher strength parameters with significantly increased formability.

Recently, widely applied classification relies on mechanical properties – mainly strength and formability parameters as the Ultimate Tensile Strength (UTS) and Total Elongation (TE) as shown in Fig. 1. This kind of classification is often used together with the designation of steel generations' development, as well.

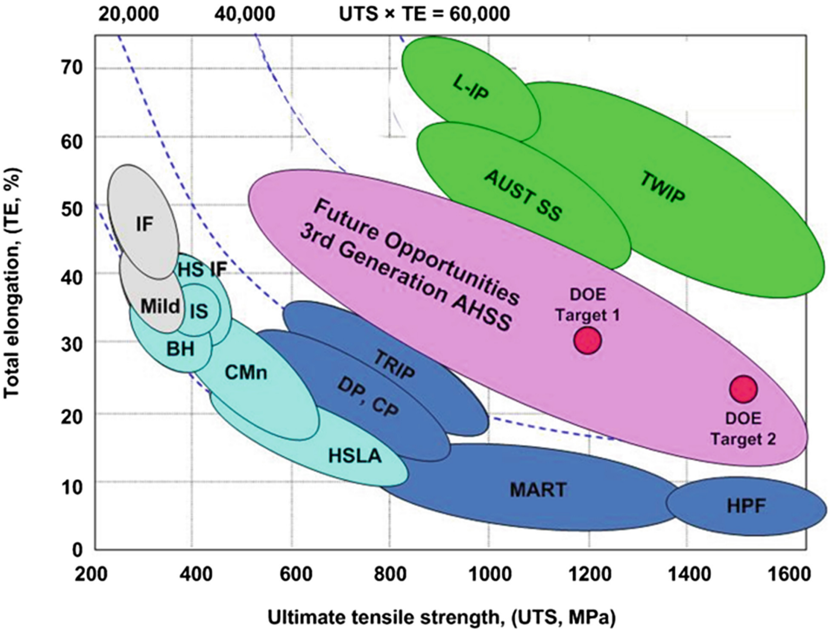

Fig. 1. Ultimate Tensile Strength (UTS) vs Total Elongation (TE) for various generations of high strength steels [4]

In Fig. 1, the relationship between strength and ductility parameters can be seen applying the classification method mentioned above. This classification added with a graphical representation, too. The product of the ultimate tensile strength and the total elongation (UTS × TE) follows a hyperbolic function, as it can be well seen from Fig. 1.

The constant (C = UTS × TE) provides a good basis for further classification of newly developed Advanced High Strength Steels.

In Fig. 1, the conventional mild steels (IF and Mild steels) formerly widely applied in Body in White (BiW) production in the automotive industry, the group of conventional high strength steels including Bake Hardening (BH), Isotropic (IS), High Strength Interstitial Free (HS IF), Carbon-Manganese (CMn) and High Strength Low Alloyed (HSLA) steels. Following the wide-spread application of conventional high strength steels, intensive development was initiated in the steel industry in close cooperation with the automotive industry to develop alternative types of Advanced High Strength Steels (AHSS) that may better fulfill the needs of lightweight principals building automotive structures.

In the next sections, some results achieved in the development of three generations of Advanced High Strength Steels will be overviewed.

4 Main Groups of Advanced High Strength Steels (AHSS)

AHSS are complex, sophisticated materials, with carefully selected chemical compositions and multiphase microstructures, achieved by precisely controlled heating and cooling processes. Various strengthening mechanisms are applied to get significantly increased strength, better formability, improved toughness, and fatigue properties to meet the various requirements that are defined for automotive body structures. We will discuss the main groups of Advanced High Strength Steels according to their development stages.

4.1 First Generation Advanced High Strength Steels (1G-AHSS)

There are several new materials grades among the 1st generation AHSS, among them the Dual-Phase-, Complex Phase-, TRIP- and MS or often termed as PHS-steels (PHS stands for Press Hardening Steels). From this 1st generation AHSS, DP- and TRIP-steels are the most characteristic members that are most widely applied in the automotive industry. Obviously, we have to mention the PHS-steels, too, but since the application of these steels requires special dedicated Hot Press Forming (HPF) processes, in this respect, we refer to an overview of this special field summarized in [8]. In this section, we will only analyze in detail the DP- and TRIP-steels.

Dual-Phase (DP) Steels

Development of Dual-Phase (DP) steels started at the beginning of the new age of steel development. Current commercially available AHSS steels have evolved from the early work on Dual-Phase steels within the late 1970s and early 1980s. Dual-Phase steels are one in all the foremost widely applied Advanced High Strength Steels in today's car making industry. This is often mainly thanks to their better strength and formability parameter combination compared to the conventional high strength steels like HSLA steels. For DP steels, high specific strength and good initial work hardening rate are characteristic besides the continuous yielding behavior, and superior ductility compared to standard steel grades. These properties make them particularly suitable for producing various body structures, closures, etc. in vehicles [9].

Dual-Phase (DP) steels generally have a ferrite matrix containing mainly hard martensite or in some cases bainite second phases as islands as shown in Fig. 2. It is very characteristic that the ferrite phase is usually continuously providing excellent ductility. During forming, the strain is concentrated within the lower strength ferrite phase surrounding the martensite islands providing a unique work hardening rate.

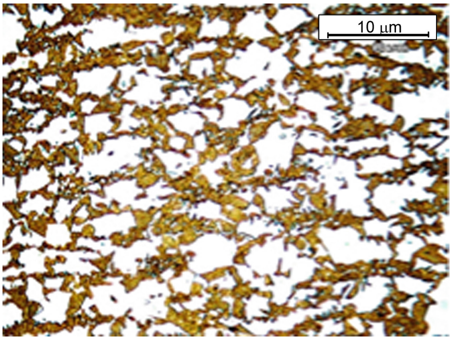

Fig. 2. Micrograph of a DP 690 steel containing martensite islands in ferrite matrix

Processing of DP Steels
There are various processing routes for producing DP steels. The time-temperature diagrams of the three most widely applied manufacturing processes can be seen in Fig. 3.

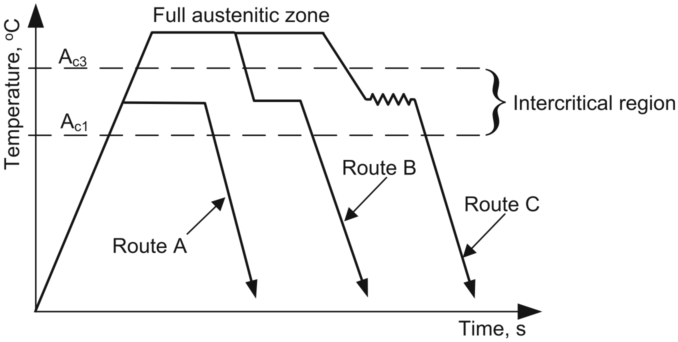

Fig. 3. Three different processing routes for producing DP steels

The first method – shown as Route A in Fig. 3 – means a rapid cooling from the intercritical temperature directly to room temperature. The resulting microstructure comprises ferrite and martensite. Higher intercritical temperatures, for the same holding period, result in larger amounts of martensite with increased tensile strength and decreased percentage elongation [10].

The other method for processing of DP steels (Route B in Fig. 3) first involves a slow cooling from the austenitic region to the desired ferrite transformation temperature, followed by quenching to room temperature for transforming the remaining austenite to martensite [11]. This processing route results in lower tensile strength and higher ductility than those gained by Route A.

The third method for producing DP steels (Route C in Fig. 3) involves hot rolling of steel in the intercritical region with a slow cooling rate, then followed by second cooling at a very fast rate and finally slow cooling (i.e. coil cooling) to room temperature. This method of cooling is known as ultra-fast cooling (UFC) and the processing route is referred to as new generation thermo-mechanical controlled processing [12]. Better properties obtained by Route C compared to those obtained by either Route A or Route B due to the higher grain refinement achieved during rolling.

Transformation Induced Plasticity (TRIP) Steels

Advanced high-strength transformation-induced plasticity (TRIP) steels are highly compatible for light-weighting car body construction with an additional advantage to reduce the safety problems. One amongst the main features of TRIP steels that the strain- or stress-induced transformation of retained austenite present within the microstructure in a sufficient amount can substantially harden the steel during deformation looking on the processing route, and so ends up in a better ductility [13].

The microstructure of TRIP steels contains retained austenite embedded in an exceedingly primary matrix of ferrite. Usually, about five volume percent of retained austenite, hard phases like martensite and bainite are present in varying amounts. Figure 4 shows the schematic microstructure of TRIP steel (TRIP 700).

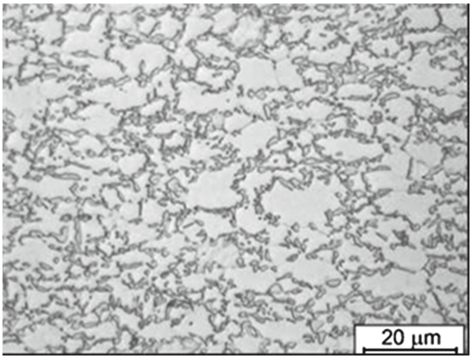

Fig. 4. Micrograph of a typical TRIP steel (TRIP 700)

TRIP steels may have been characterized by a comparatively low content of alloying elements. As an example, in TRIP 790 steel (UTS =790 MPa), the overall content of alloying elements is about 3.5 wt. Percent. Thus, the appropriate selection of suitable alloying elements and also the amount required to get the planned properties is critical during the alloy design stage. The carbon content in TRIP steels is more than in DP steels. Carbon is mostly kept within the range of 0.20–0.25% due to weldability reasons.

The upper carbon content is necessary for stabilizing the retained austenite phase to below ambient temperature. In TRIP steels, austenite stabilizers are present, mainly C, Mn, and/or Ni. These elements assist in maintaining the mandatory carbon content within the retained austenite. TRIP steels mainly contain multi-phase microstructures composed of about 50–55% ferrite, 30–35% bainite, 7–15% retained austenite, and 1–5% martensite.

The outstanding combination of ductility and strength in TRIP steels may be a result of deformation supported the transformation of retained austenite to martensite. This transformation (on deformation) of phases is termed the TRIP effect that has excellent strength and elongation combination along with high impact resistance. These characteristics predestinate TRIP steels as a decent candidate for the third generation AHSS, too. Dispersed hard second phases in soft ferrite provide high work hardening rate, as experienced in DP steels, too. Furthermore, in TRIP steels the retained austenite progressively transforms to martensite with increasing strain, thereby increasing the work hardening rate at higher strain levels [14].

Processing Methods of TRIP Steels

The basic processing route of TRIP steels consists of heating the steel to the full austenitic zone, and after the necessary soaking time cooling down to the intercritical region followed with deformation here, and quick transfer to the bainitic zone with subsequent holding there, and finally quenching to room temperature (shown in Fig. 5).

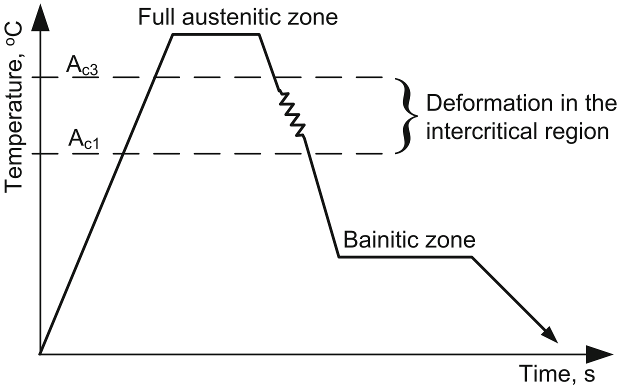

Fig. 5. Conventional processing route of TRIP steels

The deformation within the inter-critical region increases the speed of the transformation of austenite (γ) to ferrite (α). The remaining austenite is enriched with carbon content, which stabilizes the γ phase. Furthermore, this deformation increases the nucleation rate of bainite but decreases the rate of growth that leads to small plates of bainite. This also helps the enrichment of the γ phase in carbon and further increases its stability. The stability of retained austenite is enhanced by the high carbon content and the more carbon in γ phase results in more stability of γ during the TRIP effect, too, since more stable austenite needs longer time to be transformed into martensite; simultaneously, these processes contribute to the increase of the ductility, too. With this process, an improved strength–ductility combination is achieved [15]. Obviously, the described processing method for TRIP steels is more time-consuming. This is due to the need for special arrangements to deform the material at high temperature, to hold the specimen in the bainite region, and so on. This limits the use of TRIP steels in industrial applications. Some authors [16] using this route reported that rolling in the intercritical region improves TRIP steel properties by enhancing the carbon content and dislocation density, decreasing the grain size, and leading to a granular type morphology.

4.2 Second Generation of Advanced High Strength Steels (2G-AHSS)

The 2nd generation of Advanced High Strength Steels was the next step in steel development. These steels can be found in the range of $R_m \times A_{80} = 40.000–65.000$ (MPa%). Twinning Induced Plasticity, i.e. TWIP-steels are the most characteristic representatives of this group, however, there are some other material grades like high Manganese austenitic stainless steels (AUST SS) and the so-called Lightweight Induced Plasticity (L-IP) steels, too. In this section, we will only introduce the most characteristic type, i.e. the TWIP-steels.

Twinning-Induced Plasticity (TWIP) Steels

TWIP steels have a superior balance of tensile strength and elongation using the TWIP effect. The name of TWIP steel is originated from its characteristic deformation mode, i.e. the twinning induced plasticity. The twinning causes high value of the instantaneous hardening rate (n-value) as the microstructure becomes finer and finer. The resultant twin boundaries serve as grain boundaries and strengthen the steel.

TWIP steels have high manganese content (Mn = 17–24%) that results in fully austenitic microstructure even at room temperatures. TWIP steels are normally composed of Fe, Mn, or Ni (15–35%), Si (1– %), and Al (1–3%) [17]. These steels exhibit outstanding tensile strength-ductility combinations (e.g. a TWIP steel with tensile strengths above 1000 MPa may possess 50–60% ductility) [17]. The n-value may increase to a value of 0.4 that may result in 50–60% uniform elongation. In many grades in this group, the tensile strength may be even higher than 1500 MPa [18].

In TWIP steels, the strain hardening is strongly dependent on the stacking fault energy (SFE). This parameter controls the deformation behavior of the steel. Alloying elements generally decrease SFE leading to enhanced twinning behavior during deformation and hence lead to improved ductility. It is also known that SFE < 20 mJ/m^2 causes austenite to martensite conversion, and by this results in the TRIP effect. For pure twinning, SFE is desired to be greater than 20 mJ/m^2. Aluminum is added to steel to raise SFE, to retard the TRIP effect, and to result in pure twinning. Typical microstructure of a TWIP-steel is shown in Fig. 6.

TWIP steels show excellent mechanical performance with extremely high strength and ductility properties. Unfortunately, this category is not really viable for industrial applications due to its limitations: poor productivity and high production costs. The usual processing of TWIP steels includes homogenizing above the upper critical temperature and quenching to room temperature [19]. TWIP steels are often produced by homogenizing followed by deformation at temperatures above the upper critical one, with subsequent quenching to room temperature. Deformation at higher temperature

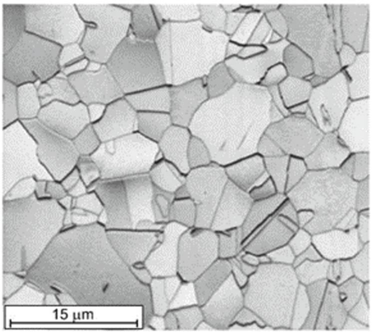

Fig. 6. Micrograph of a TWIP steel in annealed condition

provides fine grain size and a high volume fraction of twins. The finer the grain structure the more twinning occurs that improves ductility and strength. Two kinds of twins are observed in TWIP steels: (a) annealing twins caused by heat treatment, and (b) deformation twins caused by plastic deformation.

4.3 Third Generation of Advanced High Strength Steels (3G-AHSS)

The main target in developing the 3rd generation AHSS was to achieve the properties in the range between the 1st and 2nd generation AHSS with less alloying elements, hence, with less expensive processing that is suitable for early commercialization. The group of 3rd Generation AHSS (3G-AHSS) development may be clearly identified on the diagram of Tensile Strength vs Total Elongation between the 1st and 2nd generation AHSS regions (see Fig. 1).

Medium Manganese Steels combining the TRIP and TWIP effects, Quenched and Partitioned (Q&P) Steels, TRIP assisted Bainitic-Ferritic Steels (TBF) and NanoSteels are usually considered to belong into this group of AHSS.

In this section, we will mainly deal with the two most promising examples of this group, i.e. the Quenched and Partitioned (Q&P) Steels and TRIP assisted Bainitic-Ferritic Steels (TBF).

Quenched and Partitioned (Q&P) Steels

Quenched and Partitioned (Q&P) steels are one of the main results of the recent developments of 3rd generation AHSS steels. The theory of Q&P steels is partly based on the knowledge of duplex stainless steels and the quenching and partitioning process [20]. The Q&P steels usually contain carbon, manganese, silicon, nickel, and molybdenum alloying elements. The quantity of alloying elements is around 4 percent, which is far below that of within the 2nd generation AHSS. During heat-treatment of Q&P steel, quenching is interrupted and is reheated for partitioning. With this reheating process, a unique microstructure is formed containing 5 to 12 percent stable retained austenite, 20 to 40 percent ferrite, and 50 to 80 percent martensite.

The concept of Q&P process for automotive materials was first published by Speer in 2003 [21]. In Q&P process, the steel is quenched down below the M_s temperature, where austenite is not fully transformed. Thanks to the alloying concept of Q&P steels, this temperature usually is within the range of 200–350 °C. It implies that the microstructure may be a mixture of martensite and austenite. Steel is then reheated and aging is completed between 300–500 °C; this is termed the "partitioning step". During this treatment, carbon diffuses from the supersaturated martensite, providing the carbon enrichment of austenite, which increases its stability at room temperature; furthermore, it supports further TRIP effect during deformation.

However, the complex evolution of the microstructure during partitioning and the detailed mechanisms are not fully revealed, many of the Q&P evolutions are still a matter of debate. For example, the formation of bainite during partitioning cannot be completely excluded; it could explain the measured carbon enrichment in the retained austenite because the partitioning temperatures are per those for bainite formation.

Though the detailed mechanisms are not fully explained, the benefits of Q&P treatment are clearly shown by the improved mechanical properties. The range of strength that may be achieved with this new concept is between 1,000 and 1,500 MPa, with a total elongation of 20%. Moreover, because the matrix may be quite tempered martensite, damage resistance is improved compared to DP or TRIP steels with identical strength levels.

Recently, Q&P steels with 2,100 MPa tensile strength together with 9 percent uniform elongation and about 13 percent total elongation were developed. The elongation level of this steel is reminiscent of DP 980 that is a cold-formable grade. Q&P steels, initially with 980 MPa and later 1,180 MPa strength were first developed by Baosteel [22].

The development of Q&P steel grades required a very important modification of the annealing lines. Quenching and reheating step was not possible until recent years. The strong demand from the automotive market towards 3rd generation advanced high strength steels has led steel making companies investing in the upgrading of their annealing lines to make sure the processing of Q&P steel products.

Processing of Q&P Steels

Q&P steels are a series of C-Si-Mn, C-Si-Mn-Al or other similar compositions that are processed by the quenching and partitioning (Q&P) heat-treatment process. Q&P steels possess an excellent combination of strength and ductility with a final microstructure of ferrite (in the case of partial austenitization), martensite and retained austenite. This microstructure makes them suitable to use in the automotive industry as a new generation AHSS. They are suitable for cold stamping of various structures and safety parts having complicated shapes to improve fuel economy and promoting passenger safety.

It is possible to change the amount of retained austenite at room temperature and its stability with alloying elements such as carbon, manganese, nickel, etc. However, it affects the cost and may be detrimental concerning the welding properties. The third generation of AHSS grades was developed to overcome these disadvantages; one of the good examples are those 3rd generation AHSS that is based partly on the quenching-and-partitioning process (Q&P steels) and on the properties of the medium-manganese steels. In this case, the composition of steel is not adequate for keeping the retained austenite at room temperature, but annealing, cooling, and thermal processes are optimized to change the austenite's composition and decrease its Ms temperature. For medium-Mn steels, where a relatively larger manganese amount (typically 5 to 8 wt. %) is characteristic slightly simplifies the thermal treatment. The intercritical annealing provides a chance to form austenite and to increase its carbon and manganese content; then the steel is cooled down to room temperature. The complex multiphase fine-grained microstructure together with the TRIP effect arising from the progressive transformation of the retained austenite during deformation provides excellent mechanical behavior. By these processes, the UTS above 1,200 MPa and uniform elongation larger than 12% can be achieved.

There are two main versions of Quenching&Partitioning process. The basic version includes a fast quenching from the austenitization temperature down to the temperature slightly above the M_f temperature and followed by the partitioning below the M_s temperature as shown in Fig. 7.

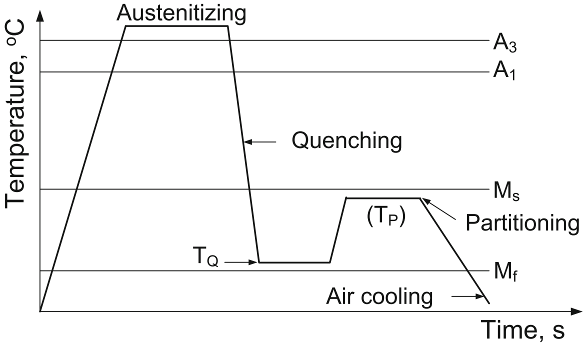

Fig. 7. Basic process of Quenching&Partitioning

There is a newer version of Quenching&Partitioning applying Double-Stabilization Thermal Cycle – DSTC as shown in Fig. 8.

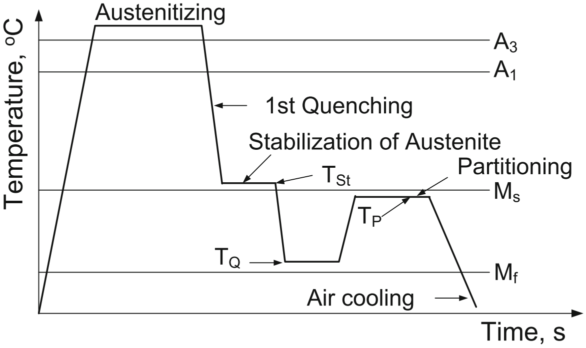

Fig. 8. Quenching&Partitioning applying Double-Stabilization Thermal Cycle (DSTC)

The main processing way of this newer Quenching&Partitioning steel grade with DSTC thermal cycle may be summarized by the following steps:

1. *Full Austenitization* is the first step in Quenching&Partitioning applying Double-Stabilization Thermal Cycle, too.
2. *1st Quenching:* the full austenitization is followed by a 1st or Initial Quenching down to the temperature slightly above the M_s temperature to avoid bainitic transformation of austenite. Applying this step, the austenite is further stabilized.
3. *Finish Quenching:* the initial quenching is followed by a finish quenching above the M_f temperature setting up the retained austenite/martensite ratio.
4. *Carbon Partitioning:* Carbon Partitioning is done slightly below the M_s temperature. During this carbon partitioning, the carbon will diffuse from the martensite to austenite thus providing even higher stability of austenite to resist its transformation to martensite.
5. *Air Cooling:* from the temperature of carbon partitioning air cooling may be applied to room temperature to get the required austenite-ferrite-martensite ratio.

TRIP Assisted Bainitic-Ferritic (TBF) Steels

TRIP assisted bainitic-ferritic (TBF) steels may be considered as a further significant development step among the 3rd generation AHSS. Their microstructure contains bainitic-ferritic matrix with retained austenite particles. Typical chemical compositions of TBF steels contain C, Si and Mn as major alloying elements. Alloy modifications include variations of the Al, Nb and Cr content [23]. The cementite formation during bainitic transformation is suppressed by the Si constituent. The added Si enhances the C content in retained austenite and it stabilizes the austenite. High Si contents of 1.5 wt % are used in these types of steels.

Processing of TBF Steels

TBF steels are produced by isothermal holding in the bainitic regions after fast cooling from the full austenitic zone. A significant benefit of these steels compared to Q&P steels processing that these can be produced by conventional heat-treatment devices, while the processing of Q&P steels requires significant modifications in the annealing lines.

5 Conclusion

In this paper, the recent developments in Advanced High Strength Steel production and application were overviewed. Considering both the customers' demand and the legal requirements, it was shown that some of these requirements are coinciding while others are contradictory. To fulfil these contradictory requirements, the application of high strength steels may be regarded as one of the most potential developments. Among these developments, the application of new Advanced High Strength Steels (AHSS) may be regarded as the most important one. In the last decades, different grades of AHSS were developed. They are classified as first, second and third generation AHSS. Some of these AHSS grades are already widely applied in the world automotive industry; some still are in the development phase. The main properties, the metallurgical background and the main processing routes of AHSS were discussed.

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