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Advanced High-Strength Steel—Basics and Applications in the Automotive Industry

Xiaohua Hu
Zhili Feng

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OAK RIDGE NATIONAL LABORATORY
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ADVANCED HIGH-STRENGTH STEEL—BASICS AND APPLICATIONS IN THE AUTOMOTIVE INDUSTRY

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1. INTRODUCTION

Challenged to improve safety and fuel economy, automakers continually search for new materials to meet high standards. Several factors drive the material R&D and selection for automotive applications, including safety, fuel efficiency, environmentalism, manufacturability, durability, and quality. In the highly competitive automotive industry, cost is an extremely important factor in material selection. As the motivation to reduce the mass of vehicles continues to grow, automakers seek to maximize the efficiency of their materials selection. Materials in automotive applications are selected to minimize weight while meeting key criteria, including crash performance, stiffness, and forming requirements.

Since the 1920s, steel has been the material of choice for automakers worldwide. The weight percentage of steel used in vehicles relative to other materials has grown from around 50% in the early 1980s to about 60% in 2010 for North American light vehicles. Today, steel makes up around 65% of an average automobile's weight and is the backbone of the entire vehicle. On average, that is 900 kg of steel used per vehicle. To further enhance passenger safety, vehicle performance, and fuel efficiency, reducing the weight of vehicles has become one of the top priorities for the automotive industry. Advanced high-strength steels (AHSSs) are a new generation of steel grades that provide much higher strength and other advantageous properties than other materials while maintaining the high formability required for manufacturing. AHSSs help engineers meet requirements for safety, efficiency, emissions, manufacturability, durability, and quality at a low cost. The relevance of AHSSs is quickly increasing in the automotive industry, and AHSSs are the key material for vehicle mass reduction [1]. 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 (Figure 1).

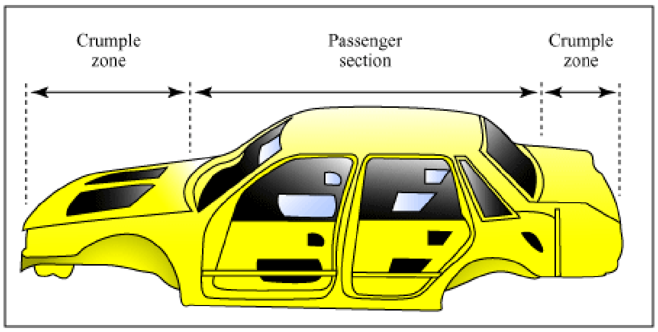


Figure 1. Crumple zone and passenger section of a car [2].

In the past two decades, the steel industry has developed different alloying and processing combinations to produce steel microstructures providing high strength for reduced steel section size and weight [3], and the pursuit of more AHSSs has continued [4-7]. The impressive combination of high strength and ductility of AHSSs is designed to help the automotive industry meet low weight requirements [8]. 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. AHSSs are not significantly less dense than traditional steels, but their strength allows automakers to manufacture very thin gauges, thus reducing the weight of the vehicles. Although steels are denser than Al alloys and Mg alloys, today's AHSSs have comparable specific rigidity (elastic modulus to density ratio) and specific strength (ultimate tensile strength [UTS] to density ratio) to those lightweight metals because of the much higher strength of AHSSs as shown in Table 1. Generally, the cost of AHSSs on a per pound or specific strength basis is much lower than the cost of Al alloy and Mg alloys.

Table 1. Comparison of specific rigidity and specific strength of AHSS to other lightweight metals.

Material	Density (g/cm^3)	Elastic modulus (GPa)	Specific rigidity ($GPa/g/cm^3$)	Tensile strength (MPa)	Specific strength ($MPa/g/cm^3$)
Al alloys					
Al5754-O	2.7	70	**26**	215	**80**
Al5754-H26	2.7	70	**26**	290	**107**
Al6061-T6	2.7	70	**26**	310	**115**
Al7075-T651	2.8	71	**25**	570	**204**
Mg alloy					
Mg AZ31-H24	1.75	45	**26**	290	**166**
Steels					
Mild steel	7.8	211	**27**	300	**38**
DP600	7.8	211	**27**	600	**77**
DP980	7.8	211	**27**	980	**126**
DP1180	7.8	211	**27**	1,180	**151**
Boron Press Hardened Steel	7.8	211	**27**	1,700	**218**
3rd gen	7.8	211	**27**	2,000	**256**

AHSSs include dual-phase (DP) and complex-phase structures, ferritic-bainitic, martensitic, transformation-induced plasticity (TRIP), 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 in which it might be best employed to meet performance demands of the part. Many groups research these new steels to better understand their properties and to continue tailoring unique sets of characteristics. Others focus on improving the technologies necessary for manufacturing parts made of AHSSs. The steel and automotive industries have forged numerous partnerships to develop the materials and technologies necessary to develop the next generation of safer and more environmentally friendly vehicles.

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, which have unique metallurgical properties and processing capabilities that enable the automotive industry to meet requirements at a low cost. Safety regulations have accelerated the incorporation of AHSSs into vehicles. The National Highway Traffic Safety Administration sets standards for vehicle safety, such as those for impact resistance, restraints, and fuel economy. Testing by the Insurance Institute for Highway Safety has also encouraged improved frontal, side, and rear impact ratings, as well as roof strength and rollover ratings, for automobiles. Meeting these standards often requires the addition of weight to the vehicle.

While adding massive safety components, automakers struggle to reduce weight and heighten efficiency to meet increasing corporate average fuel economy standards. Engineers analyze parts to identify opportunities to redesign geometries within constraints; to achieve these shapes and/or further weight reduction, new materials are sought. Considering AHSSs 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; however, additional environmental concerns extend across the entire life cycle of the vehicle, including its production and end-of-life recycling. Life cycle assessment for the greenhouse gas emissions of automobiles reveals that high-strength steel (HSS), when compared with other materials such as Al, can leave the smallest carbon footprint for the life cycle of a vehicle [9]. Additionally, steel is the most recycled material on earth [10] and can be used directly in new automotive or other products.

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 AHSSs with unique properties to meet the diverse performance requirements of vehicle components. As alternative materials, such as Al, plastics, and composites, are explored for automotive applications, AHSSs are being developed to remain fully competitive by striking a balance between strength for performance and ductility for production. AHSSs have been shown to be effective for simultaneous performance improvement and mass reduction without increased cost [11].

2. CLASSIFICATION OF STEELS

Approximately 30 steel grades are used today in the automotive industry and can be classified into three designations [1]: metallurgical, strength, and formability.

The metallurgical designation provides information about composition, processing, and microstructure of the steel. Steel for the automotive industry can be classified as traditional mild steel, conventional HSS, and AHSS.

The second important classification method for the automotive industry is the strength of steel. The terms "HSS" and "AHSS" are generally used to designate all high-strength steels. AHSSs are sometimes called "Extra-HSS" and "ultra-HSSs" for tensile strengths exceeding 780 MPa and 1,000 MPa, respectively. However, the terminology used to classify HSSs varies considerably throughout the world because of the constant development of new generations of AHSS.

The formability of steel is defined as its ability to be formed into simple and complex shapes by different manufacturing processes [3]. The important parameters that characterize the formability are high work-hardening exponent and total elongation. Although a high work-hardening exponent accounts for the ability of sheet metal to stretch and uniformly distribute strain in the presence of the applied load [12], the total elongation determines the extent to which a steel can be stretched before failure.

Banana charts of UTS and total elongations are often used as a guide of material selections of steels in terms of strength and formability (Figure 2). However, a recent study showed that materials of similar AHSS grades from different steel makers have very different hole expansion formability, although they have similar specifications [13]. Phase property disparity has been found to be a key factor [14, 15] that influences the true fracture strain and formability in cases in which no deformation instability or necking is present, such as hole expansion.

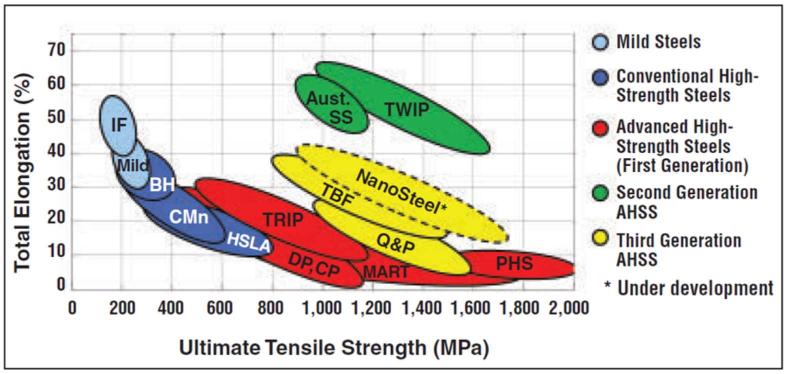


Figure 2. Banana chart of steels for automotive applications [16].

2.1 MILD STEELS

Mild or low-carbon steels are steels with a tensile strength of 400 MPa and carbon content of 0.05%–0.25%. The microstructure of mild steel causes it to be relatively ductile and easy to form, comprising one phase, which is normally ferrite [17]. Mild steels are commonly used in the body structure and trunk closures of vehicles as shown in Figure 3 [18].

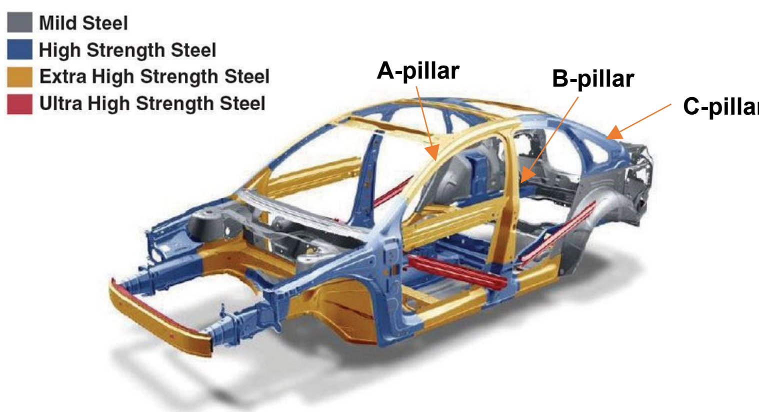


Figure 3. Steel distribution in a vehicle [18].

2.2 HSS

High-strength low-alloy steels were the first commonly used HSSs in the automotive industry [8]. These steels have high tensile strengths of up to 800 MPa. They are not made to meet a specific chemical composition but rather specific mechanical properties [17]. They have a low-alloying and carbon content to retain formability and weldability; copper, titanium, vanadium, and niobium are added for strengthening purposes [8]. HSS steels have been used in the parts of vehicles where energy absorption is important.

2.3 AHSS

The principal difference between conventional HSS and AHSS is in their microstructure. AHSSs are multiphase steels with complex microstructures that contain phases (Table 2) such as ferrite, martensite, bainite, and austenite [6]. With such an array of available AHSSs, differentiating among the many types and grades can be intimidating. A basic understanding of materials science/metallurgy clarifies the differences among AHSS grades, properties, and applications.

Table 2. Typical phase constituents of the selected AHSS (values in volume %).

AHSS classification	Steel designation	Austenite	Ferrite	Bainite	Martensite
1	Low-C TRIP	5–15	40–60	35–45	—
2	High-Mn steel	100	—	—	—
3	Quenching and partitioning steel	5–20	0–20	—	60–95
3	Medium-Mn steel	20–60	40–80	—	—

The structure of steel at an atomic and microscopic level explains its strength, spring-back, 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 4. 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, and heat treatability.

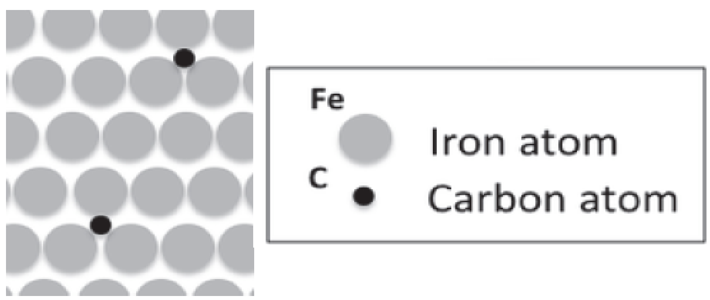


Figure 4. Carbon atoms take the interstitial position of the steel.

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 [19], in combination with a continuous cooling curve (a.k.a. a time-temperature-transformation [TTT] curve), illustrates the wide variety of structures that can result from small variations in carbon content and cooling processes.

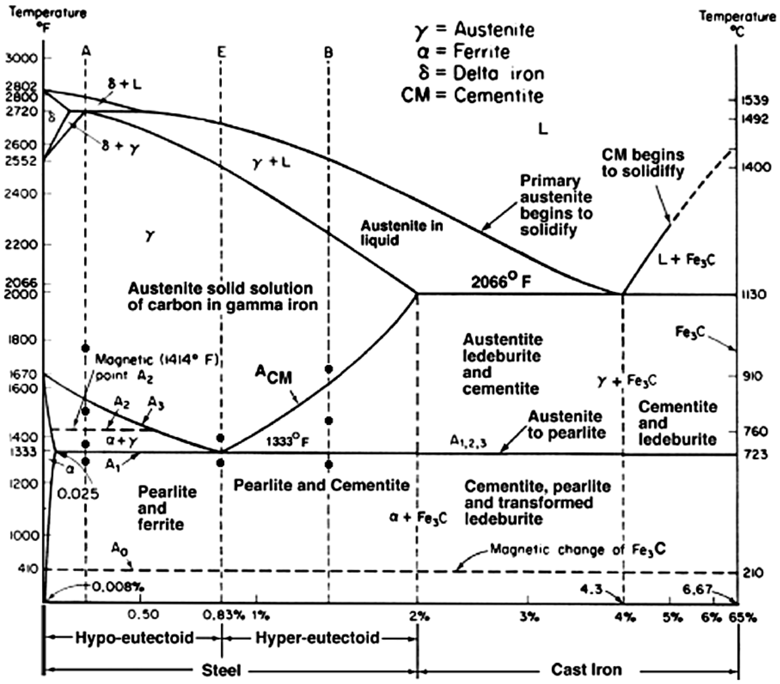


Figure 5. Iron–carbon phase diagram [20].

The final microstructure of steel can contain different phases (fractions with homogeneous characteristics), including austenite, martensite, ferrite, and bainite as shown in Figure 6. Several factors determine the grain size, shape, and distribution of these phases, which contribute to the strength, ductility, and other properties of the material.

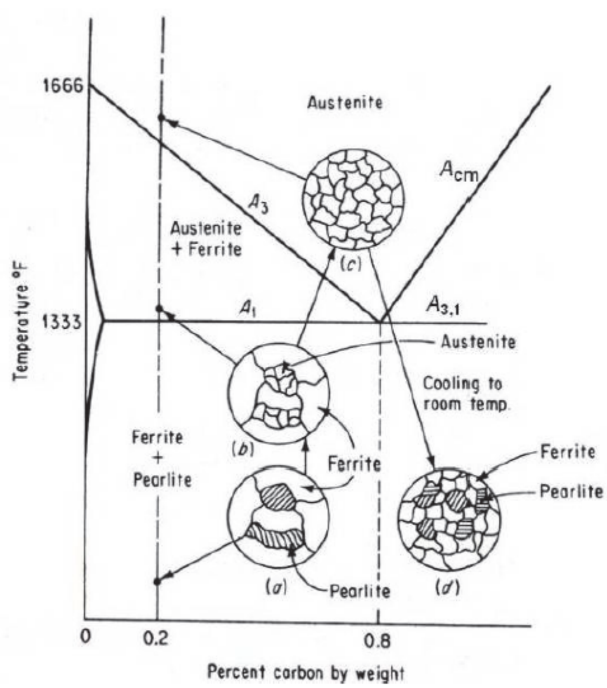


Figure 6. The phase constituents at different regions.

Engineering stress is force divided by area. Stress is often plotted against engineering strain, which is the percent change in a dimension of an object experiencing stress. The resulting stress-strain curve is helpful for understanding a variety of material and mechanical properties. The stress-strain curve for a ductile material is shown in Figure 7; some of the most important features and terms are 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 ($E = \sigma / \varepsilon$, while deformation is elastic). The elastic modulus, in combination with part geometry, determines the stiffness of a part.

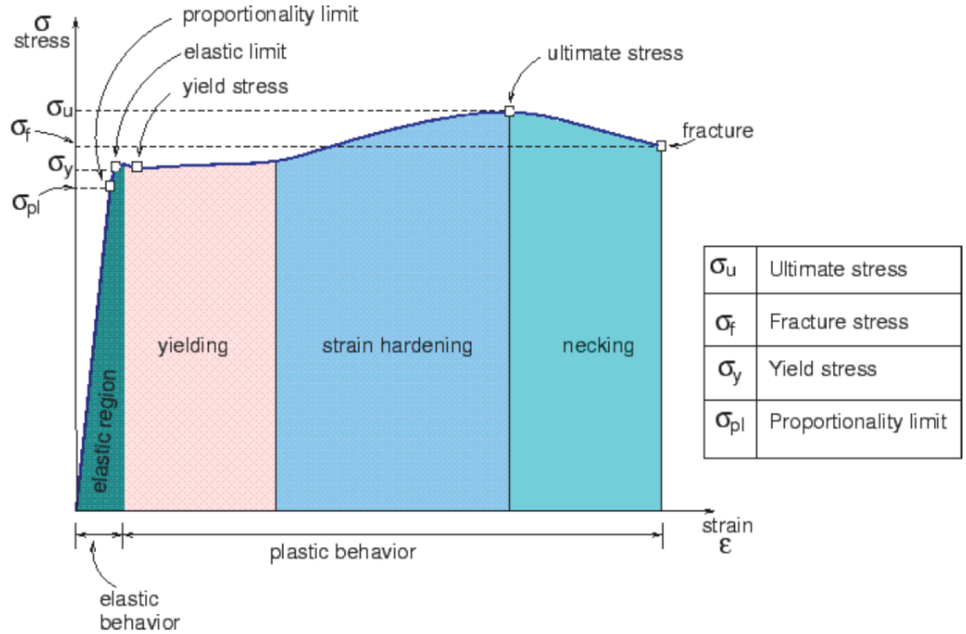


Figure 7. A typical engineering stress-strain curve.

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 [21]. The YS 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. If the load is removed in the plastic strain range, some elastic recovery, or spring-back, will occur, but some permanent deformation caused by the slip will remain. HSSs have greater spring-back than mild steels at, for example, the same total strain level as shown in Figure 8. Spring-back is the geometric change made to a part at the end of the forming process when the part has been released from the forces of the forming tool. Upon completion of sheet metal forming, deep-drawn and stretch-drawn parts spring back and thereby affect the dimensional accuracy of a finished part. The final form of a part is changed by spring-back, which makes producing the part difficult.

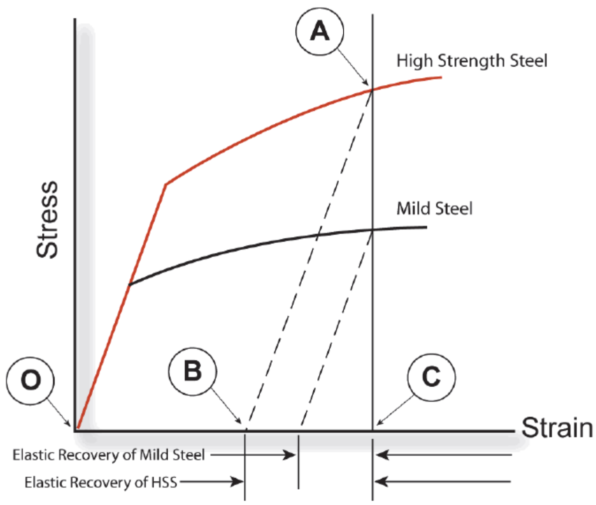


Figure 8. Plot showing the amount of elastic recovery of mild steel and HSS after unloading.

After a certain amount of stress is applied, the material will begin to neck and move toward fracture; this stress is the 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 relates to the amount of energy that can be absorbed before fracture.

Currently, with the evolutions of alloy and process design for better combinations of properties in strength and ductility with the cost of production in consideration, three generations of AHSSs have been developed.

2.3.1 First-Generation AHSS

The first generation of AHSS includes DP, complex-phase, martensitic and low-carbon, and low-alloy TRIP steels; chemical compositions are shown in Table 3. This first generation has more formability than high-strength low-alloy steel at the same strength level because of its multiphase microstructure, which contains ferritic and martensitic phases for a balance between formability and strength. The unique microstructure is created by special heat treatments [8].

Table 3. Alloying concepts of the selected AHSS (values in weight %).

AHSS classification	Steel designation	C	Si and/or Al	Mn
1	Low-C TRIP	0.10–0.30	1.0–2.0	1.0–2.0
2	High-Mn steel	0.10–0.60	0–3.0	>14.0
3	Quenching and partitioning steel	0.10–0.30	1.0–2.0	1.5–3.0
3	Medium-Mn steel	0.05–0.40	1.0–3.0	3.0–12.0

DP steels have a tensile strength from 590 to 1,400 MPa and are often used in the crash zones of vehicles. DP steels are the most used AHSSs today. They contain ferritic and martensitic phases for a balance between formability and strength. DP steels are used in applications such as crash boxes, front-end structures, A- and B-pillars, roof rails, and sill reinforcements.

Complex-phase steels have a microstructure consisting of bainite in addition to martensite and ferrite, which makes them more formable than DP steels. Their tensile strength ranges from 800 to 1,180 MPa, and they are generally used in car frames, and A- and B-pillar reinforcements.

TRIP steels have tensile strengths ranging from 590 to 1,180 MPa. The microstructure of these steels, along with ferrite and martensite, contains retained austenite, which transforms into strong martensite phases when the TRIP steel is deformed so that it can absorb a larger amount of energy. They are normally used for energy absorption in frontal- and rear-zone structures in vehicles, including cross-members and front and rear rails.

Martensitic steels are the hardest steel class in the AHSS family. Their strength ranges from 900 to 1,700 MPa. Because of the higher amount of hard and brittle martensite formation in the microstructure, they have the lowest formability. They are used in vehicle bodies where crash deformation must be limited.

2.3.2 Second-Generation AHSS

The second generation of AHSS includes the twinning-induced plasticity steels [1]. The first and second generations of AHSS were designed to meet the functional performance demands of certain parts in the automotive industry.

The first generation of AHSS has very limited formability as shown in Figure 2 (the red ellipses), and their elongation is relatively small. The formability of the second generation is significantly higher than the first because of the progressive formation of fine and hard deformation twins, which act as barriers of dislocation slips and continue to harden the materials. This progressive work hardening will delay the deformation instability and localized necking behavior, which is the limiting factor for the formability of sheet metals.

Although possessing good formability, the second-generation AHSS (e.g., the twinning-induced plasticity steel) contains a high percentage of alloy elements, especially Mn content (see Table 3). This makes the second-generation AHSS very expensive, which limits its usage in automotive applications. The current development of AHSS has focused on the third generation.

2.3.3 Third-Generation AHSS

Although the first generations AHSS are produced commercially and there is some limited usage of second generation, substantial effort is currently being directed toward the development of third-generation AHSS. These steels are intended to have improved strength-ductility ratios and are expected to reduce structural weight by more than 35% [2]. Promising third-generation AHSS candidates include the TRIP-assisted quenched and partitioned steel and medium Mn steel. The quenched and partitioned steel is produced with a quenching and partitioning heat treatment process [22] to increase carbon enrichment of stability of the retained austenite for both ductility and strength enhancements. First, the steel is heated above the full austenite-forming temperature to form a single austenite phase in the materials, and then it is quenched to a temperature below the martensitic transformation temperature to obtain martensite (the needle-shaped phase in Figure 9) with retained austenite with equal carbon content in both phases, after which the material is heated to about 300°C–500°C for about 1 min to obtain higher carbon content in the austenite to make it more stable during deformation.

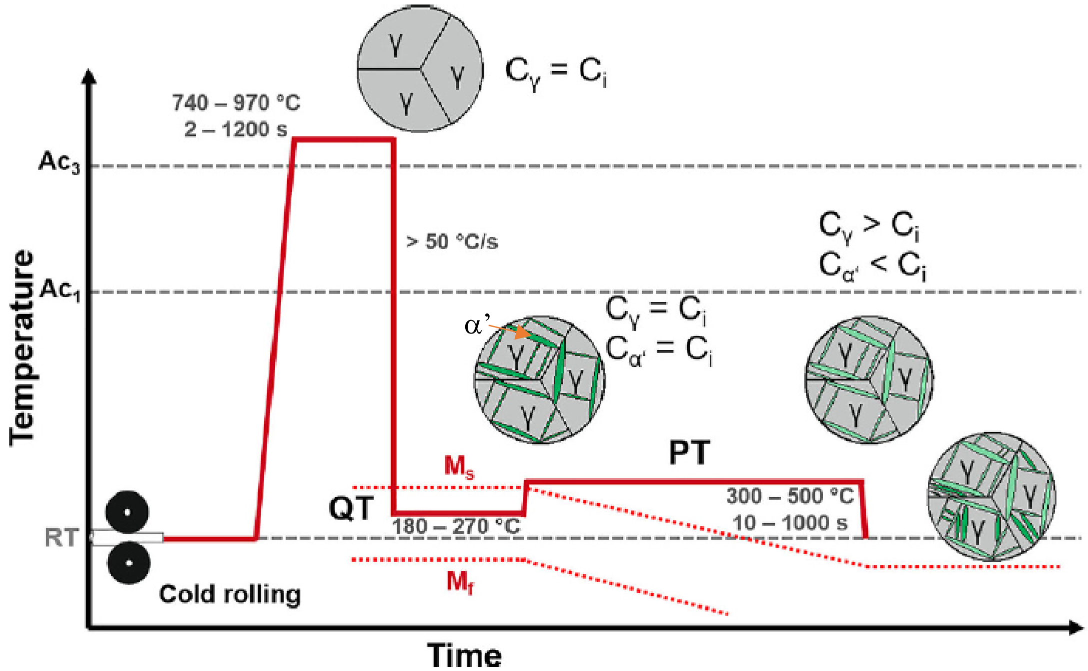


Figure 9. The quenching and partitioning process [23], where γ is the austenite phase and α' is the needle-shaped martensite phase. Ac_1 is the temperature above which the material enters the austenite and ferrite two-phase region, and Ac_3 is the full austenite forming temperature. RT is the room temperature. M_s is the temperature at which austenite will transform into martensite. C denotes the carbon content. Subscript i denotes the alloy carbon content.

The microstructure design concepts of third-generation AHSS aim to obtain a considerable amount of retained austenite (>20 vol %) in a martensitic/ferritic matrix. To achieve a sophisticated multiphase structure, complex thermal processing methods are employed. Quenching and partitioning is a novel process to produce martensitic steel with a certain amount of retained austenite by controlling carbon partitioning [22, 23]. Austenite-reverted transformation (or inter-critical annealing; Figure 10) brings new opportunities to produce an ultrafine-grained duplex ferrite-austenite microstructure in median Mn steel [23, 24]. In that case, the carbon and mainly Mn partitioning plays an essential role in stabilizing austenite [25].

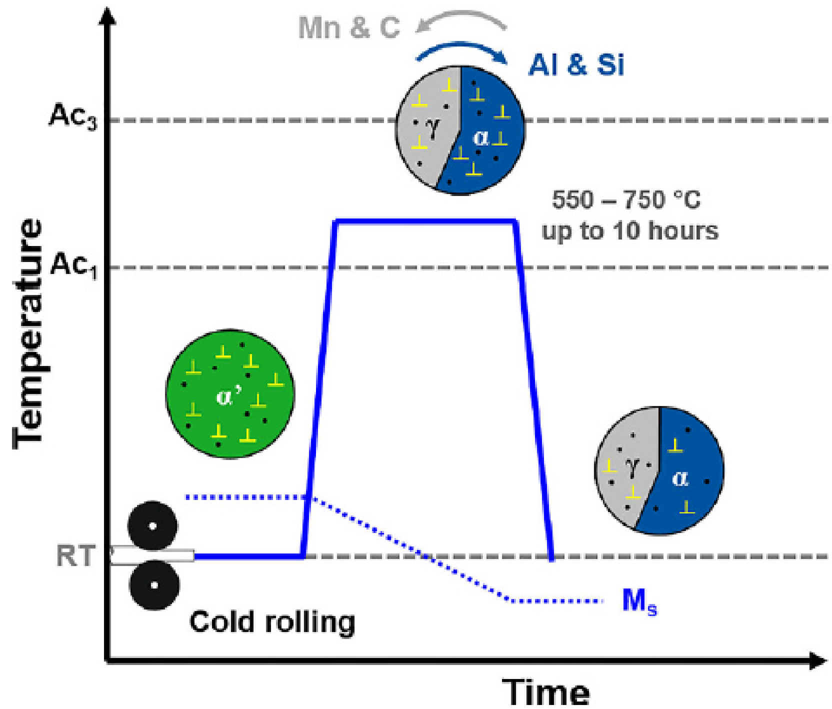


Figure 10. The austenite-reverted transformation process [23].

2.3.4 Significance of AHSS

AHSSs are used for nearly every new vehicle design. They are predicted to replace approximately 60% of the currently used conventional HSS [26].

Because AHSSs can be manufactured at very thin gauges and maintain the same strength as mild steels, designers can easily replace conventional steels with AHSS [8]. This is not the case when replacing steel with other lightweight materials, such as Al or fiber-reinforced composite materials. These nonferrous materials are expensive, incompatible with existing manufacturing processes, and have high production and manufacturing costs [26].

Cost-benefit analysis shows that steel parts are stronger and less expensive than other lightweight materials [26]. The most popular lightweight material in competition with steel is Al. Although Al use in the automotive industry has been increasing, body structures fabricated with Al cost 60% to 80% more than steel.

2.3.5 AHSS Market

2.3.5.1 Shift toward lightweight vehicles to accelerate demand for AHSS

The global AHSS market has gained significant momentum over the years because of the increasing demand for high-strength and efficient materials from automakers. Globally, the overall consumption of the AHSS market was near 14 million tonnes in 2019 and accounted for a ~1% share in the global steel sector [27].

In addition, increasing pressure from several government and regulatory authorities toward weight reduction of automotive components and control emissions has steered end-users toward manufacturers of

AHSS to get effective and lightweight materials. The global market for AHSS is anticipated to register a compound annual growth rate of 8.5% over 2020 to 2030 [27].

2.3.5.2 Automakers resort to third-generation AHSS for value-added product offerings

AHSS products have gained momentum because of their strength to elongation ratio characteristic-enhancing properties. This momentum is attributed to the high-level penetration of frontrunners (first- and second-generation manufacturers) in the global AHSS market. However, with the growing availability of potential alternatives and high cost, frontrunners in the market will emphasize different strategies to maintain their footprint. As a result, manufacturers have developed the third generation of AHSS. Moreover, only a handful of manufacturers have launched new and exclusive products in third generation AHSS. Other players are on the verge of developing proprietary versions in the mid-term forecast.

3. APPLICATION OF AHSS

Automakers recognized that an overall effective cost-weight strategy is "to put the right steel in the right place," as noted in a 1909 New York Times article about American auto steel [28]. At that time, 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 the 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, so did the demand for new materials, including new steels. By 1975, the average vehicle contained 3.6% medium-strength steels and HSSs for a total vehicle content of 61%, most of which was mild steel [29]. In the 1980s, the use of interstitial-free and galvanized steels grew for complex parts because styling, corrosion resistance, and cost were key considerations. Interstitial-free steel was initially developed as a highly formable material and was used extensively for deep drawn applications requiring high ductility and resistance to thinning. It also became the standard base for hot-dipped galvanized steels because the stabilizing alloy elements in interstitial-free steel prevent aging behavior. A third type of interstitial-free steel, with nitrogen or other elements reintroduced, could be used to meet higher dent resistance and strength requirements.

High-strength low-alloy 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 [29].

By 2007, the average vehicle contained 11.6% medium-strength steels and HSSs, for a total steel content of 57%. The simultaneous development of new processes and equipment to produce and form the material has been essential for the growing use of AHSS. Some of these processes are described in section 3.2 DP and TRIP steels are excellent in the crash zones of the car for their high energy absorption. For structural elements of the passenger compartment, extremely HSSs, such as martensitic and boron-based hot-formed, increase safety, strength, and rigidity.

The use of AHSSs in cars is quickly expanding with more research. The World AutoSteel's Future Steel Vehicle program examined the not-so-distant future of the enhanced use of AHSSs in vehicles. The program was completed in 2011, which is followed by the Ultra Light Steel Auto Body (ULSAB) program, and other programs [11]. The work demonstrated 35% mass reduction from a benchmark vehicle using 97% HSS and AHSS [11]. The Future Steel Vehicle meets or exceeds all current safety and structural requirements, and analysis showed that when combined with an electrified power train, lightweighting the Future Steel Vehicle with AHSS enables the reduction of total life cycle emissions by at least 56%.

Important considerations during the materials selection process include YS, 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 versatile because these properties can vary tremendously; YS, for example, in mild steel could be 130 MPa and in martensitic steel could be 1,500 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.

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 the following:

- 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 (e.g., rolling, drawing, bending), dislocations in steel become more entangled, preventing their relative movement. Work hardening typically increases YS, UTS, and hardness, but it 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, tempered martensite islands, or discreet 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 ways to increase strength.

- Transformation strengthening: In the production processing of steel, phase transformations can often occur that enable strengthening by creating microstructures with significant amounts of hard phases such as martensite or bainite. Such transformations occur in operations such as hot rolling, hot-dip galvanizing, or continuous annealing in which steel can cool from high-temperature austenite and transform to these harder low-temperature phases. This mechanism is fundamental to the development of AHSSs and enables DP, TRIP, and other AHSSs to be manufactured.

Because AHSSs 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 R&D in the area of processing steel. In some cases, traditional process methods are just as effective with AHSSs as with mild steels; in others, some modifications to equipment or methods are necessary; and in others, new processing technologies have enabled the development of new steel grades.

Transformation strengthening is the principal strengthening mechanism employed in manufacturing AHSSs 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 ranges to develop the desired microstructures as illustrated by the TTT diagram in Figure 11. Producers are increasingly automating controls, and various sensors monitor temperature and other conditions during the process. Because AHSSs may require more process control than found in 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.

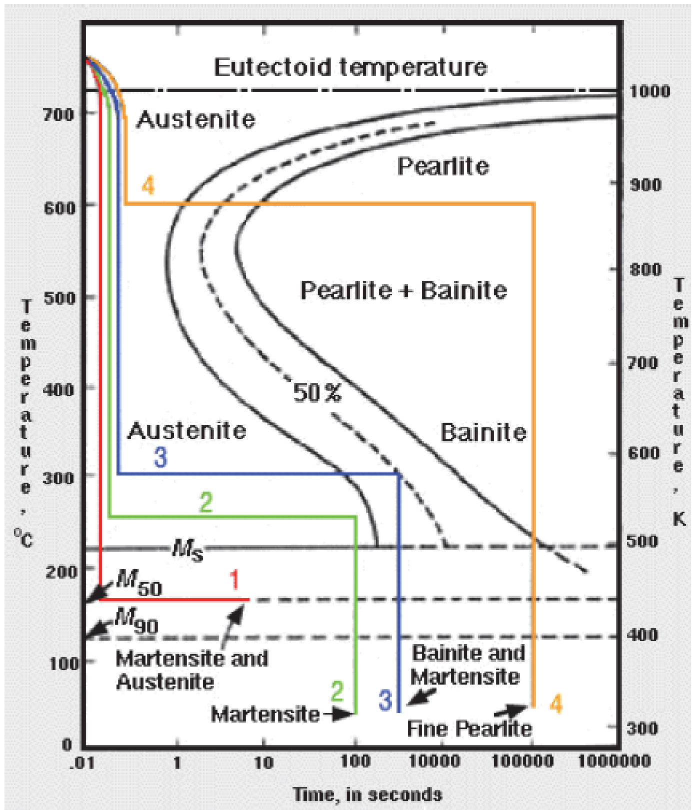


Figure 11. The TTT curve of steels.

Automotive steel is typically produced as large coils, which may be processed into blanks or tubular products. The final engineering report for the Future Steel Vehicle describes a comprehensive list 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 roll formed, tailor rolled blank roll formed, roll form with quench, multi-walled hydroformed tubes, multi-walled tubes, laser welded finalized tubes laser, and welded tube profiled sections [11].

Manufacturing processes continue to stand out as a vital factor in the development of new materials. Much of the current research focuses on identifying new processes and technologies to improve the consistency, reduce cycle time and cost, and enable the production of parts using AHSSs. 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 enough hardenability so that, on quenching hot-stamped parts in water-cooled dies, austenite to martensite transformation can occur. Some of the current areas of research are described later in section 3.2.

Several key considerations affect 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.

3.1 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. 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.

3.1.1 Crash Performance

Two generalized areas of the car have very different safety requirements as shown in Figure 1. The passenger compartment, enclosed in a rigid "safety cage," is designed to protect the passengers in the event of a 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 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.

3.1.1.1 Crumple zone

Performance requirements: High energy absorption over a distance in crash event

Material properties to meet needs: High work hardening, strength, and ductility. Evidence of this property: Large area under the stress-strain curve

Potential steel selection: DP, complex-phase, TRIP

3.1.1.2 Passenger compartment

Performance requirements: No deformation/intrusion during crash event

Material property to meet needs: High YS

Evidence of this property: Highest UTS of σ-Є curves

Potential steel selection: Martensitic, hot-formed, DP (>980 MPa) steel. The components are designed so that they form a structure that meets all requirements, particularly all crash cases, enforced by the National Highway Traffic Safety Administration and set internally by car companies.

3.1.2 Stiffness

Stiffness is a function of part geometry and elastic modulus (not YS or UTS) and relates to handling, safety, 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 of its high work hardening rates increase formability, allowing for improved shapes for optimal efficiency [12].

Additionally, AHSSs typically possess high bake-hardening ability, which can improve the final strength of a component after forming and paint-baking.

3.2 FORMING AND MANUFACTURABILITY

AHSSs were developed partly to address decreased formability with increased strength of the conventional steels. As steels became increasingly stronger, they also became increasingly difficult to form into automotive parts. AHSSs, although much stronger than conventional low-strength steels to HSSs, also offer high work hardening and bake hardening capabilities that allow increased formability and opportunities for optimization of part geometries. 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.

3.3 JOINING/WELDING

3.3.1 Joining Similar Materials

Although AHSSs have a combination of superior mechanical properties, their application in terms of forming and welding requires a different approach than the one used for low-carbon steels. A variety of welding processes are used in a high-volume autobody assembly line to join a wide variety of steels, including AHSS. They include electric resistance spot welding (RSW), gas metal arc welding (GMAW) and brazing, laser welding, and adhesive bonding. For AHSSs, RSW can be combined with adhesive bonding— so-called "weld bonding"—to improve the strength and durability of the auto body structures. RSW, laser welding, and GMAW are categorized as fusion welding because the welding heat melts parts of the steels to fuse them together to form a weld.

RSW is by far the most common welding process used—there are approximately 4,000 to 5,000 resistance spot welds in today's passenger cars [30]. RSW is very fast, typically taking about 1 to 2 s to make a spot weld. This results in extremely high heating and cooling rates around 10^3 C/s, arguably higher than the heating and cooling rates of laser welding. GMAW has the slowest heating and cooling rate, typically in the range of 10^2 C/s.

During welding, the heat produced alters the microstructure of the base material and therefore the mechanical properties. The extent of microstructure and mechanical property changes primarily depends on the steel chemistry, the base metal microstructure, and the peak temperature and heating/cooling rate of a given welding process and associated welding parameters. The changes in microstructure and properties of an AHSS weld are rather complex and highly heterogenous in nature. Figure 12Figure **13** shows examples of microhardness distributions in a GMAW weld of boron steel. There are three distinctive regions in an AHSS weld—(1) the fusion zone, where the peak temperature is above the melting point of steel; and (2) the heat-affected zone (HAZ), where the peak temperature is below the melting temperature but above a critical temperature, below which the welding heat does not significantly alter the microstructure and thereby the properties of base metal AHSS, which is (3) the base metal zone. The HAZ of AHSS welds is typically much larger than the mild steels. The HAZ of AHSS welds includes the region below the A_1 temperature in the Fe-C phase diagram (see Figure 12) where the hardened phases in the original base metal microstructure such as martensite and bainite are tempered or softened by the welding heat.

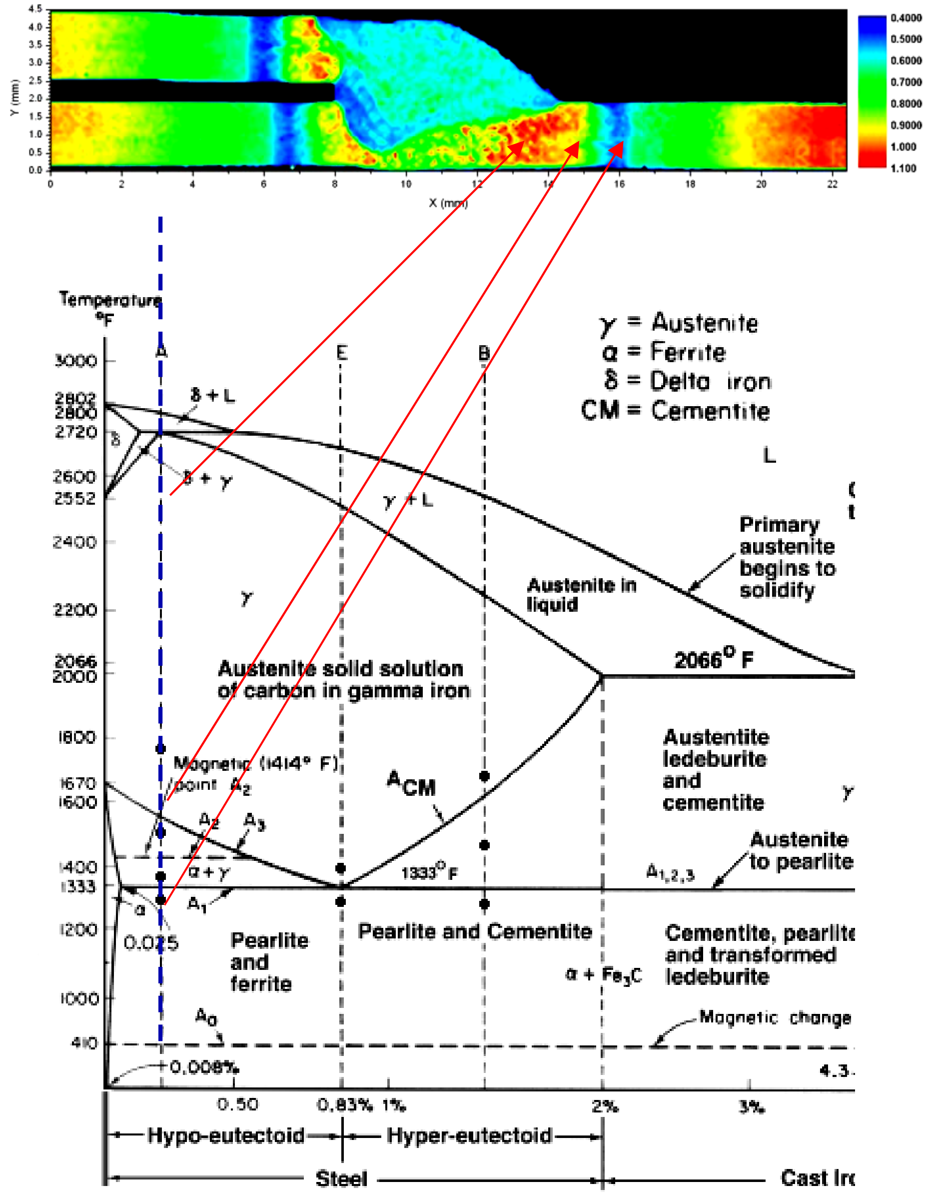
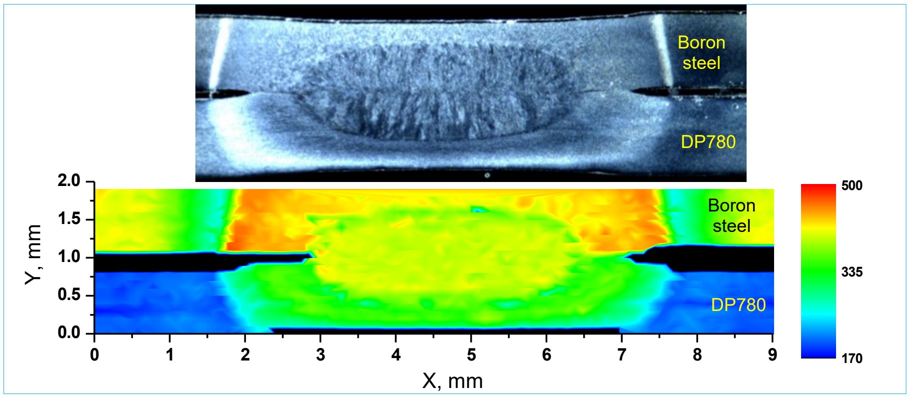
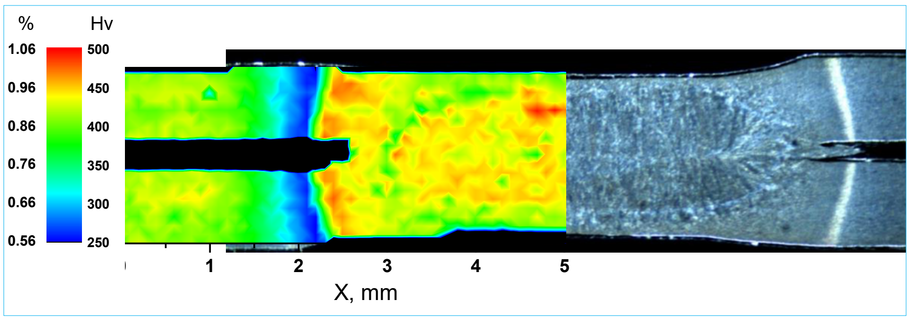


Figure 12. Different regions in an AHSS weld as determined by their peak temperature relevant to the Fe-C phase diagram.

Similar microstructure, hardness, and strength variations also exist in RSW weld of AHSS. They are illustrated in Figure 13. The figure includes a RSW weld between a DP780 steel (780 MPa nominal tensile strength) and a strength boron press–hardened steel (1,300 MPa nominal tensile strength).



(a)



(b)

Figure 13**. Vickers (Hv) microhardness distributions of RSW.** (a)**: DP780 to boron steel. (b): boron to boron steel. % = normalized hardness with respect to base metal hardness.**

For nearly all HSSs such as AHSSs, the welding heat resulted in a sub-region in the HAZ in which the hardness is lower than the base metal steel, which is the HAZ softening effect. The degree of softening and the size of the softened region are largely proportional to the strength of the AHSS. AHSSs with tensile strength below 700 MPa exhibit minimal HAZ softening. On the other hand, boron press–hardened steel, with its fully hardened martensite microstructure, has the highest degree of HAZ softening, up to 40%–50% reduction in hardness, as shown in Figure 12 to Figure 14Figure 14.

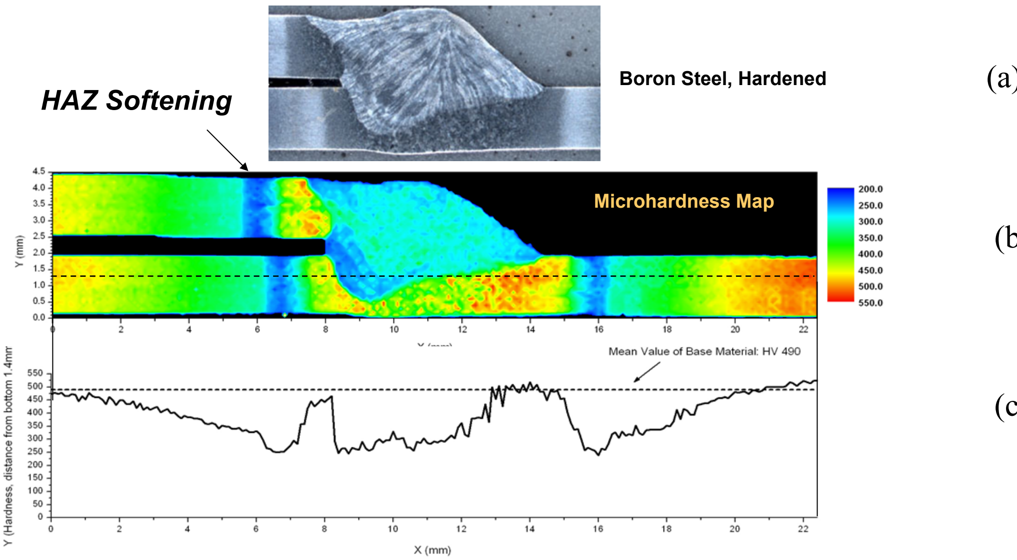


Figure 14. (a) Cross-sectional view of a GMAW boron steel weld, (b) Vickers (Hv) microhardness map of the weld, and (c) distribution of microhardness along the horizontal line in (b).

Because hardness is a measure of material strength, HAZ softening would negatively influence both static and impact strength of AHSS welds. This is shown in Figure 15. Such a negative influence can be characterized by the joint efficiency, which is the ratio of weld strength to its base metal strength. Figure 16 summarizes the GMAW joint efficiency of different types and grades of AHSS from a comprehensive study of AHSS weldability sponsored by the US Department of Energy's Vehicle Technologies Office at Oak Ridge National Laboratory. A similar relationship also exists for RSW of AHSSs. Generally speaking, the HAZ softening effect on weld strength is negligible for AHSSs with strength below 700 MPa but becomes significant for highest-strength AHSSs such as boron press–hardened steels.

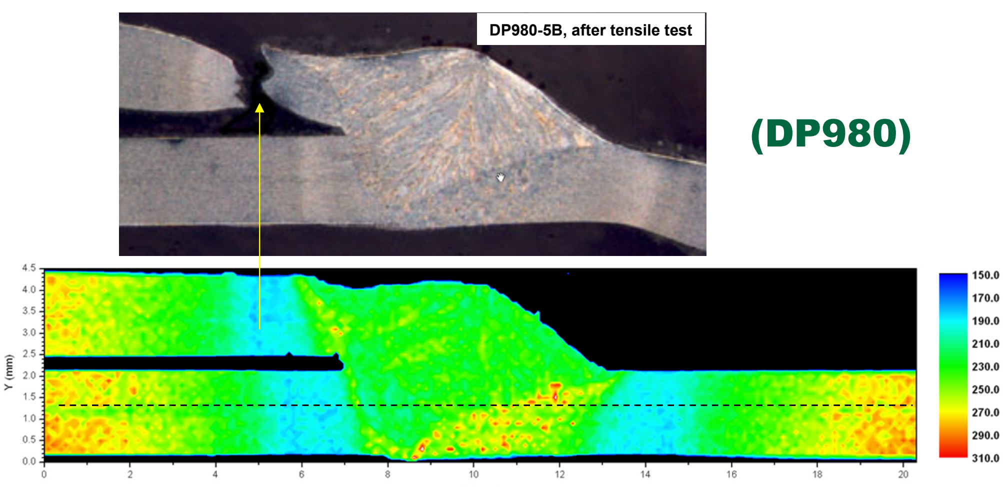


Figure 15. HAZ softening in a DP980 GMAW weld. The weld failed at the lowest hardness region of the HAZ during a lap-shear test.

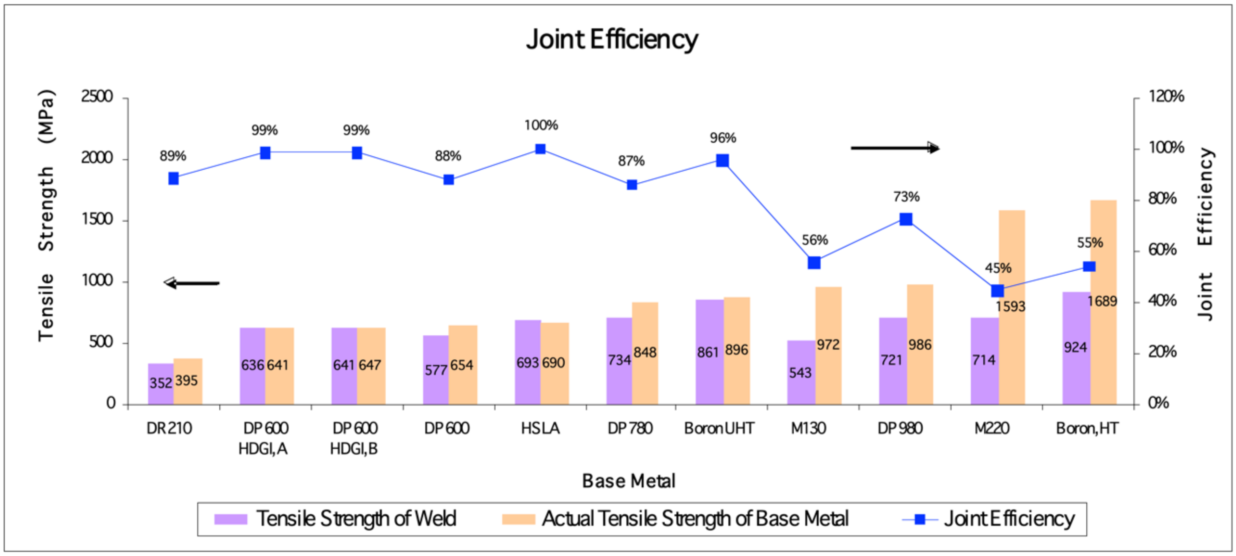
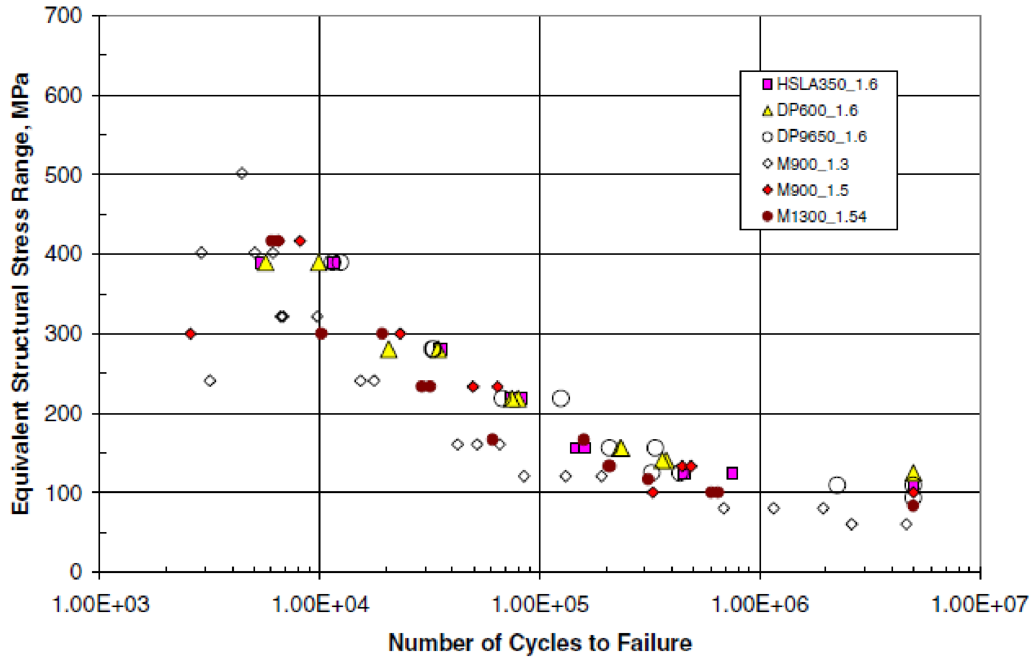


Figure 16. Static tensile strength and joint efficiency of various AHSS GMAW welds.

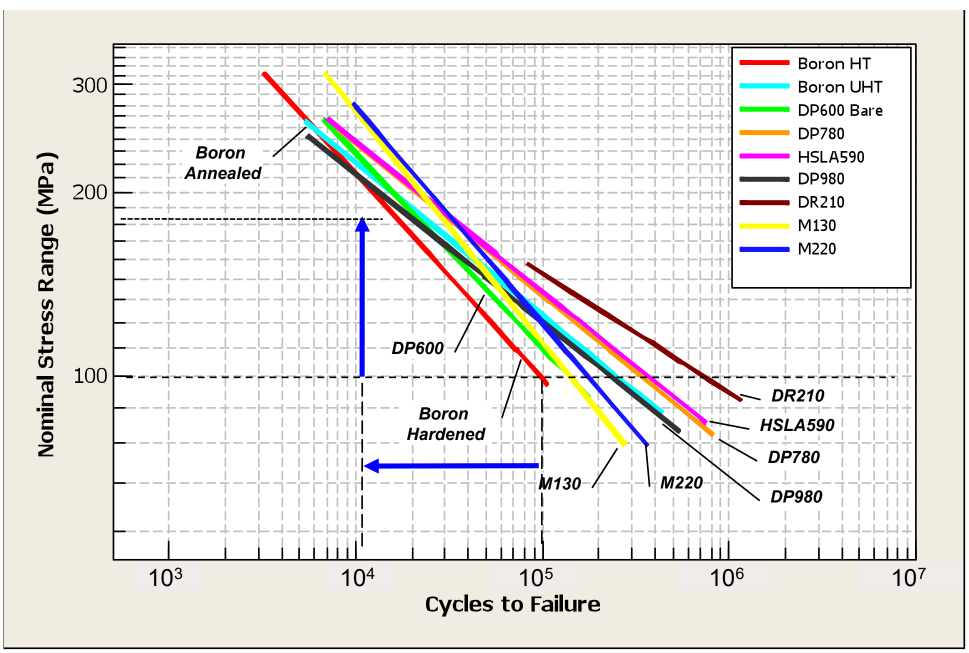
Durability is one of the primary metrics in designing and engineering automotive body structures. Fatigue performance of welded joints is critical to the durability of body structure because the most likely fatigue failure locations are often at welds. Even in the most meticulous fatigue design, a weld may have to be placed in a high-stress region, and any possible resulting fatigue crack that might result will likely preferentially initiate at the weld stress riser [1]. Because of the underlying metallurgical principle of HAZ softening—it is primarily associated with the phase transformation in the intercritical region and tempering of the base metal martensite—a key feature of HAZ softening of AHSSs is that the softest region is away from fusion boundary of the weld as shown in Figure 15. Therefore, HAZ softening should have rather limited influence on the durability or fatigue performance of AHSS weld.

On other hand, studies by the A/SP Sheet Metal Fatigue Committee, US Department of Energy's Lightweighting Materials Program, and others [31-35] have clearly revealed that, unlike the base metal fatigue strength, the weld fatigue strength of AHSSs is largely insensitive to the base metal composition, microstructure, and strength under typical welding conditions used in the "body in white"[1] . (Figure 17). The lack of inherent weld fatigue strength advantage of AHSSs over conventional steels should be recognized in vehicle weight reduction through down-gauging, which leads to increases in stresses and reduced durability under the same dynamic road loading conditions. Figure 17 shows the fatigue stresses-cycles to failure curve (also called S-N curves) for various GMAW AHSS steels reported by Yan et al. [34] and Feng et al. [31]. This figure demonstrate that the fatigue resistance does not increase with increasing strength of the base material due to the HAZ softening effects. In addition to AHSSs, other lightweight alloys such as Al and Mg alloys may not offer improved weld fatigue strengths on the "specific weight" basis [36]. Therefore, solutions to improve the fatigue strength of welds is critical to the "body in white" light-weighting.

[1] "body in white" is a common automotive term meaning the phase of manufacturing where the car body sheet metal components have been joined together as by welding, adhesives, etc.



(a)



(b)

Figure 17. Stresses-Cycles to failures (S-N) curves of GMAW lap weld joints of various AHSSs (a) from Yan et al. [34]; (b): from Feng et al. [31].

DP steels are easily weldable through RSW and have been commercially implemented in current automotive designs [37]. The typical requirement for spot welds is to have a minimum load-bearing capacity equivalent to or greater than that of the base metal. The load capacity formula includes the thickness of the sheet, the weld nugget diameter, and the UTS of the steel [37, 38]. The nugget diameter depends on the welding parameters and is critical for AHSSs because it largely controls the type of weld failure under quasi-static and dynamic loading conditions.

GMAW is mostly applied in chassis parts, where securing the strength and rigidity of the joint is important. The process also has the freedom to join parts of various shapes to structural members such as pipes and brackets. Long fatigue life of the weld joint is a prerequisite. Weld spatter, fit-up, and gap issues need to be addressed in parts formed during welding. Certain component designs preclude the use of resistance spot welds. Furthermore, some closed parts cannot be reached with RSW guns. For such applications, GMAW is preferred.

In the past two decades, laser welding has become popular because lasers have high power density (108 W/cm^2) and hence can weld steels at high speeds to meet stringent productivity targets. It provides a narrow HAZ compared with that of conventional arc welding processes. This feature is attractive for for AHSSs. Carbon dioxide lasers are the most common lasers used for sheet metal fabrication, particularly for manufacturing tailor-welded blanks involving combinations of AHSS and low-carbon formable steel. However, high-power fiber and disc lasers are being extensively used to weld AHSSs by several automotive manufacturers.

Adhesives serve the purpose of enhancing the stiffness of a member by providing a continuous joint. Because of concerns regarding the durability of adhesive joints under different environmental conditions, weld bonding is preferred by several manufacturers. This process involves a combination of spot welding and adhesive joining, wherein the benefits of durability provided by spot welding and stiffness provided by adhesives are leveraged.

The impact of the warm joining techniques described above, including RSW and GMAW, on material properties illustrates the interest in cold joining methods that do not lead to decreased strength or energy absorption. Therefore, adhesive bonding is especially appealing for joints of structural parts that are subjected to crash loads. The development of advanced toughened adhesives that achieve high strength as well as high fracture toughness and energy absorption has further increased the attractiveness of adhesive bonding as a joining method for automotive parts in recent years. Another advantage of adhesive bonding is its ability to address problems that often occur when different materials such as Al, Mg, or carbon fiber–reinforced plastic are joined. These problems include differences in the thermal expansion coefficient or the risk of galvanic corrosion. Furthermore, bonded overlap joints allow the transmission of a laminar force, which leads to the reduction or elimination of local stress peaks caused by spot welds or flow drill screws. Nevertheless, adhesive bonding also provides some technological challenges, and there are also disadvantages regarding the achievable joint strength, the dependence of adhesive properties on temperature, and the stability of the joints under aging conditions. Another point that is especially relevant for AHSSs is the influence of surface layers such as zinc coatings or cinder on the strength of the whole part. However, most of these challenges can be addressed by choosing the right joint geometries, adhesives, and surface pretreatment methods.

3.3.2 Joining AHSS with Other Materials

Dissimilar materials joining can be described as combining materials or material combinations that are often more difficult to join than two pieces of the same material or alloys with minor differences in composition; however, many dissimilar materials can be joined successfully with the appropriate joining process and specialized procedures. Because of large differences in thermal and physical properties (e.g., coefficients of thermal expansion), it is often challenging to join dissimilar materials by using the traditional fusion based joining between AHSS with other materials. Several solid-state joining techniques are receiving intensive attentions, including ultrasonic spot welding, impact welding, friction stir (Scribe) welding, mechanical fastening, self-pierce riveting, and adhesive bonding.

4. AHSS FOR OTHER INDUSTRIES

Weight reduction in agricultural equipment is an increasingly necessary application of AHSSs. Heavy agricultural vehicle traffic compacts the soil and thus reduces the land's long-term ability to produce food, adversely affecting key soil functions, including water flow and aeration, nutrient cycling, and habitats for soil organisms. Wheel loads in combines increased by 65% between 1989 and 2009 [39]. Steel manufacturer SSAB reported that larger, more expensive tires alone cannot solve this problem, and SSAB estimated that special steels can help to make machinery up to 30%–50% lighter without sacrificing durability [40].

Currently, AHSSs are also extensively used in the construction of modern buildings and infrastructure. AHSSs have various advantages over conventional steel and are thus used for building lean structures. Steel plates made of AHSSs are thinner than conventional steels, which helps in constructing slender and lightweight steel frameworks for buildings. This also helps to increase the usable floor area of the structures. Therefore, such advantages of AHSSs are expected to drive market growth.

5. FUTURE GENERATIONS OF AHSS

Beyond the third-generation AHSS (Section 2.3.3), early R&D is underway toward the ultra-strong steels with targeted tensile strength greater than 2 GPa (2,000 MPa). Four approaches have shown promising results [4-7]. For example, the approach of minimal lattice misfit and high-density nanoprecipitation has led to YS of 1,950 MPa, and UTS of 2,200 MPa, with a total elongation of 8.2% [6]. High dislocation density–induced large ductility in deformed and partitioned steels had UTS in the range of 2,000 to 2,200 MPa, and uniform elongation of 15%–20% [4]. More recently, improved fracture resistance in a steel with a YS of nearly 2,000 MPa was achieved by activating elimination toughening couples with transformation induced plasticity. The high strength induced multi-delamination strategy offers a different pathway to develop engineering materials with ultrahigh strength and superior toughness[5]. Finally, a low-density ultra-strong steel, with the addition of Mn and Al to reduce the density, using FeAl-type intermetallic compound (B2) can be effectively used as a strengthening second phase in high-Al low-density steel while alleviating its harmful effect on ductility by controlling its morphology and dispersion [7].

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