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Development of Lightweight Steels for Automotive Applications

Miklós Tisza

Abstract

The automotive industry plays a determinant role in the economy of developed countries. Sheet metal forming is one of the most important processes in car manufacturing. Recent trends in car production may be characterized by the application of lightweight principles. Its main priority is to fulfill both the customers' demands and the increased legal requirements. The application of high strength steels may be regarded as one of the potential possibilities. Applying high strength steels has a positive response for many of the requirements: increasing the strength may lead to the application of thinner sheets resulting in significant mass reduction. Mass reduction is leading to lower consumption with increased environment protection. However, increasing the strength can often lead to the decrease of formability, which is very unfavorable for the forming processes. In this chapter, an overview of recent material developments in the automotive industry concerning the use of new-generation high strength steels will be given. In this paper, the material developments are emphasized from the point of view sheet metal forming; therefore, our focus is on the body-in-white manufacturing in the automotive industry.

Keywords: high strength steels, automotive industry, low-cost manufacturing

1. Introduction

The ever-increasing competition in the automotive industry requires the application of low-cost production, which is strongly connected with lightweight manufacturing. The need for lightweight manufacturing in the vehicle industry is supported by several reasons: among them, the stringent and further increasing environment restrictions, the need for the reduction of harmful emissions, and the higher safety requirements should be mentioned. In the fulfillments of these requirements, the weight reduction has a determinant role. In the total weight of an automobile, the car body has a decisive role. Sheet metal forming is regarded as one of the most important manufacturing processes in the production of car body elements. Therefore, the elaboration of new, low-cost manufacturing processes is one of the main objectives in sheet metal forming: in these developments, the lightweight production principles are of utmost importance. The two main trends for producing lightweight automotive parts are the application of high strength steels or lightweight materials—especially various high strength aluminum alloys [1]. In this chapter, we will mainly focus on high strength steel materials.

2. Main requirements in the automotive industry as the driving forces of development

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

The competition in car manufacturing is extremely strong, and the requirements are often contradictory: for example, from the customers' side, more economical, safer, and higher comfort together with better performance are the most important issues. These are further increased by legal requirements as the ever-increasing rigorous environment restrictions as the reduction of harmful emissions and higher safety requirements. Some of the legal requirements are in accordance with the customers' demands; some imposes further requirements on car manufacturing. Due to the worldwide competition in car manufacturing, the automotive industry has to find the appropriate answers for these challenges. To meet all these requirements is impossible with conventional materials and conventional manufacturing methods. This is one of the main reasons that the development needs in the automotive industry are the main driving forces in material development, 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 [2], it can be seen that about 45% of the total weight is covered by the body parts, chassis, and suspension elements (**Figure 1**); thus we have to focus on these components. These parts are mainly produced by sheet metal forming; this is why the sheet metal forming as a key technology has a critical role in the weight reduction of automobiles and why lightweight design principles are in the forefront of research and development in the automotive industry.

Applying lightweight design principles in the body-in-white production necessitates the application of thinner sheets; however, both the customers' demand and the legal prescriptions require higher safety. To solve these contradictory requirements, higher strength materials are needed. However, applying higher strength materials, it leads to further contradictions: increasing the strength results in the decrease of the formability. It is well known that strength and ductility (formability) have a hyperbolic relationship. Therefore, it is important to find a good compromise between strength and formability properties. This is a great challenge in material developments that will be analyzed in the next sections.

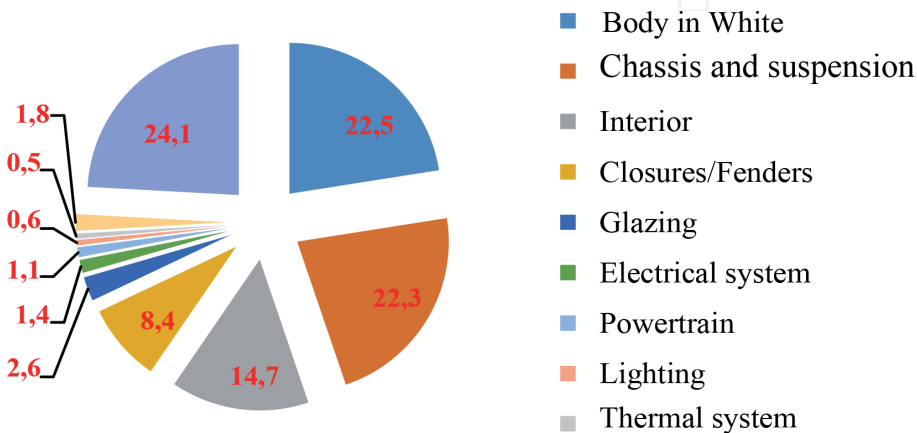


Figure 1.
Weight ratio of various vehicle components [2].

3. Material development tendencies in sheet metal forming with regard to the automotive industry

In the last 40–45 years, the reduction of fuel consumption led to the intensive development of new materials. These developments resulted in the widespread application of various grades of high strength steels. The origin of these developments can be traced back to the mid-seventieth, when the first micro-alloyed steels arrived to the industrial application. Since then, due to the continuous pressure on material development, several new high strength steel grades appeared and reached already the everyday industrial application. Systematic analysis of these developments can be found in several papers from various authors in the literature [3–7]. In the next sections, a systematic classification of these developments will be summarized.

3.1 Classification of steel developments

Steel developments—in general and particularly for the automotive industry—may be classified in several different ways. One usual way of classification is done according to the metallurgical designation. These may be grouped into 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 the newer types 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, new AHSS grades have been developed, for example, Extra Advanced High Strength Steels (X-AHSS) and Ultra Advanced High Strength Steels (U-AHSS), and various types of the so-called third-generation AHSS steels, e.g., TRIP-aided bainitic ferrite (TBF) and Quenching & Partitioning (Q&P) or different types of NanoSteels: all these with the primary aim to provide even higher strength parameters with significantly increased formability.

Another classification introduces various mechanical properties—mainly strength and formability parameters as the Ultimate Tensile Strength (UTS) and Total Elongation (TE). This type of classification is often used together with the designation of development steel generations, as well. In **Figure 2**, the well-known relationship between strength and ductility parameters is shown applying the abovementioned classification method with a graphical representation. From **Figure 2**, it may be also seen that the product of the ultimate tensile strength and the total elongation ($UTS \times TE$) follows a hyperbolic function. The constant ($C = UTS \times TE$) provides further possibility to classify the steel developments by their generation.

In **Figure 2**, the material group shown by gray color includes 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 (colored by light blue) includes bake hardening (BH), isotropic (IS), high strength interstitial free (HS IF), carbon-manganese (C-Mn), and high strength low alloyed (HSLA) steels. Following the conventional high strength steels, an intensive development started in the steel industry in close cooperation with the automotive industry to develop different types of Advanced High Strength Steels (AHSS) to meet the needs of lightweight automotive structures.

The development of first generation of Advanced High Strength Steels for automotive application may be regarded as the first step in this development process. DP steels, Complex Phase (CP) steels, certain types of TRIP steels, and martensitic steels (MART) belong particularly to this group. For these steels, the C constant

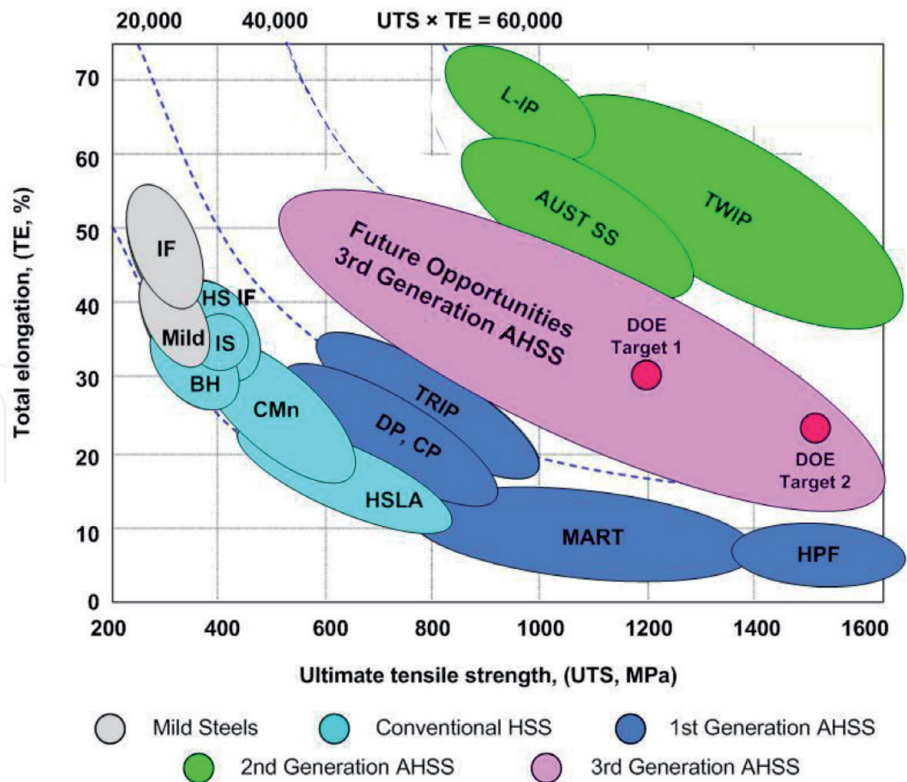


Figure 2. Relationship between ultimate tensile strength (UTS) vs total elongation (TE) for various generations of high strength steels [4].

defined above can be found between 10,000 and 25,000. The first-generation AHSS (often referred as conventional AHSS) grades have good strength but limited ductility.

However, it is worth mentioning that for these Advanced High Strength Steels, the increase of strength parameters is much more significant than the decrease of the ductility parameters. This is particularly valid for the Dual Phase (DP) steels, Complex Phase steels (CP), Martensitic Complex Phase (MART/CP) steels, and TRIP steels. This is the reason why this group gains wide application in car body production.

The group of steels that can be found around the $C = 40,000\text{--}60,000 \text{ MPa} \times \%$ may be regarded as the second generation of Advanced High Strength Steels. This group includes the Twinning Induced Plasticity (TWIP) steels and some austenitic Stainless Steels (AUST SS) with high manganese content. These steel grades provide superior combination of strength and ductility. TWIP steel had successfully been trial-produced at POSCO in the early 1990s, but the trial was not extended to commercialization due to limitations in facilities and productivity [4]. Trial productions have also been made at some European steel companies. These attempts demonstrated the outstanding mechanical performance of TWIP steels; however, these trial productions turned to be commercially unsuccessful due to low productivity and high cost [5]. New approaches and further developments are done continuously to reduce these difficulties and make them suitable for automotive parts manufacturing.

The third generation of AHSS is still in the phase of development—though there are already industrial realizations, too. In this development stage, several new concepts have been already proposed. The main target in developing the third generation of AHSS is twofold, i.e., to achieve mechanical properties in the range between the first- and second-generation AHSS shown in the strength-ductility diagram (Figure 2) but with less alloying elements and, hence, with less expensive

production than the second-generation AHSS steels [6]. The microstructure of these steels consists of a high strength phase (e.g., nano/ultrafine-grained ferrite, martensite, or bainite) combined with a further phase or constituent that provides substantial ductility and work hardening (e.g., austenite). With this development concepts, very high strength steels in the GPa range with even though remarkable formability can be produced [7].

The projected changes in the application of Advanced High Strength Steels is given by Matlock et al. [8] for North American vehicle industry (**Figure 3**), but similar trend may be estimated for other geographical regions, e.g., the European Automotive manufacturers and the Far East countries (China, Japan, and Korea). In **Figure 3**, the changes of the absolute content of AHSS applications (in kg) and percentage changes related to the total weight of vehicles are shown. Both changes show an exponential increase with a slightly higher one concerning the absolute values.

3.1.1 Development projects for Advanced High Strength Steels

In the last 30–40 years, there were several projects studying and initiating the development of new grades of Advanced High Strength Steels. Most of these projects were initiated by automotive companies, and in most cases various consortiums were established for this purpose. Each of these projects aimed to meet as much as possible the requirements analyzed in Section 2.

Among these projects, the Ultralight Steel Automotive Body (ULSAB) satisfied most of the requirements stated for a lightweight automotive structure and proved to be structurally sound, safe, executable, and affordable. Though it was a highly expensive project with the participation of 35 companies representing 18 countries, it could meet the challenges to reduce the weight of steel auto body structures at no additional costs, while maintaining or even improving the overall performance [9].

Further projects followed the ULSAB concept, among them the Ultralight Steel Auto Closures (ULSAC) [10], or the Ultralight Steel Auto Body-Advanced Vehicle Concept (ULSAB-AVC) [11], and the Future Steel Vehicle (FSV) [12]. All these projects led to the further development of Advanced High Strength Steels reaching the GigaPascal range of strength together with increased ductility.

In the previous section, we could see the main material development tendencies and their classification that included various kinds of conventional steels as well,

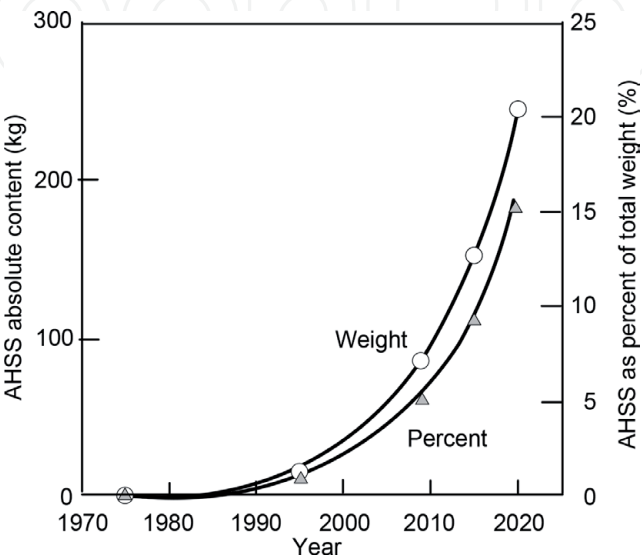


Figure 3.
Projected changes of the absolute amount (kg) and the percentage values for the total weight of vehicles.

which had a prominent role in the history of car making in the last century. In the next sections, we will mainly focus on the main types of Advanced High Strength Steels and their properties.

4. Main types and properties of Advanced High Strength Steels

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 [13].

The group of AHSS materials includes Dual Phase (DP), Complex-Phase (CP), Ferritic-Bainitic (FB), Martensitic (MS), Transformation-Induced Plasticity (TRIP), Hot-Formed Press Hardened (HF, or PHS), Twinning-Induced Plasticity (TWIP) and some austenitic stainless steels (AUST SS) with high manganese content. These first- and second-generation AHSS grades due to their unique mechanical properties are well qualified to meet many of the functional and performance requirements in automobiles. From these generations of AHSS, DP and TRIP steels are excellent in the crash zones due to their high-energy absorption [14], while structural elements of the passenger compartment can be made from extremely high strength steels, such as martensitic and boron-alloyed Press Hardened Steels (PHS), and hence, resulting in improved safety performance.

Recently, there is an increased research interest for the development of the third generation of AHSS. These steels usually apply special alloying and thermomechanical processing to provide improved strength-ductility combinations compared to the present first- and second-generation AHSS grades but at lower costs. There are several good examples for these, e.g., in the USA, a program sponsored by the Department of Energy made available the development of 1200 MPa steels with threefold improvements in ductility [15]. New generation of Advanced High Strength Steel (AHSS) grades contains significant alloying and multiple phases. The multiple phases provide increased strength and ductility not attainable with single-phase steels, such as the high strength, low alloyed (HSLA) grades. In the next sections, these AHSS will be discussed.

4.1 Dual-Phase (DP) steels

As we could see from the historical analysis, Dual-Phase steels have a dominant role in the last 40 years of automotive industry; therefore, we start the overview of Advanced High Strength Steels with this group.

The development of Dual-Phase (DP) steels was right at the beginning of the new age of steel development following the conventional high strength steel era. Current commercially available and widely applied AHSS steels have evolved from significant early work on Dual-Phase steels in the late 1970s and early 1980s. Dual-Phase steels are one of the more widely applied Advanced High Strength Steels in today's car making industry. This is mainly due to their better strength and formability parameter combination than the conventional high strength steels like HSLA steels. DP steels possess high specific strength, good initial work hardening rate, continuous yielding behavior, and superior ductility compared to conventional steel grades. These properties make them particularly suitable for body structures, closures, fuel tanks, etc. in vehicles [16].

Dual-Phase (DP) steels generally consist of ferrite matrix containing mainly hard martensite or in some cases bainite second phase as islands as shown in **Figure 4**. It is very characteristic that the ferrite phase is generally continuous providing excellent ductility. During forming, strain is concentrated in the lower strength ferrite phase surrounding the martensite islands providing unique work hardening rate that is experienced in DP steels.

4.1.1 Processing of DP steels

There are various commonly used processing routes for producing DP steels. One of the methods (Route A in **Figure 5**) involves rapid cooling from the intercritical temperature to room temperature directly. The resulting microstructure comprises ferrite and martensite [17]. Higher intercritical temperatures, for the same soaking period, result in larger amounts of martensite with increased tensile strength and decreased percentage elongation [18]. It is reported by several papers [19] that the increase in martensite fraction in DP steels promotes crack initiation and thus results in worse ductility. Therefore, martensite fraction should be kept in the range of 10–40%.

Another method for processing of DP steels (Route B in **Figure 5**) applies first slow cooling from the austenitic region to the desired ferrite transformation temperature, followed by quenching to room temperature for transforming the

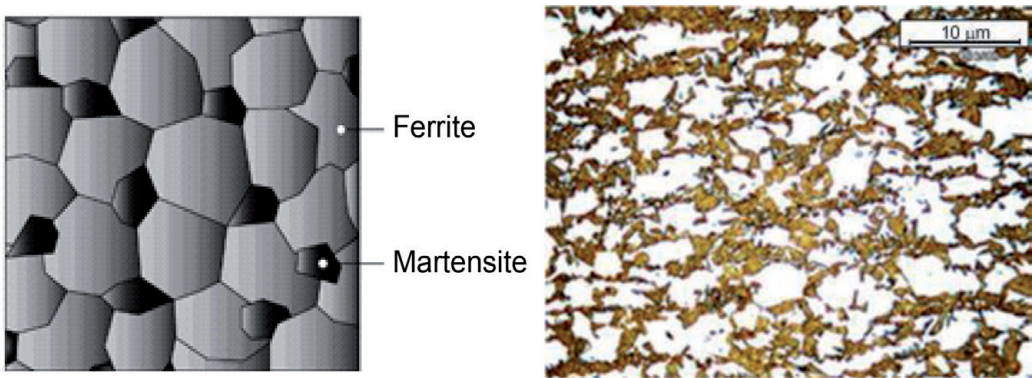


Figure 4.
Schematic view and real micrograph of a DP steel. Left: Schematic view of a microstructure of a DP steel containing martensite islands in ferrite matrix. Right: Micrograph of a DP 690 steel containing martensite islands in ferrite matrix.

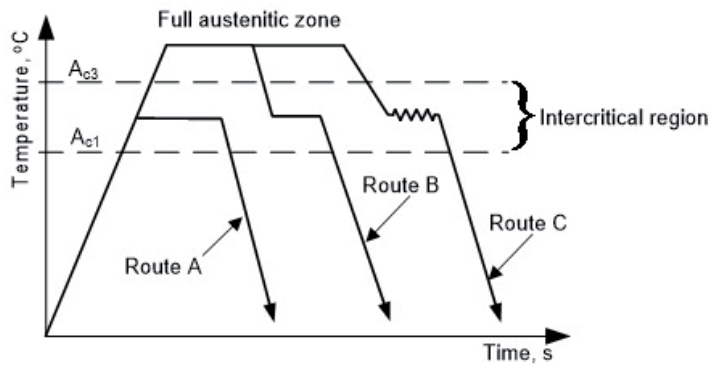


Figure 5.
Processing routes for producing DP steels.

remaining austenite to martensite [20]. The properties obtained by this method include lower tensile strength and higher ductility than those of gained by the first method (Route A).

The third method for producing DP steels (Route C in **Figure 5**) involves hot rolling of steel, followed by first slow cooling to the intermediate temperature, 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 ultrafast cooling (UFC), and the processing route is referred to as new-generation thermomechanical controlled processing [21]. The properties obtained by Route C are better (as compared to those obtained by Route A and Route B) because higher grain refinement is achieved during rolling.

Several authors have reported that DP steels with ultrafine bainite and fine ferrite-bainite/martensite microstructure with precipitation hardening can achieve good strength without loss of ductility, making this steel category more suitable for third-generation AHSS [5].

4.2 Transformation-induced plasticity (TRIP) steels

Advanced high-strength transformation-induced plasticity (TRIP) steels are well suited for lightweighting car body construction with added advantage to reduce the safety problems. TRIP steels can be found already in the 1st+ generation AHSS as shown in **Figure 2**. One of the main features of TRIP steels that the strain or stress-induced transformation of retained austenite present in the microstructure in a sufficient amount can substantially harden the steel during deformation depending on the processing route and therefore results in a higher ductility [22].

The microstructure of TRIP steels contains retained austenite embedded in a primary matrix of ferrite. **Figure 6a** shows schematic microstructure of TRIP steel, while **Figure 6b** is a micrograph of a typical TRIP steel (TRIP 700).

In addition to a minimum of 5 vol.% of retained austenite, hard phases such as martensite and bainite are present in varying amounts. TRIP steels typically require an isothermal hold at an intermediate temperature, which produces some bainite.

TRIP steels are characterized by a relatively low content of alloying elements. For example, in TRIP 790 steel (UTS \approx 790 MPa), the total content of alloying elements is about 3.5 wt.%. Thus, the selection of suitable alloying elements and the amount required to produce the intended properties is critical in the alloy design stage. The carbon content in TRIP steels is higher than in DP steels. Carbon

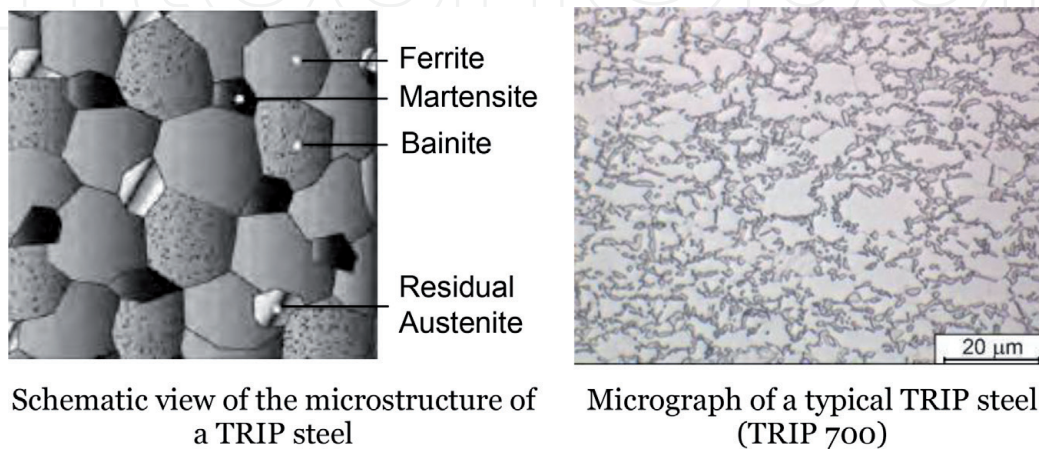


Figure 6. Schematic view and micrograph of the microstructure of TRIP steel. (a) Schematic view of the microstructure of a TRIP steel and (b) micrograph of a typical TRIP steel (TRIP 700).

is generally kept in the range of 0.20–0.25% because of weldability reasons. The higher 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 maintaining the necessary carbon content within the retained austenite. TRIP steels mainly contain multiphase 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 is a result of deformation based on transformation of retained austenite to martensite [23]. This transformation (on deformation) of phases is called the TRIP effect that provides excellent strength and elongation combination together with high impact resistance. These characteristics predestinate TRIP steels as good 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.

4.2.1 Processing of TRIP steels

The main processing of TRIP steels consists of heating the steel to the austenitic zone, cooling down to the intercritical region followed by deformation here, and quick transfer to the bainitic zone with subsequent soaking there, and finally quenching to room temperature (as shown in **Figure 7**).

The deformation in the intercritical region increases the rate of austenite (γ) to ferrite (α) transformation. The remaining austenite is enriched with carbon content, which stabilizes the γ phase. Furthermore, this deformation increases the nucleation rate of bainite but decreases its growth rate that results in small plates of bainite. This part of the T–t cycle also helps to enrich the γ phase with carbon and further increases the stability of γ phase. 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 more time to transform into martensite; these processes contribute to the increase of the ductility. The austenite to martensite transformation increases the tensile strength of the final microstructure. With this process, an improved strength–ductility combination is achieved [24]. Obviously, this processing route of TRIP steels is more time-consuming. This is because it needs 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 [25] using this route reported that rolling in the intercritical region improves TRIP steel

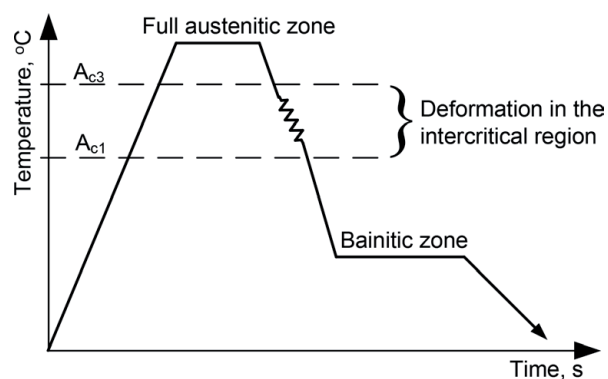


Figure 7.
Conventional processing route of TRIP steels.

properties by enhancing the carbon content and dislocation density, decreasing the grain size, and resulting in a granular type morphology.

4.3 Complex Phase (CP) steels

Complex Phase (CP) steels belong to the group of steels with usually very high ultimate tensile strength (UTS \approx 800 MPa or even greater). CP steels generally have chemical composition and microstructure similar to TRIP steels, but it contains some quantities of other elements, e.g., Nb, Ti, and V. These additional elements enhance the precipitation strengthening effect. CP steels typically do not have retained austenite, but contain more hard phases like martensite and bainite within the ferrite/bainite matrix.

The mechanical properties of CP steels may be characterized by continuous yielding and high uniform elongation. CP steels with the bainitic matrix have excellent formability. It is primarily due to the relatively small difference between the hardness of bainite and martensite. In CP steels, the bainitic ferrite is strengthened by high density of dislocations (dislocation density is above $\rho > 10^{12}/\text{cm}^2$) together with fine dispersion of martensitic second phase and carbo-nitrides or carbides. This bainite microstructure of CP steels exhibits better strain hardening and strain capacity than that for fully bainitic microstructure. In its microstructure, the martensite and bainitic ferrite phases are separated by a third phase of intermediate strength.

4.4 Martensitic (MS) steel

Martensitic steels (MS) have mostly martensitic microstructure with some small amounts of ferrite and bainite. These steels have the highest strength but lowest formability. Martensitic steels, currently available with strengths of 900–1800 MPa, are used for body parts where deformation may be limited [26].

Producing MS steels, the austenite is transformed almost entirely to martensite during quenching on the run-out table or in the cooling section of the continuous annealing line. MS steels may be characterized by martensitic matrix containing small amounts of ferrite and/or bainite. Within the group of multiphase steels, MS steels have the highest tensile strength level. Martensitic steels show the highest ultimate strength in final products, up to 1800 MPa or even higher [27]. Their concept is based upon well-established rules with respect to chemical composition and processing technology. In order to improve ductility and provide adequate formability even at extremely high strength values, MS steels are often subjected to post-quench tempering.

Additional carbon in MS steels increases the hardenability and contributes to further strengthening the martensite. Further elements (like manganese, silicon, chromium, molybdenum, boron, vanadium, and nickel) are used in various combinations to further increase hardenability. Microstructure of martensitic steels is mainly composed of lath martensite, which is developed by the transformation of austenite during quenching after hot rolling or annealing. Martensitic steels are very hard to form, so they typically are roll formed or press hardened (hot stamped): it will be detailed in the next section where the Press Hardening Steels (PHS) will be described.

4.5 Press Hardening Steels (PHS)

Among the Advanced High Strength Steels, Press Hardening Steels (PHS) form a unique group: these are mostly different kinds of boron-alloyed manganese steels

and gain wide application to produce high strength structural body elements (e.g., A- and B-pillars, etc.). Press Hardening Steels are widely used in car body manufacturing in hot forming processes. There are several grades of Press Hardening Steels; among them, the 22MnB5 alloy is regarded as the basic type of PHS steels. Here, the hot forming of Press Hardening Steels will be analyzed.

4.5.1 The hot forming process of PHS steels

Hot forming of steels is a complex forming and tempering operation: it is often termed as hot press forming or press hardening of steels, too. The full austenitization of the material is regarded as the first step in hot press forming. Forming is performed in this state when the material has good formability; then the part is cooled down rapidly in the tool applying the critical cooling rate, hence resulting in martensitic microstructure.

The usual temperature–time diagram for hot press forming is shown in **Figure 8**. Through the above-described combination of heating, holding, forming, and rapid cooling, very complex parts can be produced with excellent strength properties [28]. There are various process variants in hot press forming: among them, the so-called direct and indirect hot forming may be regarded as the basic ones. In direct or single-stage hot forming, the blank sheet is directly austenitized, then transferred to the stamping tool, and cooled down rapidly in the forming tool providing excellent strength properties [29]. In indirect or often termed as two-stage hot press forming, the initial blank is formed in cold state, and then either a hot forming is used to produce the complex parts or just a calibration process occurs in hot forming condition. The austenitization and the subsequent quenching are the inherent parts of this process chain, too, to provide the required high strength properties.

There are further process variants besides these two basic ones: the final microstructure, as well as the mechanical properties of the part, can be effectively controlled by the holding temperature and the controlled cooling process. These process variants may be derived either by altering the holding temperature or by changing the cooling rate. Depending on the holding temperature, two further process variants can be proposed: full austenitization is the basic alternative, i.e., when the holding temperature is selected in the homogeneous γ -zone. A further process variant depending on the holding temperature is derived if the holding

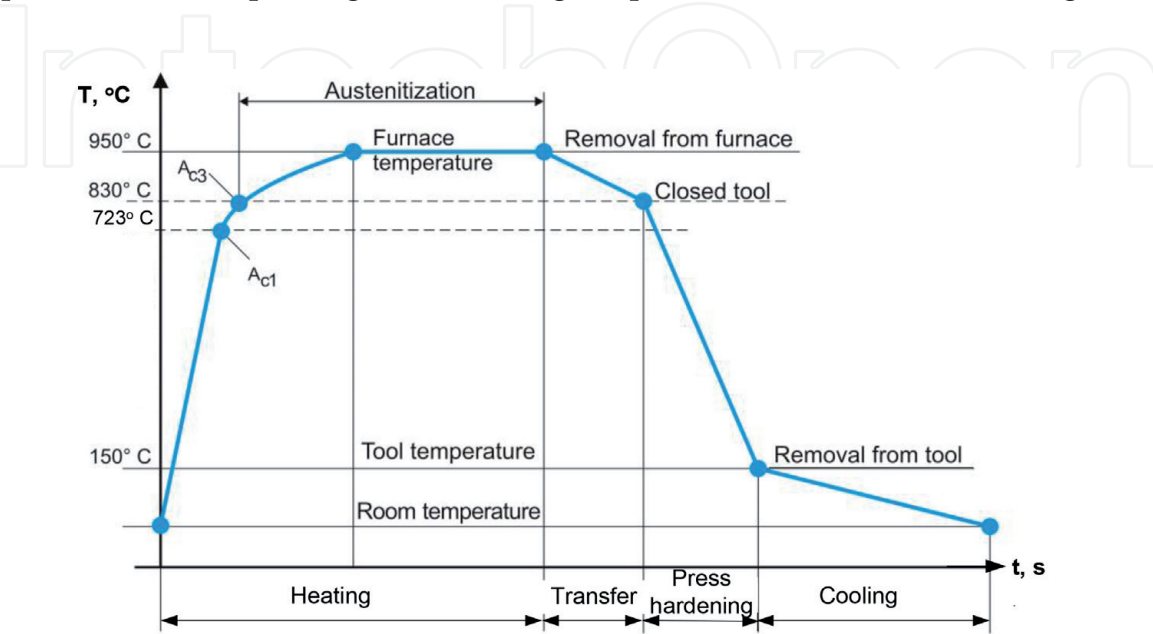


Figure 8.
Temperature vs process time for hot press forming of PHS.

temperature is in the ($\alpha + \gamma$) intercritical zone (i.e., between the A_1 and the A_3 temperature). In this case, there is no full austenitization; the starting microstructure contains, besides austenite, ferrite, too. Obviously, just the austenite content can be transformed into martensite, and the final microstructure after the hot forming and cooling process is completed has a certain amount of ferrite, too. Obviously, it results in lower strength than the full austenitization; however, it also leads to a certain amount of ductility leading to better toughness properties, as well.

Further process variants can be also derived by changing the cooling rate after the forming process. If the cooling rate is higher than the upper critical one, the final microstructure is martensite; when the cooling rate is lower than the upper critical one, besides martensite, bainite can be also found in the microstructure. However, it also results in somewhat lower strength depending on the quantity of bainite; however, it also results in the increase of toughness that may be advantageous, for example, increasing the crashworthiness of the part due to the better energy absorption properties of bainite [30].

It is essential that the forming could be finished above the M_s temperature: at this stage, these material grades still have suitable formability. After forming, the component is cooled down together with the tool: this cooling should provide the critical cooling rate to get high strength of martensitic microstructure. By this process, springback is eliminated, and very strong components can be formed to complex geometries.

Typical press hardened steels (PHS) have tensile strength of 1500–2000 MPa. In the last decades, they are already extensively used in safety and crash-resistant car body components. New-generation PHS are expected to have higher strength even above 2000 MPa. However, it should be noted that these PHS grades are used where only very small deformation is allowed. These steels have been adopted for use in many parts, including, for example, sill structures, or A- and B-pillar reinforcements. Recently, many floor panels also are made by hot forming to save weight.

4.6 Twinning-induced plasticity (TWIP) steels

TWIP steels belong to the second generation of AHSS and are based on the potential mechanism of obtaining a superior balance of tensile strength and elongation using the TWIP effect. The name of this steel is originated from this characteristic deformation mode, i.e., the twinning. 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 (**Figure 9**).

TWIP steels have high manganese content ($Mn = 17\text{--}24\%$) that causes the steel to be fully austenitic even at room temperatures. TWIP steels are normally composed of Fe, Mn, or Ni (15–35%), Si (1–3%), and Al (1–3%) [31]. These steels exhibit outstanding tensile strength-ductility combination (e.g., a TWIP steel with tensile strengths above 1000 MPa may possess 50–60% ductility) [32]. The n -value may increase to a value of 0.4 that may result in 50–60% uniform elongation. The tensile strength may be even higher than 1500 MPa [33].

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 $SFE < 20 \text{ mJ/m}^2$ 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.

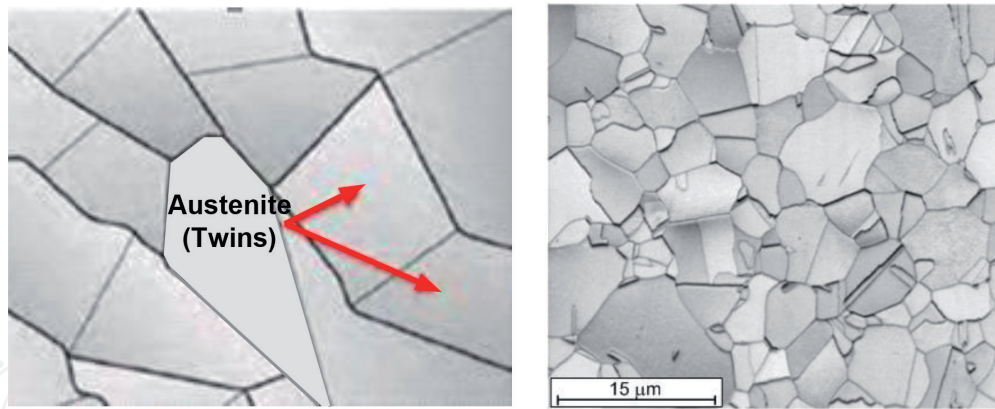


Figure 9. Schematic view and micrograph of TWIP steel microstructure. Left: Schematic view of TWIP steel microstructure. Right: Micrograph of a TWIP steel in annealed condition.

TWIP steels show superior mechanical performance, but this category is not practically viable for industrial applications because of its limitations: poor productivity and high production costs. The main production route of TWIP steels includes homogenizing above the upper critical temperature for a long period and quenching to room temperature [34]. TWIP steels can be also produced by homogenizing, followed by deformation at a temperature above the upper critical one, with subsequent quenching to room temperature. Deformation at higher temperature provides fine grain size and high volume fraction of twins. The finer the grain structure, the more twinning occurs that improves ductility and strength.

Two types of twins are observed in the TWIP steels: (a) annealing twins caused by heat treatment and (b) deformation twins caused by deformation. The yield stresses of coarse-grained TWIP steels usually result in less than 400 MPa strength, which restricts the use of TWIP steels in the automotive sector, particularly for those parts that are supposed to be active during a crash. Many attempts are reported in the literature to increase the yield strength of TWIP steels. These attempts include, for example, grain size refinement by using V, Ti, and Nb as alloying elements to enhance precipitation of carbides, cold rolling followed by annealing treatment, and partial recrystallization [35].

5. Recent results and future trends in AHSS development

As it was already discussed at the Classification of AHSS Developments (Section 3.1), the main target in developing the third-generation AHSS is to achieve the properties in the range between the first- and second-generation AHSS with less alloying elements, hence, with less expensive processing that are suitable for early commercialization. The range of third-generation AHSS (3GAHSS) development maybe clearly identified on the diagram of tensile strength vs total elongation in between the first- and second-generation AHSS regions as shown in **Figure 2**.

However, it is also obvious that potential production requires a systematic design methodology to identify the possible combinations of microstructural constituents, which may lead to the required mechanical properties.

One of the possibilities to apply a systematic design methodology is the application of a simplified composite model [36] considering various combinations of multiphase (ferrite, austenite, bainite, and martensite) materials. With the variations of phase fractions in the hypothetical microstructure, the predicted mechanical properties can be calculated.

Another possibility to use a systematic design methodology is the application of the Integrated Computational Materials Engineering (ICME). It provides a framework for utilizing computational multiscale material development driven by multidisciplinary engineering design, analysis, and performance requirements [37]. This concept is initiated and supported by the National Research Council in the USA [38]. The ICME model can be used to guide both the material selection and the design optimization. Alternatively, it can be also used to new material development to get the best-suited macroscopic properties for a given structural application, through the determination of chemical composition and microstructural characteristics in a “reverse engineering” approach. In the automotive industry, the potential of the ICME method for vehicle lightweighting was recognized by the United States Department of Energy (DOE), too, which funded the project “Integrated Computational Materials Engineering Approach to Development of Lightweight Third Generation Advanced High Strength Steel (3GAHSS) Vehicle Assembly [39]. The abovementioned ICME approach was implemented in this project in two ways. First, the ICME principles were applied in the development of a material modeling tool set by combining material models at different length scales. Second, the Combined Constraints Crystal Plasticity (CCCP) model was implemented as a microscale constitutive model [40]. In this project, two targets were set by the United States Department of Energy: one is the 1200 MPa strength with 30% total elongation (which means $C = 1200 \times 30 = 36,000 \text{ MPa} \times \%$), and the other one is 1500 MPa strength with 25% total elongation (which means $C = 1500 \times 25 = 37,500 \text{ MPa} \times \%$) [41].

Similar projects were initiated by other steel companies and research institutes in the world. Among others, ArcelorMittal announced systematic developments of third-generation steels [42]. The microstructure of these steels consists of a high strength phase (e.g. nano/ultrafine-grained ferrite, martensite, or bainite) combined with a further phase or constituent that provides substantial ductility and work hardening (e.g. austenite). In the next sections, some results and representatives of these 3G developments will be introduced.

5.1 Medium manganese steels

The development of austenitic steel grades with high alloying contents of manganese (15–30%) was already applied during the development of second-generation AHSS. It resulted in outstanding mechanical properties (high strength with excellent elongation), which made it attractive for the automotive industry. These high strength and ductility grades were based on the austenitic single-phase concept. Their deformation mechanisms were mainly the twinning-induced plasticity (TWIP). Additionally, it was also discovered that combining specific proportions of TWIP and TRIP mechanisms allows precise control of strength and ductility [43].

In recent steel developments, it was experienced that a further deformation mechanism is provoked when different alloying concepts are used. Microband-induced plasticity (MBIP) is one of these newly discovered mechanisms, which localizes the deformation within arrays of precipitates and, thus, retarding the onset of mechanical instability and supporting homogenous yielding. Beside the outstanding mechanical properties, the steels offer processing challenges compared to low carbon steels; however, they are very expensive due to the high alloy additions required to produce austenitic microstructure.

However, these high manganese content steels initiated the development of another new group of steels belonging to the third-generation AHSS grades, namely, the medium manganese steels. The microstructure of these steels consists of a high strength phase (e.g. nano/ultrafine-grained ferrite, martensite, or bainite)

combined with a further phase or constituent that provides substantial ductility and work hardening (e.g. austenite). The carbide-free bainite (CFB) or ultrafine lamellar bainite (ULB) is another possible concept. By choosing the alloying concept and the cooling condition, it is possible to suppress the carbide formation and, thus, to produce a very fine lamellar bainitic structure with austenite films between the bainite leaves. This concept provides very high strength steels right above 1 GPa and with remarkable formability.

5.2 Quenched and partitioned (Q&P) steels

Quenched and partitioned (Q&P) steels are the result of the recent developments of third-generation AHSS steels. The elaboration of Q&P steels is partly based on the knowledge of duplex stainless steels and the quenching and partitioning process [44], as well as on the properties of medium manganese steels [45]. The Q&P steels usually contain carbon, manganese, silicon, nickel, and molybdenum alloying elements. The amount of alloying elements can be around 4%, which is much lower than that of in the second-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 created containing 5–12% stable retained austenite, 20–40% ferrite, and 50–80% martensite.

Baosteel was one of the first companies to apply Q&P steels, initially with 980 MPa and later 1180 MPa strength [46]. It was demonstrated that a B-pillar reinforcement could be cold-formed using Q&P 1180. Auto/Steel Partnership (A/SP) also has tested Q&P 980 using GM's B-pillar die, proving that this steel has better formability and is less prone to edge cracking than DP 980.

Recently, Q&P steels were developed up to 2100 MPa tensile strength with 9% uniform elongation and about 13% total elongation. The elongation level of this steel is comparable to DP 980, which is a cold-formable grade.

5.2.1 Metallurgy 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. 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 new-generation AHSS. They are suitable for cold stamping of various structures and safety parts having complicated shape 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 as carbon, manganese, nickel, etc. based on the knowledge gained by duplex stainless steels. However, it affects the cost and may be detrimental concerning the welding properties. The third generation of AHSS grades were developed to overcome these disadvantages; few of the good examples are those third-generation AHSS that are based partly on the quenching and partitioning process (Q&P steels) and on the properties of 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 M_s temperature. For medium-Mn steels, where a relatively larger manganese amount (typically between 5 and 8 wt. %) is characteristic, the thermal treatment is slightly simplified. 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 the excellent mechanical behavior. By these processes, the UTS above 1200 MPa and uniform elongation larger than 12% can be achieved.

5.2.2 Microstructural properties and formability of Q&P steels

The concept of Q&P process for automotive materials was first published by Speer et al. [44]. In Q&P process, the material is quenched down below the M_s temperature, where austenite is not fully transformed. Due to the alloying concept of Q&P steels, this temperature usually is in the range of 200–350°C. It means that the microstructure is a mixture of martensite and austenite. Steel is then reheated and aging is done between 300 and 500°C; this is termed as 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. Besides these, tempering of martensite occurs, which improves its damage resistance properties, while keeping high strength.

This simplified scheme does not reveal all the complex evolution of the microstructure during partitioning, and the detailed mechanisms of Q&P evolution are still a matter of debate and not fully elucidated. For instance, the formation of bainite during partitioning cannot be completely excluded; it could explain the measured carbon enrichment in the retained austenite, as the partitioning temperatures are consistent with those for bainite formation.

Even if the detailed mechanisms are not fully revealed, the benefits of Q&P treatment by the improved mechanical properties have been clearly shown. The current range of strength that can be achieved with this new concept is between 1000 and 1500 MPa, with a total elongation of 20%. Moreover, as the matrix is a kind of tempered martensite, damage resistance is improved compared to DP or TRIP steels with the same strength level.

The development of such grades requires an important modification of the annealing line; quenching and reheating step was not possible until the recent years. The strong request from the automotive market toward third-generation Advanced High Strength Steels has led steel making companies to invest in the upgrading of their annealing lines to ensure processing of Q&P steel products.

5.3 TRIP assisted bainitic-ferritic (TBF) steels

TBF, a low-alloy grade like Q&P steels, can be produced by the existing heat treatment facilities. Stable retained austenite is its key component. Bainitic ferrite matrix with retained austenite inclusions may be regarded as the most common microstructure for TBF steels. It is produced by isothermal holding in the bainitic regions after fast cooling from fully austenitic microstructures. 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 [47]. 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. Consequently, the transformation of retained austenite into martensite produced by either deformation or thermal processes during final cooling is prevented. Although Si has major importance to prevent carbide precipitation during annealing of the cold rolled material, it causes problems

during processing via continuous annealing lines. Therefore, other alloying elements having similar effect of suppressing carbide formation have to be considered.

5.4 NanoSteel

NanoSteel[®], a third class of third-generation AHSS, is still under development and not commercially available. In 2002 (following 6 years of research at Idaho National Laboratory), a NanoSteel Co. was established in the United States [48]. Trial production of NanoSteel sheets was started in 2012. The nanocrystalline structure was produced by special chemistry and heat treatment. After casting, the steel is mainly austenitic. Applying special heat treatment, the grain size of austenite is refined to nanometer scale. During plastic deformation, stress-induced nanoscale phase transformation increases strain hardening.

German company Engineering+Design AG (EDAG) recently published a design study in which the steel used in a 2011 Honda Accord[®] was replaced with NanoSteel products. The National Highway Traffic Safety Administration (NHTSA) sponsored a research study to compare the results to formerly applied conventional AHSS. The results showed further 8% weight reduction to conventional AHSS and 30% overall weight reduction to former model Honda Accord 2011 [49].

6. Conclusions

In this chapter, the recent developments and future trends 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 fulfill these often contradictory requirements, the application of high strength steels may be regarded as one of the most promising developments. Among these developments, the application of new Advanced High Strength Steels (AHSS) is the most important one. In the last 45–50 years, 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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Conflict of interest

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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