

**AHSS 101**  
**THE EVOLVING USE OF**  
**ADVANCED HIGH-STRENGTH STEELS**  
**FOR AUTOMOTIVE APPLICATIONS**



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# **AHSS 101:**

## **The Evolving Use of Advanced High-Strength Steels for Automotive Applications**

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# 1. Foreword

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The family of advanced high-strength steels (AHSS) continues to evolve and grow in application, particularly in the automotive industry. New steel types are already being used to improve the performance of vehicles on the road, and emerging grades will be increasingly employed. But what distinguishes the different types of automotive high-strength steels and makes each type suited to specific applications? The following report assembles relevant information to answer these and other questions, while suggesting resources for deeper understanding. It seeks to provide a brief but useful guide to AHSS and its automotive applications now and in the future.

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### 3. Acronyms

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AAC	Automotive Applications Committee
AHSS	Advanced High-Strength Steel(s)
AISI	American Iron and Steel Institute
A/SP	Auto/Steel Partnership
BH	Bake Hardenable
BIW	Body in White
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CO <sub>2</sub>	Carbon Dioxide
CP	Complex Phase
DP	Dual-Phase
EPA	Environmental Protection Agency
FB	Ferritic-Bainitic
FSV	FutureSteelVehicle
GHG	Greenhouse Gasses
GPa	Giga Pascal
HSLA	High-Strength, Low-Alloy
HSS	High-Strength Steel
IF	Interstitial-Free
LCA	Life Cycle Assessment (Analysis)
MPa	Mega Pascal
MS	Martensitic
NHTSA	National Highway Traffic Safety Administration
PFHT	Post-Forming Heat-Treatable
SF	Stretch-Flangeable
SMDI	Steel Market Development Institute
TRIP	Transformation-Induced Plasticity
TTT	Time-Temperature-Transformation
TWIP	Twinning-Induced Plasticity
ULSAB-AVC	UltraLight Steel Auto Body – Advanced Vehicle Concepts
UTS	Ultimate Tensile Strength
YS	Yield Strength

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## 5. Overview

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As automakers are challenged to improve safety and fuel economy, they search for new materials to meet higher standards. Advanced high-strength steels (AHSS) help engineers meet requirements for safety, efficiency, emissions, manufacturability, durability, and quality at a low cost. AHSS are a newer generation of steel grades that provide extremely high-strength and other advantageous properties, while maintaining the high formability required for manufacturing. AHSS have been on the road for many years, but with additional research and development, automakers are using these newer grades in more applications.

AHSS grades have unique combinations of material and mechanical properties. Most have carefully selected chemical compositions and multiphase microstructures resulting from precisely controlled heating and cooling processes. Various strengthening mechanisms are employed to achieve a range of strength, ductility, toughness, and fatigue properties. Improved manufacturing processes have, in many cases, been key contributors to the implementation of these technologies.

Materials in automotive applications are selected to minimize weight, while meeting key criteria including crash performance, stiffness, and forming requirements. Different types of AHSS help parts meet the varied performance demands in different areas of the vehicle, including both the crumple zone and passenger compartment.

Conventional low- to high-strength steels include mild, interstitial-free, bake-hardenable, and high-strength low-alloy steels. They have simpler structures and have been widely used for many years. AHSS include dual- and complex- phase structures, ferritic-bainitic, martensitic, transformation-induced plasticity, hot-formed, and twinning-induced plasticity steels. Each has unique microstructural features, alloying additions, processing requirements, advantages and challenges associated with its use. Each type has unique applications where it might be best employed to meet performance demands of the part.

The future of AHSS for automotive applications is bright. Many groups are researching these new steels to better understand their properties and to continue tailoring unique sets of characteristics. Others are focused on improving the technologies necessary for manufacturing parts made of AHSS. The steel and automotive industries have forged numerous partnerships to develop the materials and technologies necessary to put the next generation of safer and more environmentally friendly vehicles on the road.

## 6. Introduction to AHSS

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As car safety, fuel economy, and performance standards increase, so does the need for new and improved steel materials. The global steel industry has met this need through the development of new AHSS grades, whose unique metallurgical properties and processing capabilities enable the automotive industry to meet requirements, while keeping cost down.

### 6.1 Why AHSS?

Several factors drive material selection for automotive applications, including safety, fuel efficiency, environmentalism, manufacturability, durability, and quality. In the highly competitive automotive industry, cost is also extremely important in material selection. As the motivation to reduce the mass of vehicles continues to intensify, automakers seek to maximize the efficiency of their materials selection. From 1980 to 2010, the percentage of steel used in vehicles relative to other materials has grown (by weight) from approximately 53-55 percent in the early 1980s to approximately 60 percent today for North American light vehicles [1]; this reflects the ability of AHSS to meet performance demands.



Safety regulations have accelerated the incorporation of AHSS into vehicles. The National Highway Traffic Safety Administration (NHTSA) sets standards for vehicle safety, such as those for impact resistance, restraints, and fuel economy [2]. Testing by the Insurance Institute for Highway Safety (IIHS) has also encouraged improved frontal, side, and rear impact ratings, as well as roof strength and rollover ratings, for automobiles on the road today [3]. Meeting these standards often requires the addition of weight to the vehicle. To learn more about NHTSA, IIHS, and other safety regulations that affect automotive designs, please see Appendix A.

While adding massive safety components, automakers struggle to reduce weight and heighten efficiency to meet increasing corporate average fuel economy (CAFE) standards. Engineers analyze parts to identify opportunities to redesign geometries within constraints; and to achieve these shapes and/or further weight reduction, new materials are sought. Considering AHSS during this optimization process can be advantageous, partly because the broad range of grades allow for design flexibility. Using stronger steel enables engineers to use thinner steel, or a reduced gauge, to produce a lighter-weight part while maintaining or improving the strength and other performance properties.

Fuel efficiency has both economic and environmental incentives associated with the use-phase of the vehicle; additional environmental concerns, however, extend across the *entire* life cycle of the vehicle, including its production and end-of-life recycling. Life cycle assessment (LCA) for the greenhouse gas emissions of automobiles reveals that high-strength steel, when compared with other materials such as aluminum, can leave the smallest carbon footprint for the life cycle of a vehicle [4, 5]. Additionally, steel is the most recycled material on earth and can be used directly in new automotive or other products [4].

Other factors, such as manufacturability, durability, quality, and cost, have also been important in the search for improved materials in the automotive industry. To meet these challenges, the steel industry has developed a broad range of AHSS with unique properties to meet the diverse performance requirements of vehicle components. As alternative materials, such as aluminum,



plastics, and composites, are explored for automotive applications, AHSS are developing to remain fully competitive by striking a balance between strength for performance and ductility for production. AHSS has been shown to be effective for simultaneous performance improvement and mass reduction without increased cost [6].

## 6.2 Defining AHSS

Conventional mild steel has a relatively simple ferritic microstructure; it typically has low carbon content and minimal alloying elements, is readily formed, and is especially sought for its ductility. Widely produced and used, mild steel often serves as a baseline for comparison of other materials. Conventional low- to high-strength steels include IF (interstitial free), BH (bake hardened), and HSLA (high-strength low-alloy). These steels generally have yield strength of less than 550 MPa and ductility that decreases with increased strength. (More information about these steel types in Section 8.2.1.)

AHSS are more complex, particularly through their microstructures, which are usually multi-phase for an improved combination of strength and ductility. This balance is carefully constructed to meet performance requirements while maintaining excellent formability. AHSS often has other advantageous mechanical properties, such as high strain-hardening capacity. Because the nomenclature for steel differs around the world, this particular report adopts the generic classification method used in reports of the FutureSteelVehicle (FSV). That is, steels are identified as “XX aaa/bbb” where:

- XX = Type of steel (abbreviations expanded in Figure 6.1 below)
- aaa = Minimum yield strength (YS) in MPa
- bbb = Minimum ultimate tensile strength (UTS) in Mega Pascal (MPa) [6]

XX	Type of steel
Mild	Mild Steel
BH	Bake Hardenable
CP	Complex Phase
DP	Dual Phase
FB	Ferritic Bainitic
HF	Hot Formed

XX	Type of steel
HSLA	High-Strength Low-Alloy
IF	Interstitial Free
MS	Martensitic
SF	Stretch-Flangeable
TRIP	Transformation Induced Plasticity
TWIP	Twinning-Induced Plasticity

**Figure 6.1:** Steel type designators [6]

The terms “high-strength” and “advanced high-strength” refer generally to steels that share a family of behaviors. Generally, AHSS are different from the early HSS (IF, BH, HSLA) because they were developed later for increased strength *and* ductility for enhanced formability. In reality, the steels fall into a continuum of strengths. So, the distinction between HSS and AHSS is defined somewhat arbitrarily. A typical definition calls steels with 210 to 550 MPa yield strength “high-strength” and anything stronger “advanced high-strength.” AHSS steels are also sometimes called “ultra high-strength steels” for tensile strengths exceeding 780 MPa. AHSS with tensile strength of at least 1000 MPa are often called “GigaPascal steel” (1000 MPa = 1GPa).

Equally important to increasing YS and UTS is achieving the appropriate combination of formability, weldability, and other characteristics necessary for the automotive application of steel in a competitive market. This necessity generates the large variety of grades in different stages of development. For example, in the FSV program, more than 20 AHSS grades, as shown in Figure 6.2, were included, and all are expected to be commercially available by 2015-2020 [6]. This portfolio of AHSS was a significant increase from the 11 AHSS steel grades included in the UltraLight Steel Auto Body – Advanced Vehicle Concepts (ULSAB-AVC)

program of 2002. More details about these grades and their applications are provided in the following sections of this report.

Mild 140/270	DP 350/600	TRIP 600/980
BH 210/340	TRIP 350/600	TWIP 500/980
BH 260/370	SF 570/640	DP 700/1000
BH 280/400	HSLA 550/650	HSLA 700/780
IF 260/410	TRIP 400/700	CP 800/1000
IF 300/420	SF 600/780	MS 950/1200
DP300/500	CP 500/800	CP 1000/1200
FB 330/450	DP 500/800	DP 1150/1270
HSLA 350/450	TRIP 450/800	MS 1150/1400
HSLA 420/500	CP 600/900	CP 1050/1470
FB 450/600	CP 750/900	HF 1050/1500
		MS 1250/1500
Denotes grades used for ULSAB-AVC		Denotes steel added in FSV

**Figure 6.2:** FSV's expanded steel portfolio [6]

### 6.3 Development of AHSS

Even in the early 20<sup>th</sup> century, automakers recognized that the secret is “to put the right steel in the right place,” as noted in a 1909 article published in the *New York Times* about American auto steel [7]. At that time, modern metallurgy could produce varied grades at assorted expense, so production depended heavily on demand. Formability and aesthetics (steels that could be cheaply and easily drawn into smooth, stylish designs) were top priority for quite some time; strength was less of a concern and could be added if necessary with increased thickness. As new priorities emerged, such as safety performance, decreased cost, and weight reduction for efficiency (as discussed in Section 6.1), so did the demand for new materials, including new steels.

By 1975, the average vehicle contained 3.6 percent medium and high-strength steels for a total vehicle content of 61 percent, mostly mild (Figure 6.3 on the next page) [8, 9]. In the 1980s, the use of interstitial-free (IF) and galvanized steels grew for complex parts, as styling, corrosion, and cost were key considerations. IF steel was initially developed as a highly formable material, and used extensively for deep drawn applications requiring high ductility and resistance to thinning. It also became the standard base for hot-dipped galvanized steels, as the stabilizing alloy elements in IF prevent aging behavior. A third type of IF steel, with nitrogen or other elements re-introduced, could be used to meet higher dent resistance and strength requirements.

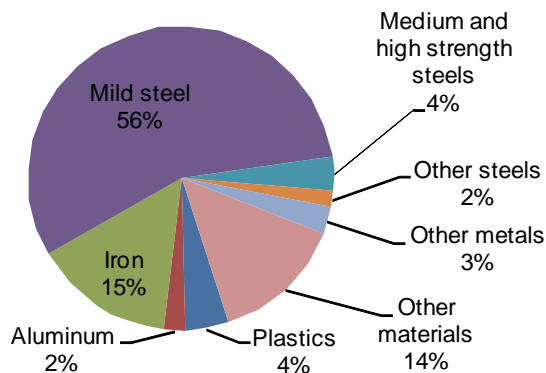
High-strength low-alloy (HSLA) steels, which had been used for major construction projects, such as the Alaska Arctic Line Pipe Project in the 1970s, were increasingly developed and selected for automotive applications through the 1990s for their consistent strength, toughness, weldability, and low cost [8].

In 1994, a consortium of 35 sheet steel producers began the UltraLight Steel Auto Body (ULSAB) program to design a lightweight steel auto body structure that would meet a wide range of safety and performance targets [1]. The body-in-white (BIW) unveiled in 1998 validated the design concepts of the program. After 2000, the new generation of AHSS including hot-formed (HF) and dual phase (DP) steels was incorporated into BIW structures.

More projects followed to demonstrate and communicate the capability of steel to meet demands for increased safety and fuel efficiency through light-weighting of various vehicle structures. The Auto/Steel Partnership (A/SP) engaged in research and demonstrated the value of AHSS through several programs [1]. One such project, Lightweight Front End Structure, used a holistic approach to meet goals of more than 20 percent weight reduction while maintaining crash worthiness. Manufacturability was examined and emphasized throughout this project. Another key program, the Future Generation Passenger Compartment project, particularly examined the effect of mass compounding.

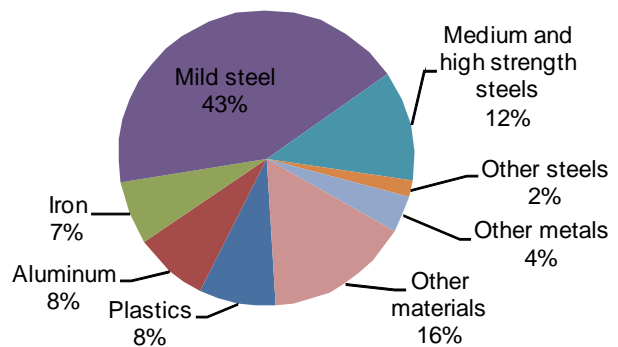
### Average 1975 Vehicle

3,900 lbs.



### Average 2007 Vehicle

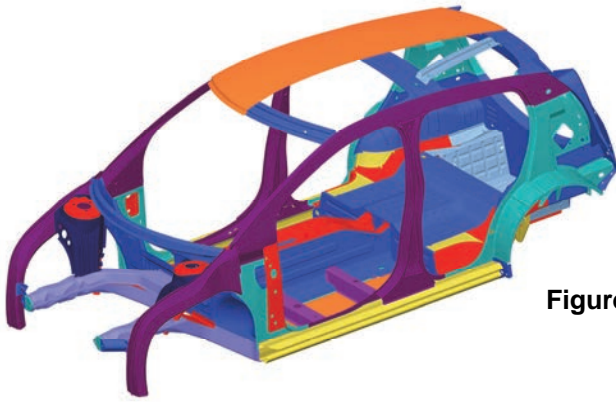
4,050 lbs.



**Figure 6.3:** 1975 and 2007 average vehicle mass breakdown by material  
[Data from Ducker Worldwide]

By 2007, the average vehicle contained 11.6 percent medium- and high-strength steels, for a total steel vehicle content of 57 percent [9]. Essential for the growing use of AHSS has been the simultaneous development of new processes and equipment to produce and form the material. Some of these processes are described later in this report. DP and transformation-induced plasticity (TRIP) steels are excellent in the crash zones of the car for their high energy absorption. For structural elements of the passenger compartment, extremely high-strength steels, such as martensitic (MS) and boron-based HF, increase safety, strength, and rigidity.

The use of AHSS in cars is quickly expanding with more research. The study that gives a peek into the not-so-distant future of the enhanced use of AHSS in vehicles is WorldAutoSteel's FutureSteelVehicle (FSV) program completed in 2011, which followed the ULSAB, ULSAB-AVC (Advanced Vehicle Concepts) and other programs. The work demonstrated 35 percent mass reduction from a benchmark vehicle using 97 percent HSS and AHSS [6]. The FSV, shown in Figure 6.4, meets or exceeds all current safety and structural requirements, and analysis shows that when combined with an electrified power train, light weighting the FSV with AHSS enables the reduction of total life cycle emissions by at least 56 percent [6].



**Figure 6.4:** FSV body structure [6]

## 7. Materials Science Essentials

With such an array of available AHSS, differentiating among the many types and grades may initially seem intimidating. A basic understanding of materials science/metallurgy, however, clarifies the differences among AHSS grades, properties, and applications. Materials science and steel metallurgy learning resources are listed in Appendix B, and the following highlights some of the essentials most relevant to AHSS steels. This section gives an extremely brief introduction to the principles that help explain the unique structure, properties, and processing of AHSS.

### 7.1 Stress, Strain, and Deformation

Engineering stress,  $\sigma$ , is defined as force divided by area. Stress is often plotted against engineering strain,  $\epsilon$ , which is the percent change in a particular dimension of an object experiencing stress. The resulting stress-strain curve is helpful for understanding a variety of material and mechanical properties of the material. The stress-strain curve for a ductile material is shown below in Figure 7.1, with some of the most important features and terms identified.

When stress is applied in the elastic region, bonds between atoms are stretched but not broken. If the load is removed while stress is still in the elastic range, no plastic deformation will occur; the part will recover its original dimensions. The slope of this portion of the graph is the elastic modulus,  $E$ , of the material ( $E = \sigma / \epsilon$  while deformation is elastic). The elastic modulus, in combination with part geometry, determines the stiffness of a part.

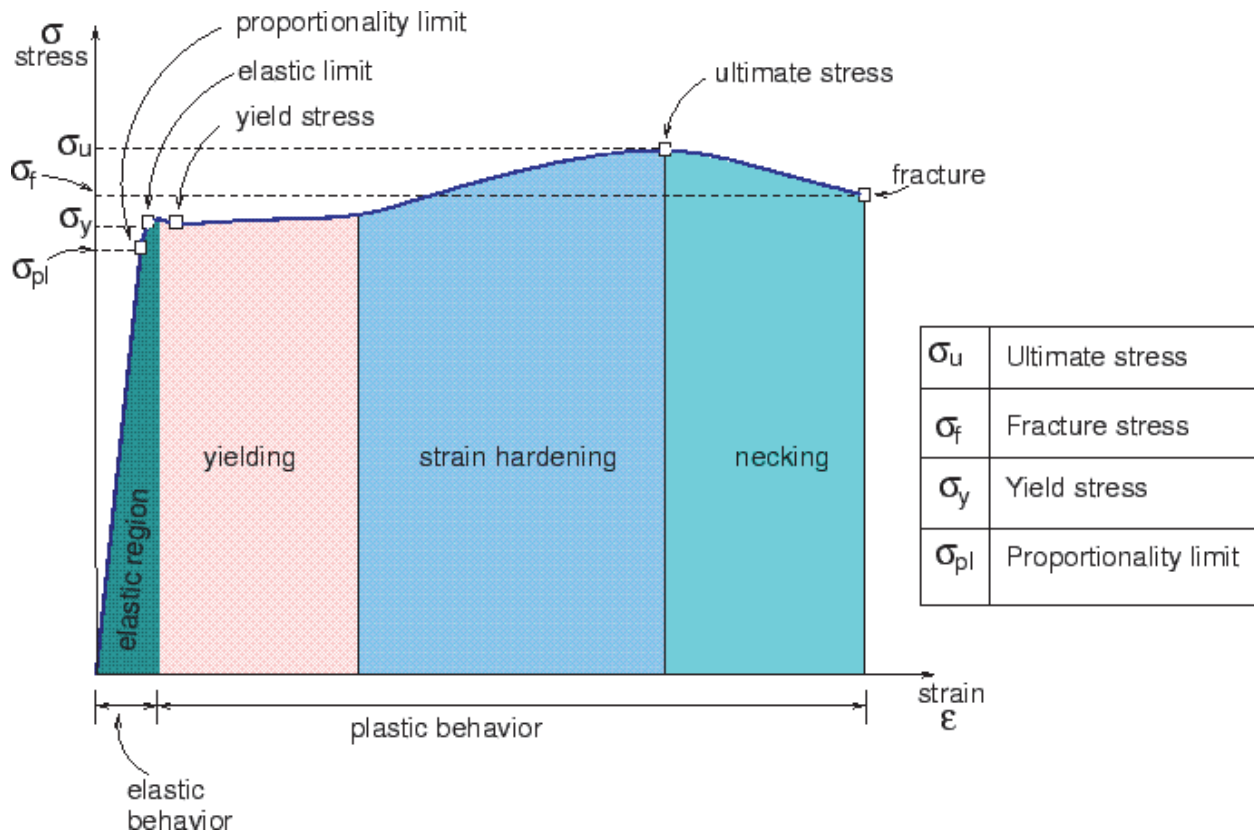
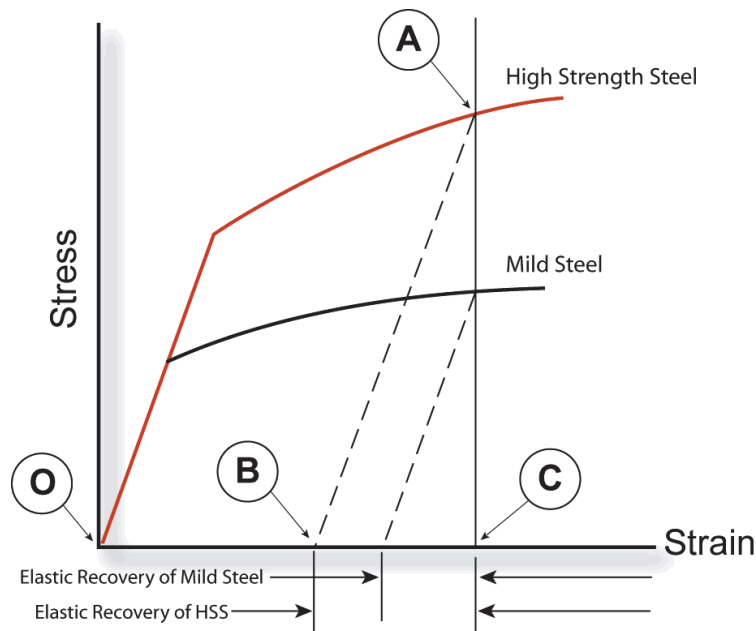


Figure 7.1: Stress-strain diagram [10]



**Figure 7.2:** Stress-strain curves illustrating that springback is proportional to stress [13]. If a mild steel and HSS with the same elastic modulus are loaded to equal strain A, when the load is removed, the HSS will have greater springback (to B). This greater elastic recovery is possible because the HSS was carrying much greater stress at the same strain.

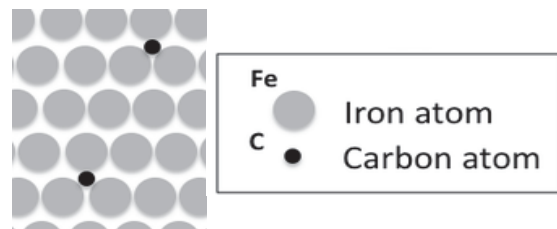
The yield strength (YS) is the amount of stress necessary to produce a small, specified amount of plastic (non-recoverable) strain (usually 0.002), marking the end of elastic deformation [11]. The yield strength is generally found at the top of the steep, linear, elastic portion of the stress-strain curve. At stress (or strain) beyond the YS, bonds between atoms are broken and atoms begin to “slip” or move past each other. These mobile dislocations are the source of plastic deformation in metals [12]. If the load is removed in the plastic strain range, some elastic recovery, or springback, will occur, but some permanent deformation caused by the slip will remain. HSS have greater springback than mild steels at the same total strain level, for example, as shown in Figure 7.2.

After a certain amount of stress is applied, the material will begin to neck and move toward fracture; this

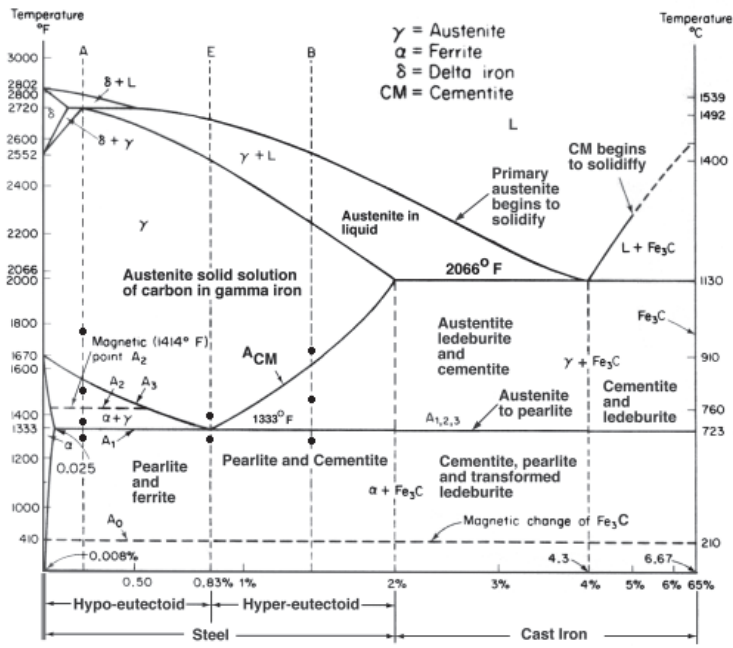
stress is known as ultimate tensile strength (UTS). The UTS is usually the maximum stress on the curve. The entire area under the stress-strain curve through the elastic region, yielding, strain hardening, and necking is related to the amount of energy that can be absorbed before fracture. To learn more about the material and mechanical properties implied by the stress-strain curve, please see the resources in Appendix B.

## 7.2 Iron, Carbon, Alloying, and Microstructures

The structure of steel at an atomic and microscopic level explains its strength, springback, and other properties. Carbon steel is much stronger than iron because the smaller carbon atoms have diffused into the interstitials (spaces between atoms) of an iron lattice at elevated temperatures, as shown in Figure 7.3. This solid solution strengthening effect produces steel that is much stronger and harder than iron. Other elements may also be added to the steel; these alloying elements can change various properties of the steel, including strength, hardness, toughness, corrosion resistance, heat-treatability, etc.



**Figure 7.3:** Schematic of carbon atoms in the interstitial spaces of the iron lattice [14]



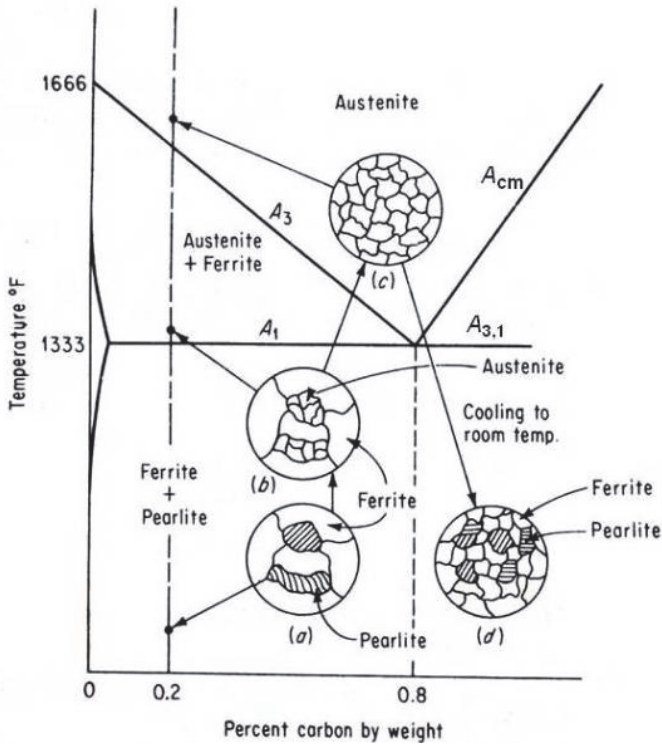
**Figure 7.4:** Iron-carbide phase diagram, with percent content shown along the x-axis [15]

Although alloying is an important way to alter properties and behaviors, steels with similar chemical compositions can still have diverse properties based on how they have been treated. In particular, cooling, forming, and post-forming processes produce several unique steel microstructures. A binary phase diagram, such as the iron-carbide phase diagram in Figure 7.4, in combination with a continuous cooling curve (also known as a time-temperature-transformation or “TTT” curve), illustrates the wide variety of structures that can result from small variation in carbon content and cooling process.

The final microstructure of steel can contain different phases (fractions with homogeneous characteristics), many with names ending in *-ite*: austenite, martensite, ferrite, bainite, etc., as shown in Figure 7.5. Several factors determine the grain size, shape, and distribution of these phases, which in turn contribute to the strength, ductility, and other properties of the material. For more resources and information about phase transformations, TTT diagrams, and microstructural features of steel, please see Appendix B.

### 7.3 Strengthening mechanisms

Important considerations during the materials selection process include: yield strength (YS), ultimate tensile strength (UTS), ductility (sustaining plastic deformation before fracture), toughness (absorbing energy before fracture, indicated by the total area under the tensile stress-strain curve), and hardness (resisting deformation on the surface). Steel is so versatile because these properties can vary tremendously; YS, for example, in mild steel could be 130 MPa and in martensitic steel could be 1500 MPa or more. The chemistry and microstructure that determine these characteristics may be tailored to meet the broad range of requirements of the automotive industry.



**Figure 7.5:** Some of the microstructures produced during the annealing of hypoeutectoid carbon-steel [16]

Metallurgists employ various methods to obtain the desired properties from steel. Strengthening and hardening mechanisms are often used in various combinations to meet specific requirements, such as fatigue strength or dent resistance. Strengthening mechanisms typically work by hindering or impeding the movement of dislocations through the steel, and include:

- *Solid solution strengthening*: When another species is added to form a solid solution, the interstitial or substitutional atoms form localized strain fields that can increase the strength and hardenability, although they may simultaneously decrease ductility.
- *Grain refinement*: As dislocations travel through a material, they tend to pile up at grain boundaries, preventing further plastic deformation. As grain size decreases, the effective area of grain boundaries increases, increasing the strength of the material.
- *Work hardening (a.k.a. strain hardening)*: As a result of cold working (rolling, drawing, bending, etc.), dislocations in steel become more entangled, preventing their relative movement. Work hardening typically increases YS, UTS, and hardness, but often has an adverse effect on ductility and toughness.
- *Dispersion strengthening or precipitation hardening*: The steel matrix, usually ferritic or austenitic, often contains other phases, which may range from fine particles (e.g. cementite particles, islands tempered martensite, or discrete carbide or nitride alloy precipitates) to lamellar sheets (e.g. the ferrite and cementite layers of pearlite). These microstructural features can affect the overall properties of the material considerably and illustrate some of the many ways to increase strength.
- *Transformation strengthening*: In the production processing of steel, phase transformations can often occur which enable strengthening by creating microstructures with significant amounts of hard phases, such as martensite or bainite. Such transformations occur in operations like hot rolling, hot-dip galvanizing, or continuous annealing where steel can cool from high-temperature austenite and transform to these harder low-temperature phases. This mechanism is fundamental to the development of advanced high-strength steels and enables dual-phase, transformation-induced plasticity (TRIP), and other AHSS steels to be manufactured.

To learn more about these mechanisms, please consult the resources listed in Appendix B.

#### **7.4 Steel and Part Processing**

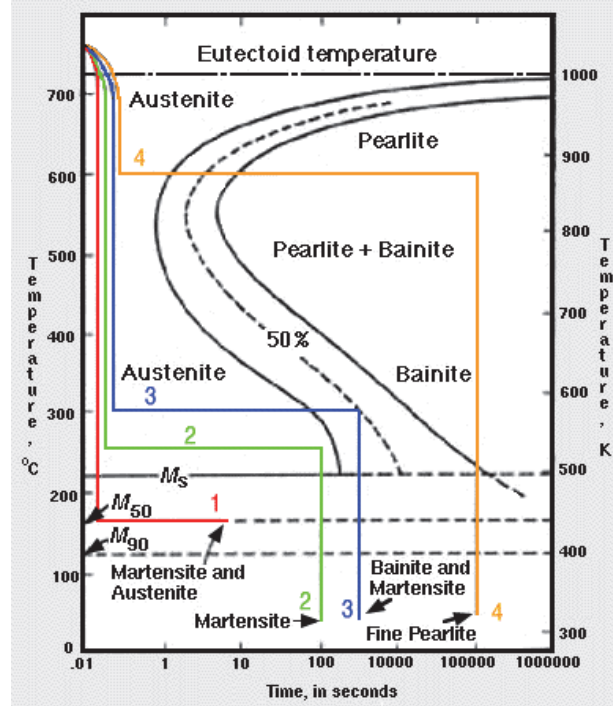
As AHSS are developed for combinations of characteristics ideal for the final part, the feasibility of manufacturing is paramount to actual application and implementation in vehicles. Concerns about formability and weldability have prompted much research and development in the area of processing steel. In some cases, traditional process methods are just as effective with AHSS as with mild steels; in others, some modifications to equipment or methods are necessary; and in others, new processing technologies have even enabled the development of new steel grades.

As discussed above in section 7.3, transformation strengthening is the principal strengthening mechanism employed in manufacturing AHSS in steel plant processes. Heating cycles are especially important in the production of these grades. Temperature and cooling rates must be carefully controlled within tight windows to develop the desired microstructures, as illustrated by the time-temperature-transformation (TTT) diagram in Figure 7.6 on the next page. Producers are increasingly automating controls, and various sensors monitor temperature and other conditions during the process. Because AHSS may require more process control than found on current hot and cold rolling, annealing, and galvanizing lines, plants are updating their technologies. New processing lines, such as continuous annealing lines and modern hot-dip galvanizing lines, are being investigated and installed. Many resources are available online to explore various steel production methods, and some of these are listed in Appendix B.



Automotive steel is typically produced as large coils, which may then be processed into blanks or tubular products. The Final Engineering Report (Section 3.2) for the FutureSteelVehicle describes a comprehensive listing of manufacturing options and technologies, including:

- Conventional cold stamping
- Laser welded blank
- Tailor rolled blank
- Induction welded hydroformed tubes
- Laser welded hydroformed tubes
- Tailor welded hydroformed tubes
- Hot stamping (direct and indirect)
- Laser welded blank quench steel
- Tailor rolled blank quench steel
- Roll forming
- Laser welded coil rollformed
- Tailor rolled blank rollformed
- Rollform with quench
- Multi-walled hydroformed tubes
- Multi-walled tubes
- Laser welded finalized tubes
- Laser welded tube profiled sections [6].



Manufacturing processes continue to stand out as a vital factor in the development of new materials. Much of the current research is focused on identifying new processes and technologies to improve the consistency, reduce cycle time and cost, and enable the production of parts using AHSS. In some cases, the processing of the part can be instrumental in developing the final strength in AHSS applications. The most notable example of this is with boron-treated hot stamped parts. Boron is alloyed with these steels to provide sufficient hardenability so that, on quenching hot-stamped parts in water-cooled dies, the austenite-to-martensite transformation can occur. Some of the current areas of research are described later in this report (Section 9.2).

## 8. AHSS and Applications

Several key considerations drive material selection for automotive applications, including safety, fuel efficiency, environmentalism, manufacturability, durability, and quality. These factors manifest themselves differently in each component of the vehicle, and materials are selected to match each set of performance requirements in the most efficient means possible.

### 8.1 Automotive Materials Selection

The ability to carry the required static and dynamic loads, particularly in a crash event, is one of the key design considerations for vehicle structures. Both materials strategy and geometric design play important roles in determining the final load paths and part details. For exposed parts, aesthetic concerns related to paint finish and dent resistance are also important.



Figure 8.1: The major crash management zones of a vehicle [Adapted from 18]

#### 8.1.1 Crash Performance

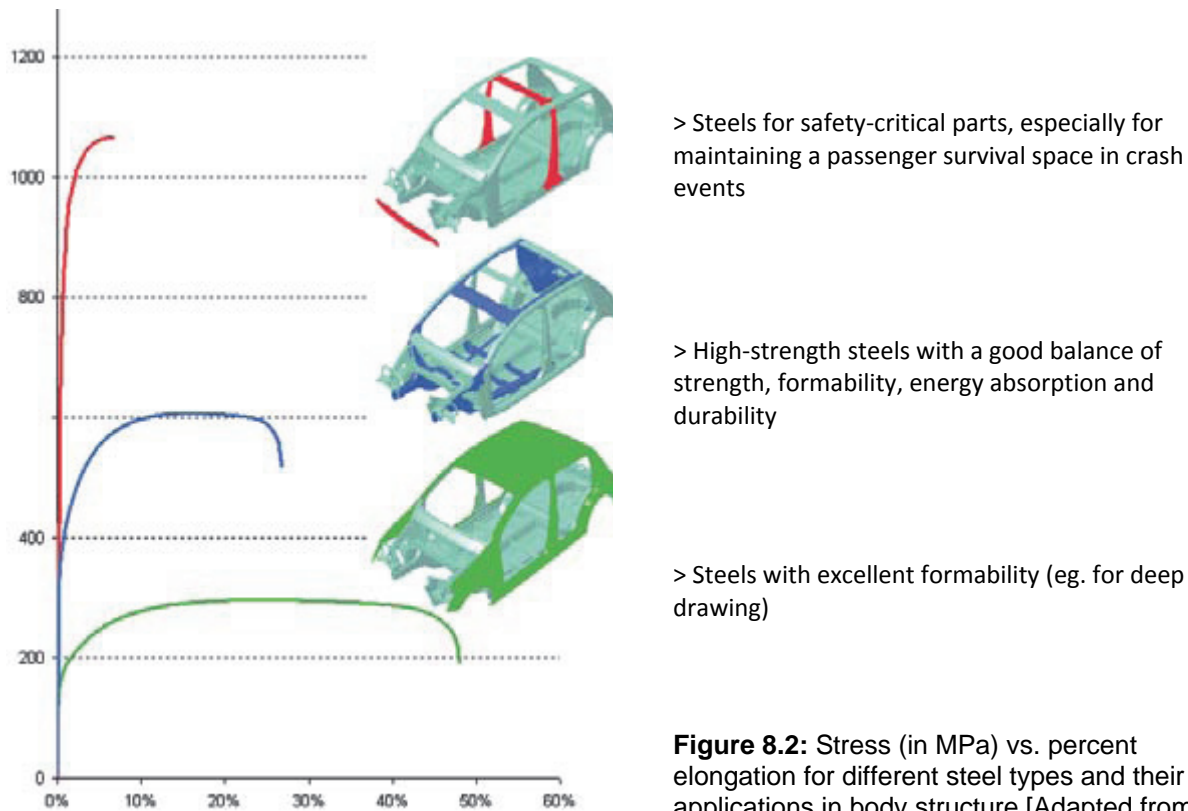
Two generalized areas of the car have very different safety requirements, as shown in Figure 8.1 above. The passenger compartment, enclosed in a rigid “safety cage,” is designed to protect the passengers in the event of a low- to high-speed crash; the structure should prevent any deformation or intrusions that would compromise the integrity of the structure and impinge on the space around the passengers. The so-called “crumple zones,” located at the front and rear of the vehicle, are designed to absorb as much energy as possible in the event of a front or rear collision. By absorbing the energy over a distance, the crumple zone will cushion the impact and help preserve the structure of the passenger compartment. The general guidelines for materials selection in these zones are outlined below:

##### Crumple zone:

Performance requirements:	High energy absorption over a distance in crash event
Material property to meet need:	High work hardening, strength, and ductility
Evidence of this property:	Large area under the stress-strain curve
Potential steel selection:	Dual phase (DP, complex phase, transformation-induced plasticity)

##### Passenger compartment:

Performance requirements:	No deformation/intrusion during crash event
Material property to meet need:	High yield strength
Evidence of this property:	Highest ultimate tensile strength of $\sigma$ - $\epsilon$ curves
Potential steel selection:	Martensitic, HF, DP (>980 MPa)



Clearly, the choice of steel properties like those shown in Figure 8.2 guides the selection of steel types for specific applications. The components are designed so that together they form a structure that meets all requirements, particularly all crash cases, both those enforced by National Highway Traffic Safety Administration and those set internally by car companies.

### 8.1.2 Stiffness

Stiffness is a function of part geometry and elastic modulus, not YS or UTS, and is related to handling, safety, and also noise, vibration, and harshness concerns. Although using AHSS helps to increase strength and decrease weight by using thinner material, stiffness can suffer as a result. Geometry, in particular the moment of inertia of the cross-section about the primary load axis, plays a significant role in determining stiffness. The flexibility to adjust cross sectional and overall geometries allows for structural design solutions that more efficiently carry loads in the vehicle. The use of AHSS offers many advantages in this process because its high work hardening rates increase formability, allowing for improved shapes for optimal efficiency [12]. Additionally, AHSS typically possess high bake-hardening ability which can improve the final strength of a component after forming and paint-baking (curing).

### 8.1.3 Forming and Manufacturability

AHSS were developed partly to address decreased formability with increased strength in conventional steels. As steels became increasingly stronger, they simultaneously became increasingly difficult to form into automotive parts. AHSS, although much stronger than conventional low- to high-strength steel, also offer high work hardening and bake hardening capabilities that allow increased formability and opportunities for optimization of part geometries [12]. Both overall elongation and local elongation properties are important for formability; for some difficult-to-form parts, high stretchability at sheared edges is important (as discussed in the following sections about complex phase and ferritic-bainitic steels).

## **8.2 Steel Types**

This next section of the report provides an overview of some of the many types of steel, both conventional and AHSS. Each page is a brief introduction to the material and what makes it unique, based on a review of its microstructure, properties, processing, and performance. Applications for each type of steel are included, as well as current examples. A table for each steel type summarizing its key features, advantages, and limitations is also included.

The information in this section was compiled from several sources, with heavy borrowing in particular from “Steel Basics” on WorldAutoSteel.com [4]. For more general AHSS references and some more technical resources, please see Appendix C.

### 8.2.1 Conventional Low- to High-Strength Steels

Mild-, low- to high-strength steels have been widely used in cars for many years. This report includes brief reviews of the following conventional steels:

- Mild
- Interstitial free (IF)
- Bake hardenable (BH)
- High-strength low-alloy (HSLA)

#### 8.2.1.1 Mild Steel

Conventional mild steel has a relatively simple ferritic microstructure; with low carbon content and minimal alloying elements making it soft and formable. Widely produced and used, mild steels are inexpensive and often serve as a baseline for comparison for other materials. Mild steels have relatively low strength, but excellent formability. Mild steels have long been used for many applications in vehicles, including the body structure, closures, and other ancillary parts.

#### 8.2.1.2 IF Steel

IF steel has ultra-low carbon content, achieved by removing carbon monoxide, hydrogen, nitrogen, and other gasses during steelmaking through a vacuum degassing process. Interstitial elements like nitrogen or carbon also form nitrides and carbides with alloying elements such as columbium or titanium to stabilize the residual interstitials. Therefore, IF steels are typically non-aging. (IF steels became the standard base for hot-dipped galvanized products because they do not age.) The lack of interstitial atoms in the atomic structure enables IF steel to have extremely high ductility, ideal for deep-drawn products. In fact, IF steels are sometimes called extra-deep-drawing steels (EDDS). They have relatively low strength (although they are sometimes strengthened by the reintroduction of nitrogen or other elements), but high work hardening rates and excellent formability. Applications for IF steel include elements of the body structure and closures.

#### 8.2.1.3 BH Steel

Although they have a simple ferritic microstructure, solid solution strengthening gives BH steels a boost in strength. They have a more complicated chemistry than mild or IF steels; special techniques are employed to keep carbon in solution through processing until it is released during paint baking. The bake hardening procedure increases the YS of BH steels, while maintaining excellent formability. BH steels have high dent resistance and are often selected for closure panels like door outers, hoods, and decklids..

#### 8.2.1.4 HSLA Steel

HSLA steels were among the first widely-used used high-strength steels (HSS) in automotive applications. Finely dispersed alloy carbides and ferrite-pearlite aggregates sit in a ferrite matrix, with minimal alloying content. This complex structure combined with grain size refinement for increased strength give HSLA its name. HSLA is usually designed to meet mechanical specifications and is typically tough, corrosion resistant, formable, and weldable. Many automotive ancillary parts, body structure, suspension and chassis components, as well as wheels, are made of HSLA steel.

### 8.2.2 *Advanced HSS*

These newer steels have enhanced strength and formability achieved through the development of more complex microstructures through controlled cooling processes. The first generation of these AHSS is ferrite based. This report includes descriptions of:

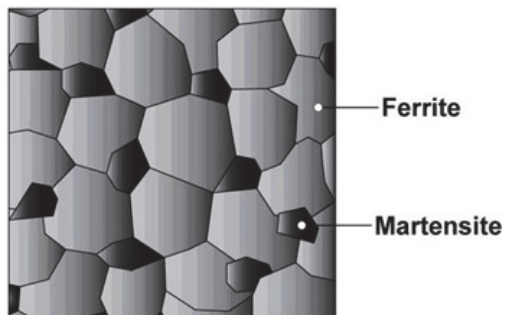
- Dual phase (DP)
- Ferritic-bainitic (FB), including stretch-flangeable (SF)
- Complex phase (CP)
- Martensitic (MS)
- Transformation-induced plasticity (TRIP)
- Hot-formed

The second generation AHSS are more austenite-based, and include:

- Twinning-induced plasticity (TWIP)

A table summarizes key features of each AHSS steel type at the end of its section. Comments about cost are based on the information used in the cost assessment for FutureSteelVehicle [6].

### 8.2.2.1 DP Steel



**Figure 8.3:** DP microstructure schematic [4]

The microstructure of DP steel consists of a soft ferrite matrix and discrete hard martensitic islands, as shown in Figure 8.3. The ferrite is continuous for many grades up to DP780, but as volume fractions of martensite exceed 50 percent (as might be found in DP 980 or higher strengths), the ferrite may become discontinuous. The combination of hard and soft phases results in an excellent strength-ductility balance, with strength increasing with increasing amount of martensite.

DP steels can be hot- or cold-formed and also have high bake hardening behavior. If hot-rolled, cooling is carefully controlled to produce the ferritic-martensitic structure from austenite. If continuously annealed or hot-dipped, the final structure is produced from a dual phase ferritic-austenitic structure that is rapidly cooled to transform some of the austenite to martensite [22]. The soft ferrite in the final DP material is exceptionally ductile and absorbs strain around the martensitic islands, enabling uniform elongation with high work hardening rate and fatigue strength. Additionally, DP steels can absorb a lot of strain energy. Unlike conventional steels (even the traditional BH steels), bake hardening does not decrease with increasing pre-strain for DP steels.

DP is currently one of the most widely used AHSS. Automakers are increasingly employing DP to increase strength and down gauge HSLA structural components. Important to consider when designing with DP, as with other AHSS, is the effect of strain and bake hardening. DP steels may be developed with low to high yield strength (YS) to ultimate tensile strength (UTS) ratios, allowing for a broad range of applications from crumple zone to body structure. DP is sometimes selected for visible body parts and closures, such as doors, hoods, front and rear rails. Other popular applications include: beams and cross members; rocker, sill, and pillar reinforcements; cowl inner and outer; crush cans; shock towers, fasteners, and wheels.

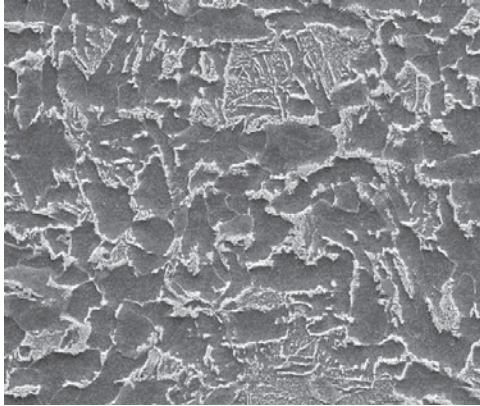
In 2010, the Auto/Steel Partnership published “Advanced high-strength steel applications: Design and stamping process guidelines,” a special edition with 12 in-depth AHSS case studies [20]. Most of the parts in this report were produced from DP steel. Details from part geometry design, stamping process design, formability analysis, die process, springback compensation, press load predictions, fixture and clamping, etc. are noted, as well as lessons learned from the study. DP is increasingly used by automakers in current car models. For example, in the 2011 Chevrolet Volt, the overall upper body structure is six percent DP by mass, and the lower structure is 15 percent, including such parts as the reinforcement for the rocker outer panel [21].

(Summary table on the next page.)

<b>Figure 8.4: Summary of DP steel</b>			
<b>Microstructure features</b>	Soft ferrite matrix, hard martensitic islands	<b>Typical additions</b>	C, Si, P strengthen but must be balanced for weldability, Mn, Cr, Mo, V, Ni increase hardenability
<b>Formability</b>	Excellent	<b>Weldability</b>	Good; at highest strengths requires careful selection of schedules
<b>Advantage</b>	<b>Performance</b>	<b>Application</b>	
High bake hardening capability, high-strength	Resists fracture	Beams, cross-members and other structural components	
High work-hardening rates and strain energy absorption	High UTS for given strength, delays necking	Crash energy absorption	
Excellent elongation, weldability	Good manufacturability	Tailored blanks, hydroformed tubes	



### 8.2.2.2 FB Steel



**Figure 8.5:** Microstructure of ferritic - bainitic steel [22]

FB steel is also DP, with soft ferrite and hard bainite. The microstructure, shown in Figure 8.5, is finer than the typical DP steel, however, and can be even more finely tuned to be SF. This characteristic can be measured by the hole expansion test and gives FB/SF the ability to resist stretching on blanked edge. The second hard-phase bainite and grain refinement make FB a strong material with excellent formability.

FB steel performs well under dynamic loading conditions, making it well suited to carry vibration loads. The stretchability of FB (or SF) at sheared edges makes it an

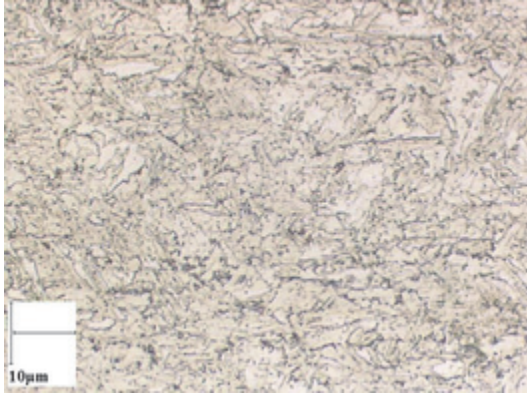
excellent choice for tailored blank applications. Often cold-drawn FB is used for profiles, mechanical parts, cross beams and reinforcements, and wheels. SF is also recommended for suspension and chassis. Because FB has good fatigue properties in dynamic load conditions, it is an outstanding candidate for shock towers and control arms, as shown in Figure 8.6.



**Figure 8.6:** Control arm made from SF steel (Image courtesy of B. DePompolo, United States Steel)

<b>Figure 8.7: Summary of FB steel</b>			
<b>Microstructure features</b>	Ferrite matrix, fine second phase bainite	<b>Typical additions</b>	Al, B, Nb, and/or Ti
<b>Formability</b>	Excellent	<b>Weldability</b>	Good, longer spot welding times
<b>Advantage</b>	<b>Performance</b>		<b>Application</b>
High hole expansion	High stretchability at sheared edges		Tailored blanks, complex parts
Good fatigue properties	Good in dynamic loading conditions		Carry vibration loads

### 8.2.2.3 CP Steel



**Figure 8.8:** CP microstructure [22]

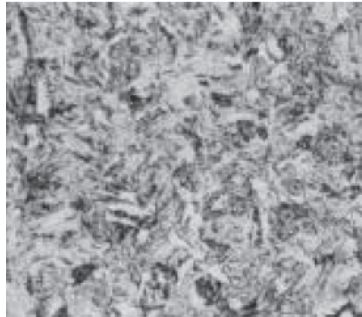
CP steels have a mixed microstructure with a ferrite/bainite matrix containing bits of martensite, retained austenite, and pearlite, as shown in Figure 8.8. Grain refinement is essential to obtaining the desired properties from CP steel; delayed recrystallization is often employed to develop very small grains for a very fine microstructure. Microalloying elements such as titanium or niobium may also be precipitated.

The fine, complex microstructure gives CP steel high YS and high elongation at tensile strengths similar to DP steels. CP can have good edge stretchability. Additionally, CP steels have good wear characteristics and fatigue strength and they may be bake hardened.

CP steel has several automotive applications, particularly in body structure, suspension, and chassis components. The high YS and elongation enables high energy absorption, also making it a good choice for crash safety components, such as fender beams, door impact beams, and reinforcements for B-pillar, etc. BMW has used CP in several components to improve rear crash safety. According to ThyssenKrupp Steel, replacing conventional microalloyed steel with CP in a B-pillar reinforcement can double its strength [23].

<b>Figure 8.9: Summary of CP steel</b>			
<b>Microstructure features</b>	Ferrite/bainite with martensite, austenite, pearlite	<b>Typical additions</b>	Similar to DP, with additional microalloying elements such as Ti, Nb, V
<b>Formability</b>	Good	<b>Weldability</b>	Lower conductivity requires special considerations, but good
<b>Advantage</b>		<b>Performance</b>	<b>Application</b>
Very high UTS	High energy absorption and resistance to deformation	Good durability	Crash safety components
High residual deformation capacity			
High wear resistance			Parts with heavy wear
<b>Limitation</b>	<b>Effect on processing or performance</b>	<b>Special considerations / solutions</b>	
Decreased formability at higher strength	Necking can quickly cause cracking	Careful part design	

### 8.2.2.4 MS Steel

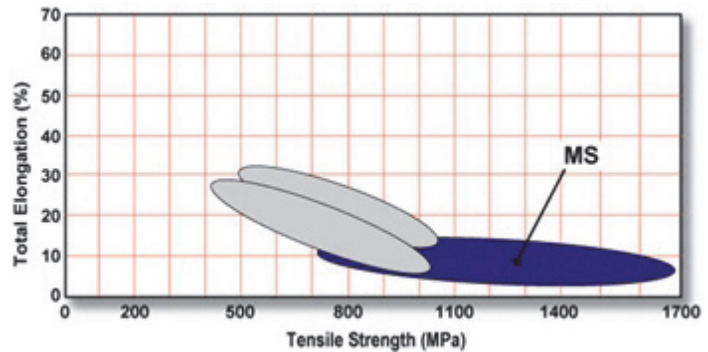


**Figure 8.10:** Tempered martensite microstructure [11]

In MS steels, nearly all austenite is converted to martensite. The resulting martensitic matrix contains a small amount of very fine ferrite and/or bainite phases. This structure typically forms during a swift quench following hot-rolling, annealing, or a post-forming heat treatment. Increasing the carbon content increases strength and hardness. The resulting structure is mostly lath (plate-like) martensite, as in Figure 8.9 [24]. Careful combinations of silicon, chromium, manganese, boron, nickel, molybdenum, and/or vanadium can increase hardenability.

The resulting martensitic steel is best known for its extremely high strength, as shown in Figure 8.11; UTS from 900 to 1700 MPa have been obtained. MS has relatively low elongation, but post-quench tempering can improve ductility, allowing for adequate formability considering its extreme strength. Often used where high strength is critical, MS steel is typically roll formed and may be bake hardened and electrogalvanized for applications requiring corrosion resistance, but heat-treating MS decreases its strength.

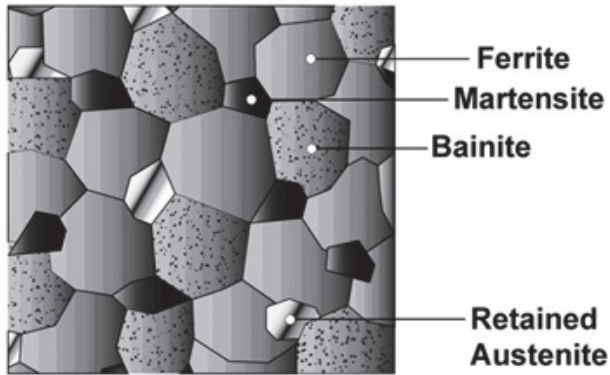
Because MS steel has such high strength to weight ratio, it is weight and cost effective. It is often selected for body structures, ancillary parts, and tubular structures. MS grades are recommended for bumper reinforcement and door intrusion beams, rocker panel inner and reinforcements, side sill and belt line reinforcements, springs, and clips [22]. For example, in the 2007 Honda Acura MDX, the rear martensitic bumper beam assists in rear crash protection [33].



**Figure 8.11:** MS elongation vs. tensile strength [4]

<b>Figure 8.12: Summary of MS steel</b>			
<b>Microstructure features</b>	Martensitic matrix, some ferrite and/or bainite (finer than CP)	<b>Typical additions</b>	Si, Cr, Mn, B, Ni, Mo, V to increase hardenability
<b>Formability</b>	Adequate	<b>Weldability</b>	Good, with increased electrode forces
<b>Processing notes</b>	Post-quench temper can increase ductility	<b>Cost</b>	High strength-to-weight ratio, cost effective
<b>Advantage</b>	<b>Performance</b>	<b>Application</b>	
Highest YS	Resists deformation	Strong, light-weight components	
<b>Limitation</b>	<b>Effect on processing or performance</b>	<b>Special considerations / solutions</b>	
Low elongation, high springback	Traditional forming techniques require adjustments	Roll forming in multiple operations and over-bending	

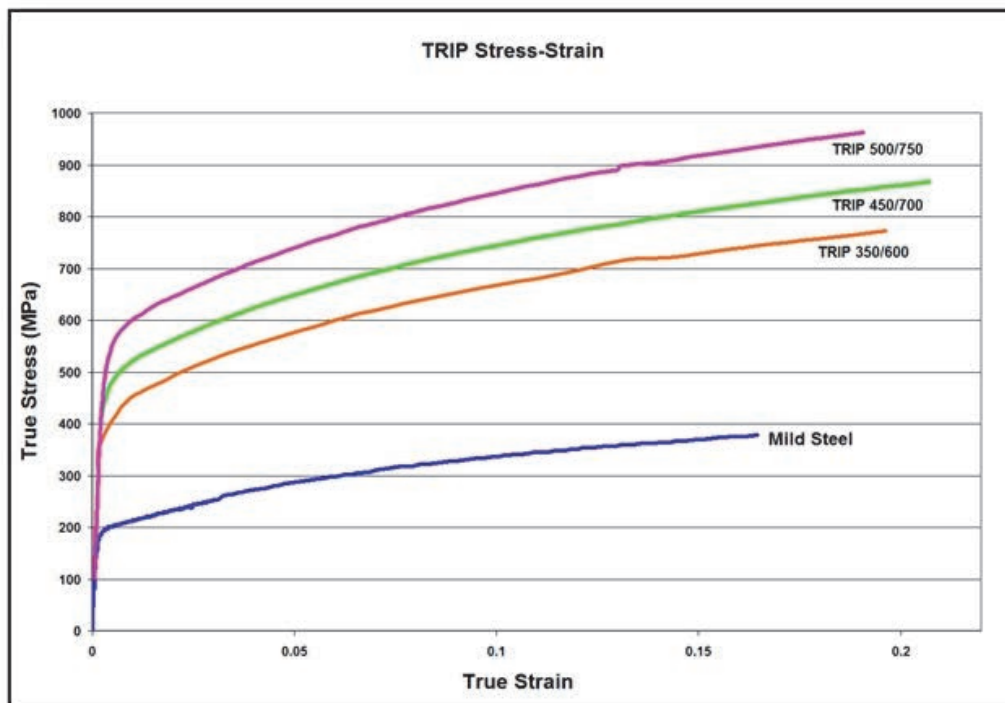
### 8.2.2.5 TRIP Steel



**Figure 8.13:** Schematic of a typical TRIP microstructure [4]

Like CP grades, TRIP benefits from a multi-phase microstructure with a soft ferrite matrix embedded with hard phases. The matrix contains a high amount of retained austenite (at least 5 percent), plus some martensite and bainite, as shown in the schematic of Figure 8.13. TRIP has a high carbon content to stabilize the meta-stable austenite below ambient temperatures. Silicon and/or aluminum are often included to accelerate the ferrite/bainite formation while suppressing carbide formation in this region [4].

TRIP steel received its name for its unique behavior during plastic strain: in addition to the dispersal of hard phases, the austenite transforms to martensite. This transformation allows the high hardening rate to endure at very high strain levels, hence “Transformation-Induced Plasticity.” The amount of strain required to initiate this transformation may be managed by regulating the stability of the austenite by controlling its carbon content, size, morphology or alloy content. With less stability, the transformation begins almost as soon as deformation transpires. With more stability, the austenitic transformation to martensite is delayed until higher levels of strain are reached, typically beyond those of the forming process. In highly stabilized TRIP steel automotive parts, this delay can allow austenite to remain until a crash event transforms it to martensite. Other factors also affect the transformation, including the specific conditions of deformation, such as the strain rate, the mode of deformation, the temperature, and the object causing the deformation. When the austenite-martensite transformation occurs, the resulting structure is toughened by the hard martensite. Deformation can continue through very high strain levels, as shown in Figure 8.14.



**Figure 8.14:** True stress - strain diagram for TRIP grades, compared to mild steel. Note the high strain hardening rate maintained even at high strain [4]

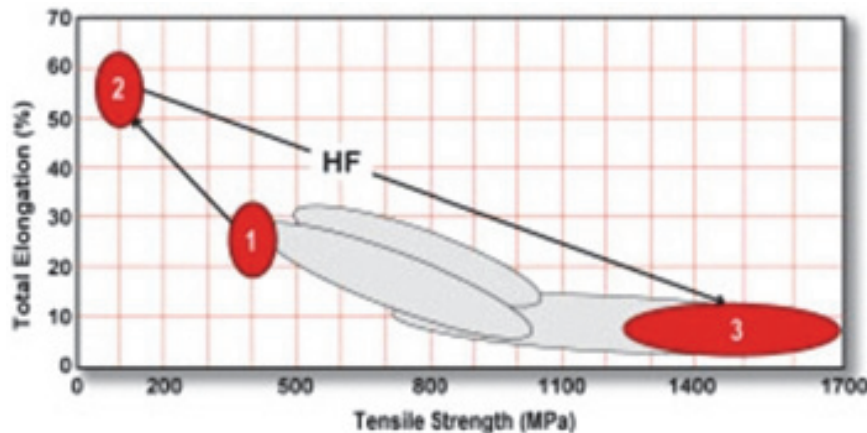
TRIP, as a result of its high work hardening rates, has excellent formability and a high capacity for stretch. Complex shapes are possible because TRIP exhibits good bendability and resists the onset of necking. TRIP also has excellent bake-hardening capacity. High work hardening, total stretchability, and total elongation, however, limit local elongation and edge stretchability; shear cracking at the interfaces between the ductile ferrite and the hard martensite phases also reduces the hole expansion limits for edges of TRIP steels [20]. Careful design can minimize areas with stretch flange edges; trimming and notching can also alleviate problems with poor edge stretchability. Poor resistance spot-welding behavior caused by alloying can be addressed by modifying welding cycles (for example, using dilution or pulsating welding).

TRIP steels are some of the newest in development, but steel companies are quickly offering a greater variety of TRIP steels for automotive applications. They boast of its wide applicability, especially in complicated parts, and its high potential for mass savings. It can now be obtained in a variety of grades. Automotive applications of TRIP include body structure and ancillary parts. With high energy absorption and strengthening under strain, it is often selected for components that require high crash energy management, such as cross members, longitudinal beams, A- and B- pillar reinforcements, sills and bumper reinforcements [22]. For example, in 2007 Honda introduced the use of TRIP in the frame and side structure of the MDX, RDX, and CRV [33].

<b>Figure 8.15: Summary of TRIP steel</b>			
<b>Microstructure features</b>	At least five percent retained austenite, plus martensite and bainite	<b>Typical additions</b>	More C, Si, and other alloying elements
<b>Formability</b>	Excellent	<b>Weldability</b>	Requires tight control of welding parameters for effective spot welding
<b>Advantage</b>			
<b>Performance</b>		<b>Application</b>	
Austenite to martensite transition during plastic strain	High work hardening rate	Stamping applications	
	High energy absorption under strain	Crash energy absorption	
	High bake hardening effect	High-strength components, weight reduction	
High fatigue endurance limit [22]	Excellent durability	Parts with high load cycles	
<b>Limitation</b>			
<b>Effect on processing or performance</b>	<b>Special considerations / solutions</b>		
Poor local and edge stretchability	Cracking at edges	Minimize stretch flange areas, utilize notching	
High alloying requirements	Poor resistance spot- welding behavior	Use dilution or pulsating welding	
Changing microstructure	Changes and limits repair methods	Area of current research and development	

### 8.2.2.6 HF Steel

HF steel is typically boron-based, containing 0.002-0.005 percent boron, and may even be called “boron steel.” The processes used to produce HF bestow a unique combination of properties. “Direct hot-forming” may be used to deform the blank in the austenitic state (at high temperatures) or “indirect hot-forming” may be used to heat and finish the piece after most forming is completed at room temperature. In either case, the steel undergoes a series of transitions in elongation and strength (as shown in Figure 8.16 below), finishing with a rapid cooling to achieve the final desired mechanical properties.



**Figure 8.16:** Transitions in HF steel.

1: Initial, room temperature state where the steel is blanked.

2: Raised temperature state where forming is completed.

3: Final strength-elongation achieved after rapid cooling.

[4]

In direct hot-forming, the boron-based steel is blanked at room temperature and then heated to high enough temperature for austenization. The steel is then formed while hot and quenched in the forming tool, developing the martensitic microstructure. Some special post-forming work may be required to finish the pieces, which are exceptionally high strength. For indirect-hot forming, the steel is blanked and pre-formed at room

temperature. The part is then heated and forming is completed while the steel is in this low strength, high elongation state. A final quench in the die produces the final properties and shape.

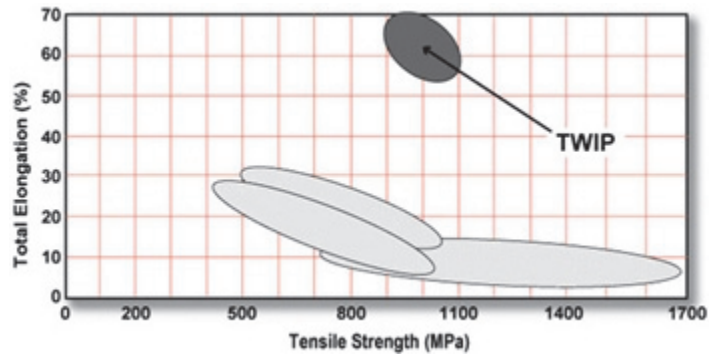
Parts made from HF steel benefit from several material advantages, including high strength and improved (reduced) springback. The part remains in the die through the cooling phase, and so springback is virtually nonexistent. Repairability is limited, however, because HF steel becomes brittle through the work hardening of a crash event; the heat required to straighten the damage degrades the strength of the part [25].

The use of HF boron steel, called ultra-high-strength steel (UHSS) by some automakers, has grown rapidly in Europe; other materials for hot forming are also being investigated, as well as new coatings to improve corrosion resistance [26]. Other areas of current research and development include improving the heating, forming, and tooling technologies. Applications for HF steels include reinforcements for and A- and B-pillars, roof bows, side-wall members, and beams for crash management structures and other parts that carry severe loads. Volvo was one of the early adopters of hot-formed steels, as they call UHSS (YS of 1500 MPa). First used in the C70 convertible, the boron-steel helped Volvo earn a reputation for building cars that win high marks for safety and style. More recently, the Volvo XC60 received the 2010 International Truck of the Year Award. UHSS was used in the A and B posts, as well as the floor sill reinforcements.

<b>Figure 8.17: Summary of HF steel</b>			
<b>Microstructure features</b>	Martensitic	<b>Typical additions</b>	Boron (0.002-0.005 percent), Mn, Al
<b>Formability</b>	Excellent	<b>Weldability</b>	Good
<b>Advantage</b>	<b>Performance</b>		<b>Application</b>
Final hot-forming in the die	Improved (reduced) springback		Complex parts requiring high strength
High strength	Resists deformation		
<b>Limitation</b>	<b>Effect on processing or performance</b>		<b>Special considerations / solutions</b>
High initial investment in equipment	Initial barrier to implementation		Long-term commitment yields pay-off
Specialized forming	Limited repairability		Current area of research

### 8.2.2.7 Twinning-Induced Plasticity TWIP Steel

TWIP steel is part of the “second generation” of AHSS. Austenite based, it sits apart from conventional and first generation AHSS on the elongation-tensile strength diagram, as shown in Figure 8.18. High manganese content enables this austenitic structure to exist at room temperature [4]. In fact, the manganese content is so high that some argue that TWIP steel is not steel at all, but rather an advanced alloy.



**Figure 8.18:** Total elongation vs. tensile strength of TWIP steel [4]

TWIP steel received its name for its particular mode of deformation: deformation twinning, where slip causes the formation of symmetric twin boundaries. These boundaries are much like grain boundaries in their functionality, restricting the movement of dislocations through the material. They strengthen TWIP steel and increase the work hardening rate. As part of the second generation of AHSS, TWIP steel is known for its combination of very high strength with extreme elongation capacity.

TWIP applications are being explored and developed. In the final FutureSteelVehicle design, TWIP was selected for the shock towers and apron reinforcements, although it was also considered and deemed a suitable option for other components in vehicle design, such as the front rail [6].

<b>Figure 8.19: Summary of TWIP steel</b>			
<b>Microstructure features</b>	Austenitic, twin boundaries	<b>Typical additions</b>	High Mn content (17-24 percent)
<b>Formability</b>	Excellent	<b>Weldability</b>	Good
<b>Advantage</b>		<b>Performance</b>	<b>Application</b>
High strength	Excellent formability	Resists deformation	High strength, potentially complex parts
High instantaneous hardening			
Extremely high stretchability			
<b>Limitation</b>	<b>Effect on processing or performance</b>	<b>Special considerations / solutions</b>	
High cost	Economic considerations	Use for select applications	
Corrosion	Durability concerns	Current area of research	
Delayed cracking			



### 8.3 Current Examples

Honda and BMW, two car manufacturers that most quickly and warmly welcomed AHSS grades into their portfolios, have each become known for their forward-thinking use of materials [27].

Honda was one of the first companies to incorporate

some of the highest grade AHSS (980 MPa strength and beyond) into body

structures, as shown in Figure 8.20. Two of Honda's major initiatives in recent years have been safety and environmental leadership, both which are supported through the use of AHSS. They advertise the ACE™ (Advanced Compatibility Engineering™) Body Structure, now incorporated into all of their vehicles, as a next-generation body design to enhance passenger safety. The structure was designed particularly to improve crash-worthiness in the case of collision between size-mismatched vehicles.

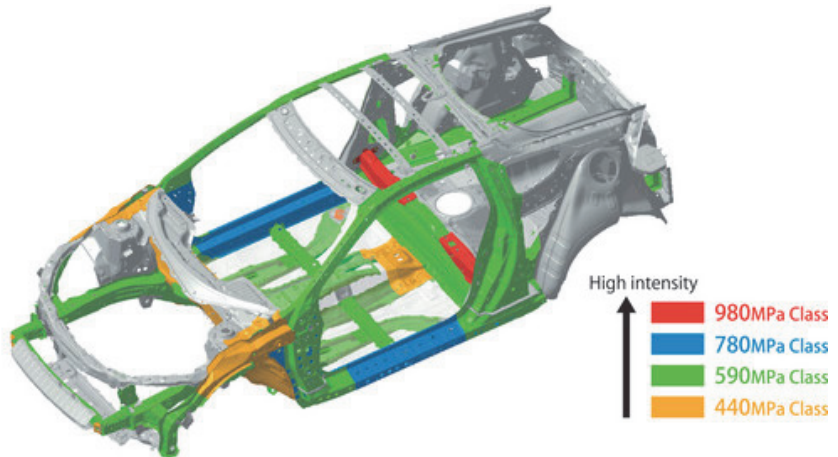


Figure 8.20: HSS in the 2011 Honda CR-Z [28]

BMW has successfully integrated several steel grades into its deliberately multi-material approach to materials selection. They have used hot-stamping to produce parts in A- and B-pillar reinforcements, side members, tunnel reinforcements, and other parts in the 5 and 7 series for several years, as shown in Figure 8.21 [29].

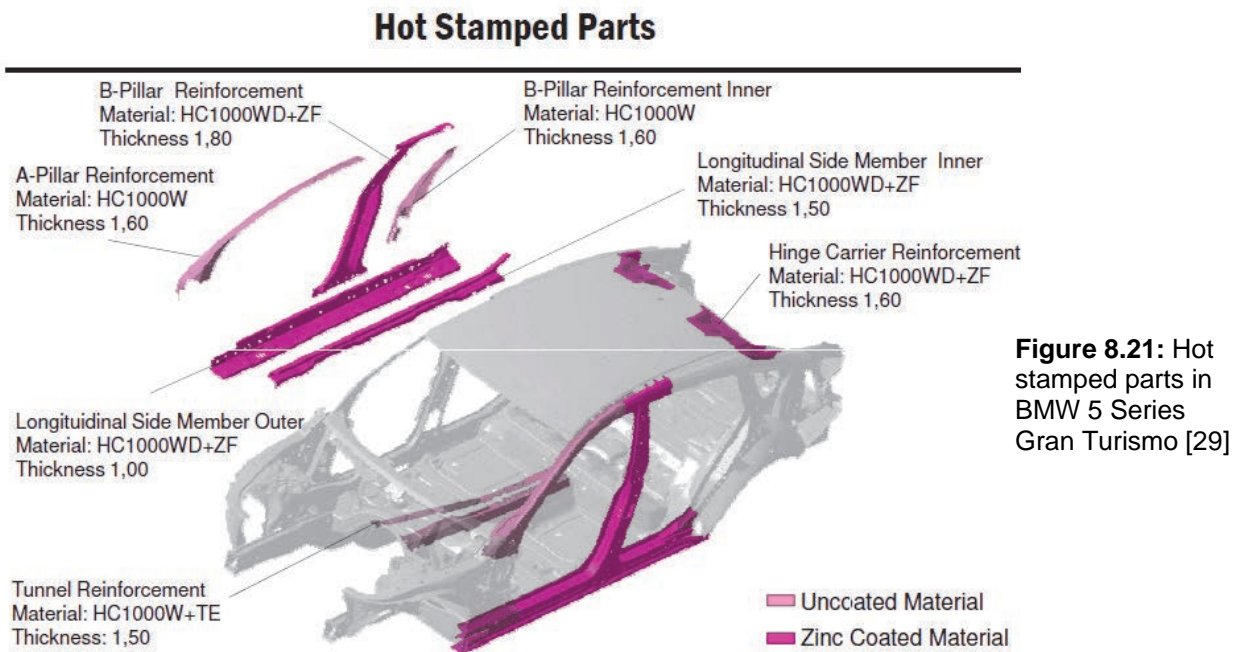


Figure 8.21: Hot stamped parts in BMW 5 Series Gran Turismo [29]

Other automakers are also increasingly incorporating HSS and AHSS to cars produced each model year. As discussed in Section 6.3, the use of medium, high, and advanced HSS have grown tremendously in the last several years. General Motors is moving toward the use of more AHSS, as is evident in the new Chevrolet Volt; 25 percent of the steel in the Volt is AHSS [21].

The steel content in the 2011 Jeep Grand Cherokee has increased from 28 percent to 50 percent HSS and AHSS, and Chrysler predicts an increase to 70 percent in new models [30]. Ford similarly reports that the share of HSS and AHSS has increased in its vehicles, such as the Explorer and Fiesta [31]. Volvo and other European automakers make extensive use of hot-stamped boron steels, as well.

## 9. Future of AHSS

The use of HSS and AHSS in the automotive industry has grown tremendously over the past several years. New information, grades, and technologies are emerging that will continue to shape the industry.

### 9.1 Automotive Applications

In the past several years, automakers have increasingly incorporated HSS and AHSS into vehicles, especially structural and safety components. Examples were included in descriptions of the AHSS types in the previous section. Research at Ducker Worldwide predicts that 50 percent of the average body-in-white (BIW) will be converted to AHSS in this decade [9]. Proposed regulations for 2017-2025 will impose much stricter Corporate Average Fuel Economy (CAFE) standards and, if passed, would potentially boost AHSS use significantly [9].

The Automotive Applications Council (AAC) is a subcommittee of the Steel Market Development Institute (SMDI) that focuses on advancing the use of steel in the highly competitive automotive market. SMDI sponsors many programs to research and develop AHSS, the fastest-growing automotive material, and communicate the information to customers. AAC often partners with engineering contractors and universities to develop fundamental, pre-competitive knowledge to improve the industry.

### 9.2 Research

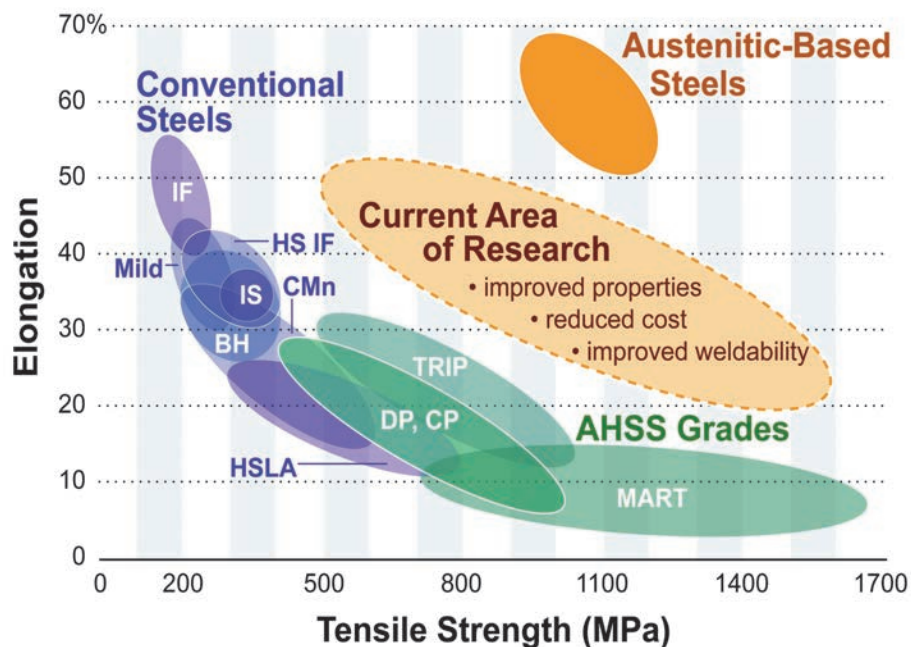


Figure 9.1: Area of opportunity for third generation steels [4]

Current research aims to continue to expand the broad spectrum of HSS. One area of particular interest is the “third generation steels” to bridge the gap of strength – elongation balance (both global and local) between conventional and AHSS steels and the austenitic-based steels, as shown in Figure 9.1 at left. Some materials under development include nano-steels that use finely dispersed, nano-scale particles for excellent total and local elongation even at high strengths [4].

Other research focuses on improving processing methods for already-developed AHSS steels. Many see opportunities for developing novel approaches to produce and form these new steels, such as induction heating methods and innovative cooling systems [32]. One area generating considerable interest is a special thermal processing cycle that produces a “quench and

partition” response in steel [34]. The quench and partition generates a ferritic-martensitic structure high in retained, carbon-rich austenite. The retained austenite, in transformation-induced plasticity steels for example, can be beneficial for various automotive applications requiring high energy management and resistance to fracture. Researchers are now investigating the thermodynamics of the process by which carbon preferentially partitions into austenite, the optimal quenching temperature, and how to best prevent carbide precipitation, both in long products and sheet steel [32].

Stamping and tooling operations are also being examined, as well as joining strategies and models for formability. Additionally, materials properties are a large focus, as both steel companies and automakers are interested in further investigating strain paths, fatigue properties, corrosion resistance, and other properties to improve formability and performance and/or decrease cost.

### **9.3 Advocacy**

One of the most important aspects of current and future work includes communicating the advantages of AHSS to the many communities who could benefit from its use. A close partnership between steel producers and automakers is essential to building an effective collaboration so that AHSS are efficiently incorporated into vehicles to improve safety, sustainability, etc. SMDI, Auto/Steel Partnership, and other groups facilitate such work. Each year conferences around the world, such as the Great Designs in Steel Seminar, provide a venue for discussion and transfer of technical knowledge and ideas. Consumers have a strong desire to purchase vehicles in which they can be confident; safety, fuel economy, and cost are key concerns that can be readily addressed through the incorporation of AHSS.

The use of HSS in vehicles highly affects the first responder community. In cases where they must extract passengers by cutting through a B-pillar or other parts made of AHSS, they require updated tools powerful enough to handle the stronger material. Communication of updated information is essential to help equip rescuers with what they need to work effectively. First responders note that, although AHSS poses challenges when extrication is required, the increased crashworthiness of vehicles with AHSS decreases the likelihood of injury or entrapment of passengers [35].

Policy makers are another vital audience for the message of AHSS. The real goal of reducing carbon emissions can be easily obscured by the hype about producing the lightest weight vehicles possible. Environmentalists advocate for an approach that considers the entire life



cycle assessment (LCA) of a product. This method is helpful when evaluating automotive products and helps to avoid unintended consequences and adverse outcomes, i.e. a light-weight solution that actually produces more emissions. CAFE and tailpipe emissions comprise most current environmental regulations related to vehicles. Policy makers, such as the Environmental Protection Agency (EPA) and California Air Resources Board (CARB), however, are beginning to consider incorporating the more holistic approach of LCA in future directives.

## 10. Conclusion

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The family of AHSS continues to grow and evolve. Many grades of AHSS have been developed to meet the unique and varied performance requirements of the many components of the vehicle. Each type may be tailored to have a specific set of characteristics from a broad range of possibilities. These steels, while improving the strength and safety of cars on the road today, also offer flexibility for automotive engineers who seek to design novel, light-weight solutions.

Increasingly selected for application in vehicles to address challenges faced by automakers, AHSS can help improve safety, fuel efficiency, manufacturability, durability, and quality, while minimizing the lifetime greenhouse gas emissions from production, use, and end-of-life phases of the vehicle. AHSS also remain an economical choice in the highly competitive automotive industry.

While this report gives a concise overview of the major characteristics of AHSS grades, much more detail can be obtained from steel producers. The Automotive Application Council members of the sSteel Market Development Institute (SMDI) each have many AHSS products that represent the steels described in this report. Specific information on particular grades is best found from these member steel producers who are listed on the SMDI automotive website: [www.autosteel.org](http://www.autosteel.org) under the "ABOUT AUTOSTEEL" tab.

## 11. Acknowledgements and References

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A special thanks to Bart DePompolo (United States Steel Corporation), Jonathan Powers (Severstal North America Inc.), Dean Kanelos (Nucor Corporation), and Bruce Wilkinson (ThyssenKrupp Steel USA, LLC).

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# Appendix A: Safety Requirement Resources

National Highway Traffic Safety Administration:

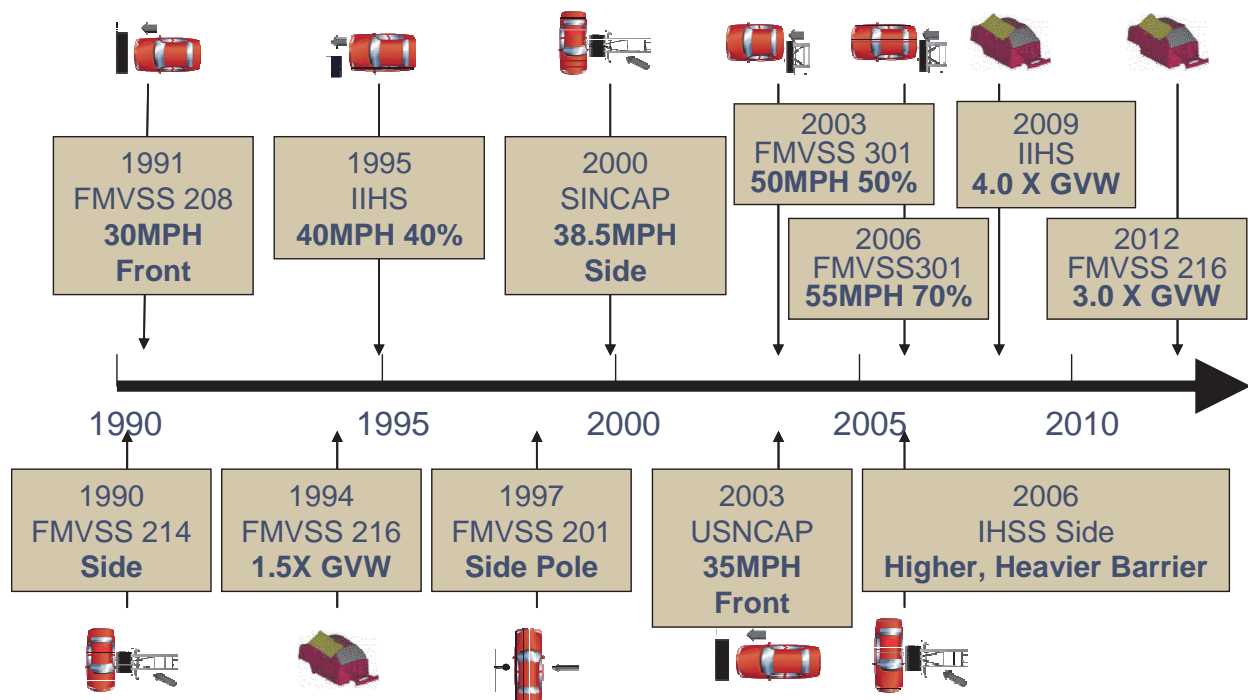
The National Highway Traffic Safety Administration has many resources to learn about driving and vehicle safety, as well as data research and legislation, on their website (<http://www.nhtsa.gov>).

Insurance Institute for Highway Safety:

On its website (<http://www.iihs.org>), the Insurance Institute for Highway Safety has a variety of vehicle safety ratings, news, and other consumer information, plus more about research, laws, and regulations.

SaferCar.gov:

Run by the US Department of Transportation, this website (<http://www.safercar.gov>) provides resources to help vehicle shoppers, owners, and manufacturers understand the safety technologies, ratings and resources that are available.



**Figure A.1:** Timeline of recent major U.S. automotive safety legislation [3]

## Appendix B: Materials Science Resources

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Introductory materials science textbook:	Any elementary materials science, materials engineering, or metallurgical textbook will give a good introduction to the concepts necessary to understand AHSS. One popular text is Callister's <i>Materials Science and Engineering: An Introduction</i> [11].
steeluniversity.org:	This free online resource ( <a href="http://www.steeluniversity.org">www.steeluniversity.org</a> ) was developed by the World Steel Association and MATTER, the University of Liverpool. Interactive modules give information about steel technologies, covering iron and steelmaking processes through to steel products, their applications and recycling.
Massachusetts Institute of Technology:	MIT OpenCourseWare offers lecture notes and other materials for many courses, including Fundamentals of Materials Science, Physical Metallurgy, Intro to Solid State Chemistry, and others ( <a href="http://ocw.mit.edu/courses/materials-science-and-engineering/">http://ocw.mit.edu/courses/materials-science-and-engineering/</a> ).
University of Virginia:	Class notes from a basic MSE class are available online and briefly cover the most important concepts and definitions ( <a href="http://www.virginia.edu/bohr/mse209/">http://www.virginia.edu/bohr/mse209/</a> ).
Key to Metals:	Although the complete database must be purchased, many basic metallurgical articles are available free online ( <a href="http://www.keytometals.com">www.keytometals.com</a> ).

## Appendix C: AHSS Resources

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WorldAutoSteel:	The WorldAutoSteel website ( <a href="http://www.worldautosteel.org">www.worldautosteel.org</a> ) includes several informative pages about conventional and AHSS types of steel, including “Steel Basics” and “Applications.” It also offers an image library with several helpful graphs and figures.
AHSS Application Guidelines:	These guidelines published by WorldAutoSteel, the automotive division of the World Steel Association, have technical descriptions of AHSS, forming, and joining ( <a href="http://www.worldautosteel.org/uploaded/AHSS%20Application%20Guidelines%204-1%20June%202009.pdf">http://www.worldautosteel.org/uploaded/AHSS%20Application%20Guidelines%204-1%20June%202009.pdf</a> ).
Association for Iron & Steel Technologies:	AIST seeks to advance the technical development, production, processing and application of iron and steel. Its main website ( <a href="http://www.aist.org/">http://www.aist.org/</a> ) has many resources, as well as a steel search engine ( <a href="http://steellinks.com">http://steellinks.com</a> ).
Society of Automotive Engineers:	SAE International has many publications specific to vehicle design available for purchase ( <a href="http://www.sae.org">http://www.sae.org</a> ).
FutureSteelVehicle:	Overview and complete Final Engineering Reports for the FSV are available online ( <a href="http://www.autosteel.org/Programs.aspx">www.autosteel.org/Programs.aspx</a> ). The final report includes a detailed description of the steel technologies and material portfolio used in the project. Reports from other vehicle studies, including UltraLight Steel Auto Body – Advanced Vehicle Concepts, are also available.
Great Designs in Steel:	Hosted annually in Livonia, Michigan, the Great Designs in Steel Seminar features presentations about cutting-edge steel technologies. Slides from 2011 are available for download ( <a href="http://www.autosteel.org/Resources.aspx">http://www.autosteel.org/Resources.aspx</a> ).
Steel companies:	<p>Most steel companies publish product information online. Some include fact sheets with more background information and figures about the steel. These are some examples:</p> <p>ThyssenKrupp Steel Europe has published product information for its automotive steels, including several AHSS, available as pdfs (<a href="http://www.thyssenkrupp-steel-europe.com/en/publikationen/produktinformationen/auto.jsp">http://www.thyssenkrupp-steel-europe.com/en/publikationen/produktinformationen/auto.jsp</a>).</p> <p>United States Steel Corporation also publishes helpful information about its automotive steel grades, both HSS and AHSS, on its website (<a href="http://www.uss.com/corp/auto/index.asp">http://www.uss.com/corp/auto/index.asp</a>).</p>
General Introduction to AHSS (Articles):	Keeler, S. (2009, Apr). “The Science of Forming: Defining Advanced High-Strength Steels.” <i>Metal Forming</i> , 32-33.

Shaw, J. R. and Zuidema, B. K. (2001). "New High Strength Steels Help Automakers Reach Future Goals for Safety, Affordability, Fuel Efficiency and Environmental Responsibility" *SAE Paper* 2001-01-3041.

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Kuvin, B. F. (2008, Feb). "Advanced High-Strength Steels: New Types on the Block" *Metal Forming*, 42 (2), 28-35.

Type or topic specific:

A search in any database for technical articles about specific topics of interest related to AHSS will yield no shortage of results.



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2000 Town Center, Suite 320  
Southfield, MI 48075  
248-945-4777  
[www.autosteel.org](http://www.autosteel.org)