

Advanced steels for lightweight automotive structures

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Abstract: High strength steels are commonly used in the automotive industry to reduce mass and improve structural performance. This chapter discusses the history of steel in the manufacture of automobiles, the types of steels currently being used and the new advances in the types of steels that can be used for lightweighting automotive structures. The chapter also reviews the manufacturing and forming aspects of these steels along with some design considerations for the selection of these materials.

Key words: steel, advanced high strength steel, dual phase, trip, complex phase, martensite, boron steel, press hardening, spot welding, adhesive bonding, spot welding, welding, MIG welding, vehicle design.

2.1 History of steel in automobiles

The use of steels in the manufacture of automobiles has a rich and varied history. By most accounts, the era of the automobile is considered to have started in the late 19th century. It was in 1885 that the German engineer Karl Benz built what is generally considered to be the first automobile powered by an internal combustion engine. By today's standards, these first internally combustion driven automobiles were little different from the horse-drawn carriages common in the 18th and early 19th centuries. Both were largely constructed from wooden frames and body panels and even used wooden wheels.

Sometime in the late 19th and early 20th centuries, after the advent of sheet metals and the manufacturing processes to form them into complex shapes, the largely wooden structures of early automobiles were gradually being replaced by sheet metals. It was sometime in the early 1900s, that bodies manufactured from a combination of metal sheets of steel and aluminum, although still built largely on wooden frames, were being driven around the streets of North America. With the introduction of the Model T Ford in 1908, the era of mass produced, largely steel automotive bodies was up and running, and the automobile was well on its way to becoming what many consider to be the invention that most significantly impacted the lives of common working people and, just as importantly, led to the development of today's mobile and modern society.

The use of steel virtually dominated automotive body design for the next 100 years. The primary grades used in these first automobiles were mild

steels, or as they are more accurately referred to, low carbon steels. For the existing demands of the time, these steels provided the nearly perfect balance of strength, formability, cost and design flexibility that the industry needed to expand throughout the developed regions of the world. It was not until the first oil shock in the early 1970s and the adoption of fuel economy standards in North America that the industry began to seriously look towards higher strength steels to lower the mass of their vehicles and to improve fuel economy. Since that time, the structural designs used for automobiles and the grades of steel used to manufacture them have been in a constant state of evolution in response to not only consumer demands, but also to the complex array of regulations for fuel economy, emissions and crashworthiness that the modern automotive industry must now account for in the designs of their products.

It was common in the early development of the automobile, and even through the late 1930s and early 1940s, that most vehicles were built on frames that carried the body and skin panels – hence it was commonly referred to as body on frame construction or BOF. This type of construction not only allowed automotive designers to easily change the visual styling of the body to meet the ever changing demands of consumers, but also provided an easy and cost effective way to maintain styling differentiation between manufacturers. However, as vehicles became smaller during the 1960s, and especially after the oil shock in the early 1970s, a new type of body construction became popular. This new design, called body frame integral (BFI), gained favor and started a steady transition to this construction philosophy. Largely unknown to the industry at the time, the increase use of this integrated vehicle structural design would eventually become a key enabler for the future widespread use of high strength steels

In contrast to the BOF designs, this new design was considered to be more mass and fuel efficient, since the body and frame are designed as one system. This is in contrast to the BOF design where the body and frame are independent from each other, resulting in part function redundancy and increased mass. With the increasing focus on mass and fuel economy in the 1970s and 1980s, the more efficient BFI structural designs became more popular and eventually began to dominate automotive designs for passenger cars. In contrast, light trucks and heavy duty vehicles, where high load capacity and durability were considered more important than fuel economy, largely kept the BOF design that was considered superior for the needs of those vehicles.

With the automotive industry's large scale conversion to BFI designs that did not require heavy frames, the stage was set for an increased use of high strength steels. The increased number of stampings used in this design, and the ability to tailor the strength and shape of these panels, gave designers and manufacturing engineers new freedom to adapt part shape and forming

technologies to the characteristics of high strength steels. As a result, a new age in automotive steel development would be ushered in to improve product safety and meet the increasing demands of government regulators and consumers for safer, more fuel efficient vehicles: the face of automotive design and engineering would be changed forever.

However, unknown to the automotive industry at the time, the road they were about to embark on was steep and full of potholes. Not surprisingly, the industry's initial attempts at using high strength steels, which largely consisted of high strength low alloy and solid solution strengthened steels, were largely unsuccessful. The relatively low ductility of these steels compared with the low carbon steels in general use at the time presented many challenges that designers and manufacturing engineers were unprepared to handle. The part designs and manufacturing processes used on these initial applications were the same, or at best little changed, from those used with low carbon steels and did not suit the specific needs of high strength steels. Compounding matters, steel companies had not yet perfected their processes to make high strength steels consistently, and the resulting variability in mechanical properties essentially sealed the fate of these first attempts to use them.

Initial attempts to form high strength steels routinely resulted in severe forming cracks and springback that could not be effectively resolved with techniques that were available at the time. The lessons learned during these early experiences were both difficult and costly. Unfortunately, the lessons did not come fast enough to prevent the industry from returning to the low carbon steels that they understood much better and that had contributed to the early successes of the industry. These first attempts at using high strength steels were, by nearly all accounts, a virtual disaster. Even so, the benefits of these steels were recognized across the industry and manufacturers continued to use them in a select number of the most critical structural parts in the automobile. This foresight and perseverance would end up teaching the entire industry valuable lessons that would be used in later years to effectively incorporate these steels into future vehicle designs.

2.2 Types of high strength steels

There are many types of steels used by today's automotive designer to reduce mass and improve energy absorption in crash events. These steels can easily be divided into three general categories that roughly separate materials by their microstructures. The first category consists of both low carbon and conventional types of high strength steels (HSS) that have been the backbone of automotive design for a number of decades. The second category is generally referred to as the first generation of advanced high strength steels (AHSS) and the third category consists of the second generation of AHSS. Each of these categories has a number of different materials that, while different

from each other, share some unique physical and metallurgical properties that distinguish them from materials in the other categories. These categories and the materials included in them are shown in Table 2.1.

Low carbon steels with carbon levels of 0.13% or less have been the most commonly used steels in automotive body panels and structural components for many years. The combination of low cost, excellent formability, weldability, high quality appearance after painting and overall ease of manufacturing has contributed to their widespread use. There are many grades of low carbon steel used in the automotive industry, but the most common types are hot rolled and cold rolled grades with much lower carbon contents than the maximum generally allowed by industry specifications. The lower carbon content grades such as SAE 1005 and the highly formable, ultra-low carbon interstitial free (IF) steels, are still very commonly used on most of today's vehicles. However, the amount of these steels used in structural components has been steadily declining in the last ten years as more high strength steels are designed into critical stampings to reduce weight and improve strength and overall vehicle performance.

2.2.1 Interstitial free and bake hardenable steels

With the advent and proliferation of continuous casting technologies, homogeneous alloys of very formable steels are now commonly available to the industry. In particular, interstitial free (IF) steels have had a major impact on how steels are stamped and the use of the complex features commonly incorporated in today's vehicle designs. These steels are produced with very low carbon contents, typically in the range of 30–50 ppm, and frequently

Table 2.1 Types of automotive steels

Low carbon and conventional high strength steels (HSSs)

- Low carbon steels (LC)
- Solid solution strengthened (SSS)
- Bake hardenable (BH)
- High strength low alloy (HSLA)

First generation advanced high strength steels (AHSSs)

- Dual phase (DP) – ferrite/martensite
- High hole expansion (HHE) – ferrite/bainite
- Stretch flangeable (SF)
- Transformation induced plasticity (TRIP)
- Complex phase (CP)
- Fully martensitic (MS)
- Boron heat treatable steels

Second generation advanced high strength steels

- Twinning induced plasticity (TWIP)
 - Lightweight steels with induced plasticity (L-IP)
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have manganese levels of less than 0.25%. They offer very high elongations that can approach and sometimes even exceed 50%, and very high strain hardening coefficients that are advantageous when stamping very difficult-to-form parts.

Perhaps more importantly, at least from the aspect of steels used for lightweighting, the use of vacuum degassing technology to produce ultra-low carbon (ULC) steels has served as a base for the development of new classes of highly formable high strength steels. These steels owe their combination of high formability and high strength to the use of solid solution strengthening (SSS) and grain size control. The ultra-low carbon rephosphorized steels and some bake hardenable steels are good examples of how ULC technology and SSS have produced new grades of steel that meet many of the needs of modern automotive designs. In some cases, multiple strengthening mechanisms are used in conjunction with ULC technology. The addition of micro alloying elements such as niobium, in conjunction with the SSS elements such as phosphorus, manganese and silicon, along with grain sizes in the 7 to 8 μm range, have also produced some steels with very high strength and good formability. In this specific case, niobium is added in excess of what is needed to stabilize carbon. The resulting steel is not only interstitial free, but also contains well-dispersed fine carbo-nitride precipitates that contribute to higher tensile strengths through a refined grain structure as well as precipitation hardening (Toshiaki *et al.*, 2003). Some of these steels are shown in Table 2.2.

In addition to these grades of steel, micro-alloyed high strength low alloy (HSLA) grades of steel are commonly used throughout the body structure, especially for structural parts that carry significant loads and where very good spot weldability is required. These steels combine very good formability, high strength and modest cost, and are therefore commonly used by many automotive manufacturers. Parts such as motor compartment rails, rocker side panels and rear longitudinal rails are prime applications for these steels. Some of the more common HSLA steels are shown in Table 2.3.

Bake hardenable steels are commonly used in the automotive industry on exposed body panels and even structural stampings. The effect of bake hardening on the improvement in dent resistance is well established and bake hardenable steels have been used for many years to downgauge exterior panels without reducing denting performance (Schaeffler *et al.*, 1996; Okamoto, 1982; Campbell, 1989). These low carbon steels are thermally treated such that small amounts of solute carbon are held in solution which, upon heating, allows carbon to diffuse and pin dislocations. Mechanistically, solute carbon migrates to the dislocations until the concentration of carbon increases to the point that it precipitates and pins the dislocation (Wuebbels *et al.*, 2002). Typically, hardening from this bake hardening effect causes the yield strength to increase by 30–40 MPa in steels of this type. The key for

Table 2.2 Mechanical properties and chemistries of selected solid solution strengthened and bake hardenable steels (source: Toshiaki, 2003 and General Motors Corp., 2008)

	Mechanical properties					Chemistry				
	YS (MPa)	TS (MPa)	El (%)*	<i>n</i> -value	<i>r</i> -value	C (%)	Mn (%)	Si (%)	P (%)	Nb (%)
180 MPa SSS	186	340	37	0.22	1.6	.005 max	0.4	n/a	0.05	–
210 MPa SSS	223	335	35	0.20	1.5	.005 max	0.4	n/a	0.07	–
240 MPa SSS	252	363	34	0.19	1.4	.005 max	0.4	n/a	0.09	–
180 MPa BH	193	342	37	0.21	1.5	0.005 max	0.5	n/a	0.04	–
210 MPa BH	218	337	35	0.18	1.3	0.005 max	0.6	n/a	0.05	–
240 MPa BH	245	344	34	0.18	1.3	0.005 max	0.6	n/a	0.06	–
440 IF HSS	290	446	34	n/a	1.9	0.005	0.62	0.01	0.04	0.068

*Total elongations are in 50 mm with an ISO #1 tensile bar.

Table 2.3 Mechanical properties of common HSLA steels (source: SAE, 1999 and General Motors Corp., 2007)

Grade designation	Yield strength, (MPa) minimum	Tensile strength (MPa) minimum	%Total elongation, minimum, cold reduced*	%Total elongation, minimum, hot rolled
300	300	400	24	26
340	340	410	22	25
380	380	450	20	23
420	420	490	18	22
550	550	620	–	18

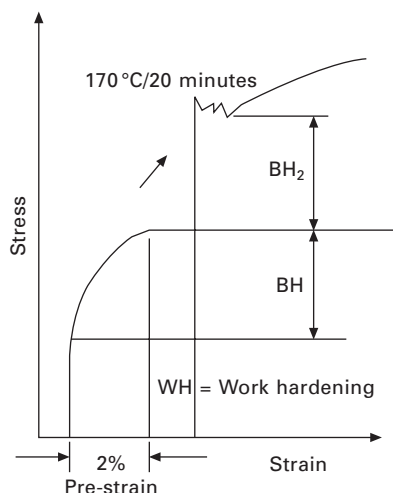
*Total elongations are in 50 mm with an ISO #1 tensile bar.

producing bake hardenable steels is to stabilize the carbon in solution such that they do not harden over time at room temperature, but rather harden after exposure to elevated temperatures such as those that occur in automotive paint bake ovens. By convention, the bake hardening index is measured after the steel is strained 2% in the direction of rolling, as shown in Fig. 2.1. The procedure consists of testing a standard tensile bar to determine its yield strength. Another tensile bar is then strained by 2% and is baked at a standard temperature, typically 170 °C for 20 minutes, at which time the tensile bar is pulled again until it breaks. The bake hardening index is determined by the difference in the yield strength of the original tensile bar and the bar that was strained and then baked.

It is important to note that the hardening effect from baking and from ambient age hardening will occur with less than 2% strain; tests show that strains of 0.5% are sufficient to activate the hardening mechanism. It is also interesting to note that there is strong strain path dependence for bake hardening. Several papers have reported that both batch annealed and continuously annealed bake hardenable steels do not show a bake hardening effect if the steels are biaxially stretched prior to baking. The change in strain path between a uniaxial tensile bar taken from a biaxially strained sample has been proposed as a reason for this effect, although mechanistic explanations for this observation have not yet been proposed (McCormick *et al.*, 1998; DiCostanzo and Matlock, 1996).

2.2.2 Dual phase steels

The term Advanced High Strength Steels (AHSS) generally refers to a wide range of steel grades that are part of the first generation of AHSS. While conventional HSS are principally composed of ferritic structures, the AHSS are characterized by their multiphase structures where ferrite is accompanied by other phases that have a significant effect on the mechanical, forming and even energy absorbing properties. In contrast to the use of precipitation

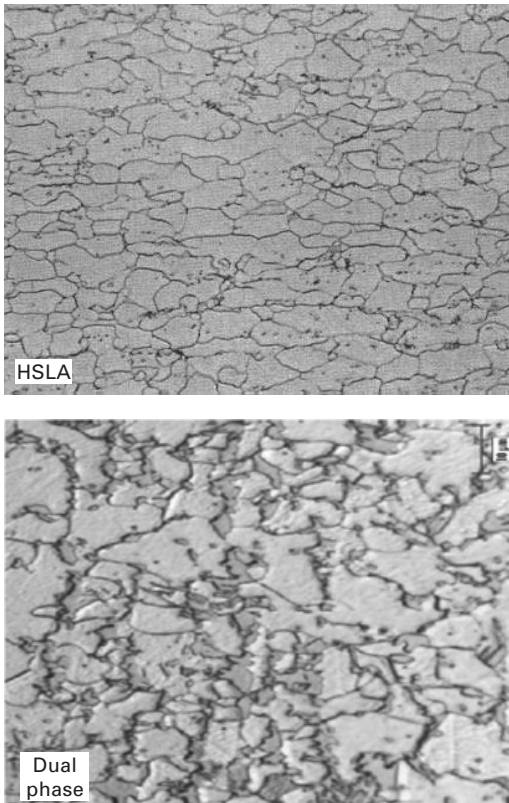


2.1 Bake hardening measurement (source: General Motors Corp., 2007).

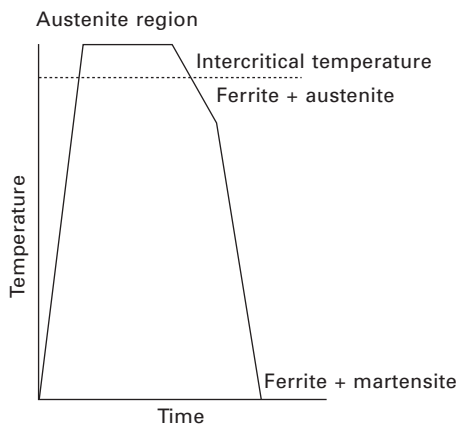
hardening or solid solution strengthening common in many of the early HSS, the AHSS are noteworthy not only by their use of microstructural hardening, but, increasingly, steel manufacturers are incorporating other hardening mechanisms and multiple metallurgical phases in their products. Of all the types of AHSS that are currently available, the most commonly used in automotive applications are the dual phase steels. The difference in the microstructures of dual phase and the precipitation hardened HSLA steels is shown in Fig. 2.2.

The appearance of dark and irregular shaped martensitic islands in a ferrite matrix is clearly evident in the dual phase steel. In contrast, HSLA steel is mostly ferrite with evidence of fine and well dispersed niobium, titanium or vanadium carbides. Dual phase steels generally contain 10–70% volume fraction martensite, where increasing martensite content corresponds to increases in tensile strength (Shaw and Zuidema, 2001). Dual phase steels are also notable for their high tensile strengths compared to conventional HSLA steels at similar yield strengths, their high work hardening rates, and higher energy absorbing capabilities.

Dual phase steels are produced by controlled cooling from the austenite or austenite plus ferrite phase such that some of the austenite is converted into martensite. This is followed by rapid cooling that transforms the remaining austenite to martensite. With the addition of appropriate alloying elements, hardenability of the alloy is adjusted such that the austenite to martensite transformation occurs at cooling rates that are achievable in modern continuous annealing lines for cold rolled products, or the run-out table of a hot mill in the case of hot rolled products. A typical cooling curve for a dual phase steel is shown in Fig. 2.3.



2.2 Typical microstructures of HSLA and dual phase steels.



2.3 Typical dual phase steel cooling curve (Shaw, 2001).

The alloying elements commonly used to achieve the required hardenability include carbon, manganese, chromium, molybdenum, vanadium or nickel. While proper alloy content is required, it is important to balance hardenability and cooling rate to minimize alloy additions (Shaw and Zuidema, 2001). Alloy additions are not only expensive, but high alloy contents increase carbon equivalent and result in reduced spot weldability. Even with finely tuned welding processes, interfacial fracturing of weld buttons can occur, especially with higher tensile strength grades. This may cause traditional weld inspection techniques, such as chisel impact evaluations, to be less reliable with AHSS than with conventional steels that routinely result in weld button pull-out from the surrounding steel. To some extent, increasing the size of the spot weld fusion zone has been shown to have a positive effect on the fracture mode of dual phase steels (Sun *et al.*, 2006) and is one of the ways automotive engineers commonly modify design requirements to adapt to specific material characteristics.

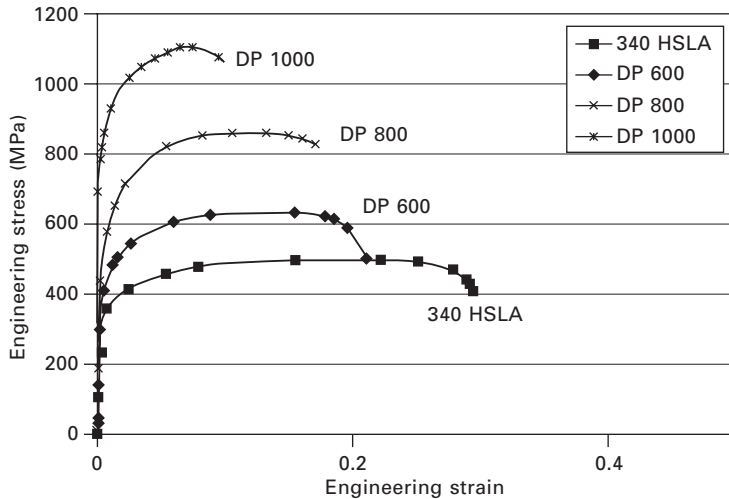
Some of the standard dual phase steels and their mechanical properties are shown in Table 2.4 along with a number of common precipitation hardened steels. The higher tensile strength characteristics of dual phase steels is clearly evident in this table and in the engineering stress–strain curves shown in Fig. 2.4. For the selected dual phase steels, the yield strength to tensile strength ratios are much lower than for precipitation hardened steels. This is a characteristic that was common during the early stages of dual phase steel development. In later stages, metallurgists began to modify the yield to tensile strength ratios, sometimes by the use of multiple strengthening mechanisms, in an attempt to improve the performance of these products and to address specific formability needs. The incorporation of multiple strengthening mechanisms in the ferrite–martensite dual phase steels eventually resulted in a new classification of advanced high strength steels commonly referred to as multiphase steels. These steels will be discussed later in this chapter.

Table 2.4 Comparison of dual phase and precipitation hardened steels (source: SAE, 1999 and General Motors Corp., 2007)

Grade designation	Yield strength (MPa, minimum)	Tensile strength (MPa, minimum)	%Total elongation, minimum, cold reduced*	YS/TS ratio
DP600	340	590	21	0.58
DP800	420	780	14	0.54
DP1000	550	980	8	0.54
340 HSLA	340	410	22	0.83
420 HSLA	420	480	18	0.88
550 HSLA	550	610	18 [†]	0.9

*For 550 HSLA, the reported elongation value is for hot rolled substrate.

[†]Total elongations are in 50 mm with an ISO #1 tensile bar.

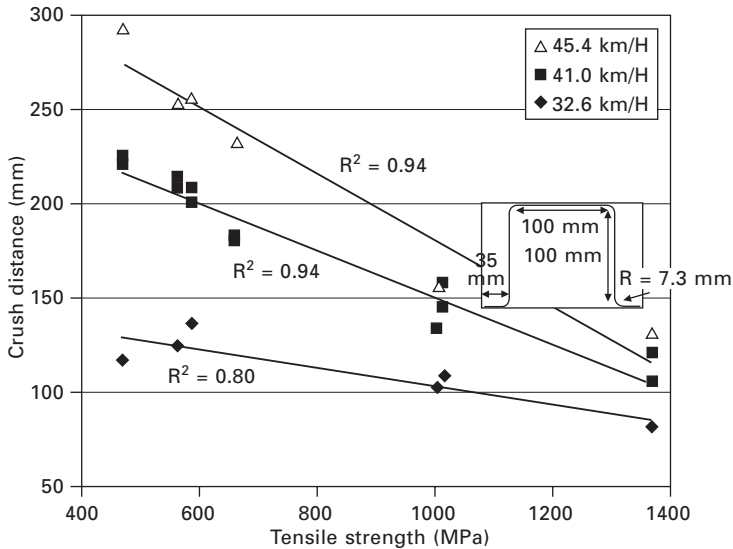


2.4 Engineering stress–strain curves of selected HSLA and dual phase steels (source: General Motors Corp., 2008).

Numerous studies of the energy absorbing behavior of these steels have shown the significant benefit of dual phase steels for absorbing energy during crash events (Yan *et al.*, 2005; Chen *et al.*, 2005). Furthermore, the potential for absorbing energy has also been shown to be highly correlated to tensile strength. This feature makes it convenient to make a general estimate of the improvement in energy absorption with different tensile strength grades.

Figure 2.5 shows a plot of the crush height of a U channel section with flat plates welded to the flanges, which is a common design for load absorbing rails in the motor compartment or in the rear compartment. The plot shows a highly linear relationship between crush distance and the ‘as produced’ tensile strength of the steel. This effect is evident with the impact speeds that are commonly used in testing steels for automotive use.

Another type of dual phase steel, the ferrite–bainite steels, are commonly referred to as stretch flangeable or high hole expansion steels. While both products are technically dual phase steels, it is convention in the automotive industry to distinguish these materials by referring to the ferrite–martensite products as ‘dual phase’ and the ferrite–bainite products as simply ‘ferrite–bainite’ or more conventionally, hole expansion steels. These steels have a higher resistance to edge cracking compared to conventional ferrite–martensite dual phase steels and precipitation hardened steels, making them well suited in applications where flanged holes are required. They are generally available only as hot rolled products, and they are generally limited to heavier thicknesses, usually greater than 2.0 mm. Given their thickness restrictions, the ferrite–bainite steels are most valuable in applications where there are flanged holes that experience high loads which demand high strength and



2.5 Crush distance of axially loaded longitudinal sections as a function of tensile strength of the steel (source: Yan, 2005).

heavy gauges. These characteristics make them especially suited to a number of applications for chassis and suspension parts, especially control arms.

The most common grade of ferrite–bainite steel currently used in automotive applications has a tensile strength of 580 MPa, with some manufacturers relying almost exclusively on this type of product for control arms. However, development of a 780 MPa tensile strength grade with adequate ductility to form control arms holds promise in the future to challenge aluminum in mass savings potential while providing a much lower component cost. One of the limitations of these steels is that they are not available with hot dip applied zinc or zinc–iron coatings. The thermal treatment caused by the molten zinc bath and the post zinc coating furnace required for galvanneal are not generally compatible with this microstructure. In addition, suppliers generally will not electroplate corrosion protective coatings on hot rolled substrates. This lack of corrosion preventative coatings somewhat limits the application of these products.

2.2.3 Advanced high strength steels – multiphase

Multiphase steels were developed as a modification of the early dual phase steels and, in their purest form, incorporate multiple strengthening mechanisms to improve mechanical properties without the addition of high levels of alloying elements that not only reduce weldability, but also significantly increase costs. The specific strengthening mechanisms used in these steels

are selected based upon a number of factors, including the desired properties and the types of heat treatments that are available to the steel maker.

This wide definition for these steels has led to an increasing number of steels that are available at high tensile strengths. In particular, in the 980 MPa tensile strength category, there are many versions available with various combinations of yield strengths, elongations and hole expansion capability. In a recent review of available products (General Motors Corporation, 2008), the several dozen different grades that are being offered were identified by their manufacturers as drawing types, high elongation, low silicon, bending, high hole expansion, high yield and intermediate types. Adding to the confusion, there seems to be little relationship between mechanical properties and these product descriptions. As is likely becoming evident by now, there is little standardization in this tensile strength category. The term ‘multiphase’ is therefore a somewhat wide definition and it is cautioned not to take the term too literally. Over time, some materials could be re-classified, or additional classes may be developed to better describe them. Work is ongoing in the industry in attempting to evaluate the different variations of this grade to determine if the number of variations can be reduced. This is important since the large number of currently available grades in this tensile strength range is resulting in lower volumes than steelmakers generally want to produce for any individual product. As a result, higher prices and availability problems are not uncommon and are beginning to present significant issues to automotive manufacturers, especially if one of these materials is required in multiple regions around the world.

While global commonization of the 980 MPa tensile strength grade has not yet occurred, there are a number of strength levels that are loosely becoming standards in the industry. Some grades that are becoming relatively standard are shown in Table 2.5.

Applications for high strength multiphase steels include structural parts where very high strength is desirable to restrict part deformation, such as in and around the passenger compartment. Typical parts for these steels include

Table 2.5 Selected multiphase steels at 980 MPa tensile strength (source: General Motors Corp., 2007)

Grade designation	Yield strength (MPa, minimum)	Tensile strength (MPa, minimum)	%Total elongation, minimum, cold reduced*	YS/TS ratio
980T/550Y	550	980	~ 8	0.56
980T/650Y	650	980	~ 8	0.66
980T/700Y [†]	700	980	~ 8	0.71

*Total elongation is in 50 mm with an ISO 1# tensile bar.

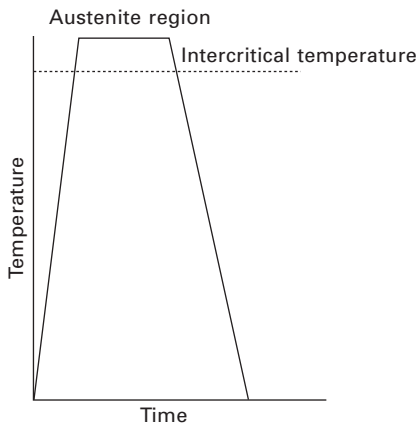
[†]Grade designation has not been standardized.

the lower side members (rocker panels), the center pillar outer reinforcement and associated parts, and in upper body roof structures that are critical in limiting roof crush in roll over events. These very high strength grades have also gained widespread application in seat tracks and seat structure parts that previously were dominated by low carbon, SSS and HSLA steels. The use of these steels has provided significant opportunities for mass reduction and improvements in strength and performance of these structures.

2.2.4 Cold rolled martensitic and heat treated boron steels

Martensitic steels, which consist of a matrix rich in martensite with smaller amounts of bainite and/or ferrite, are produced by quenching at very high rates from the austenite–ferrite region. In the automotive industry, martensitic steels are produced by several different methods; the microstructure is developed while the steel coil is being produced or after the part is stamped from steel with high hardenability. In coil form, cold rolled products are produced on water quenched continuous annealing lines with high cooling rates while hot rolled products are produced by water quenching on the run-out table in the hot mill. A typical cooling curve for water quenched martensitic steel is shown in Fig. 2.6.

In the water quenching process, steels of varying carbon content are used to produce martensitic steels with different strength levels. The use of lower carbon content steels of around 0.09% carbon and 0.50% manganese will result in martensitic steels with tensile strengths around 900–1000 MPa. If higher strengths are desired, the carbon content of the steel can be increased. When carbon contents are increased to about 0.23% carbon, the martensitic structure is strengthened such that the tensile strength is increased



2.6 Martensitic steel cooling curve. Source: Shaw, 2001.

to 1300–1400 MPa. All of this strength comes at a cost, however, in that the ductility of the steel is reduced such that total elongations are now 5% or less. Even so, there is enough ductility for this steel to be roll formed or bent into the necessary shape. Martensitic steels are very useful in automotive applications for door beams, bumpers, very lightweight and high strength lower side members (rocker panels), and cross car bars and beams that are designed to prevent intrusion into the passenger compartment.

There are other methods used to make martensitic steel structural parts, and all of them form martensite '*in situ*' after the parts have been formed. One technique is to employ water cooled dies to stamp steel blanks that have been pre-heated above the intercritical temperature. Cooling in the die is designed to provide high enough cooling rates to form the martensite in the formed part. Quite logically, this process is commonly referred to by the industry as '*hot stamping*' or '*die quenching*'.

Producing martensitic structures in water cooled dies has been increasing for a number of automotive applications, and likely will continue to increase as fuel economy and safety regulations increase. Since the cooling rate in water cooled dies is lower than that which can be achieved in direct water quenched continuous annealing lines, the alloys used in this process must have a higher hardenability rate. Increased hardenability is achieved by the use of steels with moderately high carbon, generally in the range of 0.20 to 0.25%, with manganese at approximately 1.2% along with the addition of 0.0005–0.001% boron. With chemistries such as these, tensile strengths of 1400 MPa can routinely be achieved. In the industry, steels used in the hot stamping process are commonly known as boron steels.

The advantage of hot stamped boron steels over fully martensitic cold rolled or hot rolled steels is that they are stamped at high temperatures where ductility is much higher than at room temperature. This allows for the formation of much more complicated stampings than could be formed from conventionally stamped, cold rolled martensitic steel. The downside is that the cycle time required to stamp and cool the steel in the die is long and the tooling is quite expensive. Compared with stamping conventional steels, where it is not uncommon to produce twelve or more parts per minute, hot stamping generally is restricted to about one per minute, although this production rate can be increased somewhat by designing dies that stamp more than one part.

Other techniques for making martensitic steel parts include direct water quenching after forming, and heating tubes produced from steels very similar to those used in hot stamping. For years, tubes made in this manner were extremely common in applications such as door beams. Another method is to fixture the cold formed part in a rigid fixture, and then selectively induction heat the part followed by an immediate water quench. This process is commonly referred to as post-form induction heat treatment. It has the

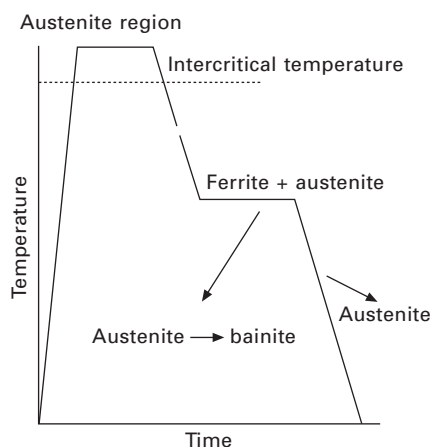
advantage of being able to selectively heat treat areas of a part and not heat treat others. In this way, strength is added where it is needed, but is not added where it is not desirable. This allows the potential to ‘tune’ how a part will crush or bend.

2.2.5 Transformation induced plasticity steels

Transformation Induced Plasticity, or TRIP steels, are produced in a similar manner to dual phase steels. Both require continuous annealing lines except that TRIP steels require a somewhat slower cooling rate and an isothermal hold at a temperature below the intercritical temperature. It is this isothermal hold, along with the higher carbon and silicon or aluminum contents of these steels that leads to a microstructure with appreciable amounts of metastable retained austenite. A typical cooling curve is shown in Fig. 2.7.

The microstructure of TRIP steels consists of ferrite with interdispersed hard phases of martensite and bainite, along with volume fractions of austenite that are greater than 5%. Typical chemistry for a TRIP steel with a tensile strength of approximately 700–800 MPa is shown in Table 2.6.

The primary benefit of TRIP steels is their increased formability as compared with dual phase steels of similar strength. This high level of formability is attributed to their extremely high work hardening rate and the presence of austenite in the matrix that, upon straining, changes into martensite. This takes advantage of the soft ferrite matrix for enhanced formability with a very high strain hardening rate provided by the transformation of austenite to martensite, which also strengthens the matrix. A comparison of the strength of a TRIP steel to selected other steels is shown in Table 2.7.



2.7 TRIP and complex phase cooling curve. Source: Cornette, 2001.

Table 2.6 Chemistry of a typical TRIP steel (source: General Motors Corp., 2008)

%C	%Mn	%Si	%Al	%P	%Cr	%Ni	%N	%Ti
0.18	1.5	0.05	2	0.01	0.02	0.002	0.003	0.003

Table 2.7 Comparison of TRIP mechanical properties with other steels (source: Cornette, 2001 and General Motors Corp., 2008)

	Tensile strength (MPa)	Yield strength (MPa)	Total elongation* (%)	(uniform, %)	n
Mild steel	181	296	42.4	21.4	0.208
340 HSLA	375	480	24	13	0.15
Dual phase 600	355	623	26	19	0.18
Dual phase 800	440	825	17	18	0.13
TRIP800	503	831	27.6	21.5	0.236

*Elongation is in 50 mm with an ISO #1 tensile bar.

It is evident from these mechanical properties that the formability of TRIP steels is much like that of low carbon steels. Compared to the other high strength steels shown in this table, the high strain hardening capabilities (n -value) along with high elongations are very favorable for the TRIP steels. As a result, these steels are very applicable to stampings that are relatively complex, but which also need to be of very high strength. Until the development of TRIP steels, these attributes were not available in any commonly produced steel. However, there are downsides to these steels. In particular, the very high alloy contents and resultant high carbon equivalents are detrimental to spot welding. As a result, these steels have not been as widely applied as other grades of AHSS by automotive manufacturers as of this time (2009). As welding practices advance or other joining methods become more popular, this trend could change and may allow the properties of this steel to be more widely utilized.

2.2.6 Complex phase steels

Complex phase steels are similar to TRIP steels in composition except that they are adjusted to contain less retained austenite. A typical cooling curve is similar to that used to produce TRIP steel and is shown in Fig. 2.7. In place of the large volume fraction of retained austenite as in TRIP steels, the complex phase steels contain fine precipitates along with a fine microstructure of ferrite and a high volume fraction of hard phases. Precipitation hardening of these steels is accomplished with the use of the addition of niobium, titanium and/or vanadium in addition to the normal alloying elements that dual phase and TRIP steels utilize (Cornette *et al.*, 2001). The resultant materials are of very high strength and are becoming a more common strategy for achieving strength levels of 800 MPa and above. While the formability

does not approach that of TRIP steels, the complex phase steels are capable of achieving higher strengths with lower alloy contents, which improves weldability at lower cost.

These steels and the performance improvement they provide have ushered in a new era in the types of steels that are used in the automotive industry. It has been said that most of the steels being specified on new vehicle architectures were not available 10 or 15 years ago. While that claim might be hard to prove, it would be equally difficult to find anyone involved in specifying steels for the automotive industry who would take much of an issue with that statement. The automotive and steel industries are in the midst of a revolution in the types of steels being manufactured for use on today's automobiles, and there appears to be no end in sight to that rate of change.

2.2.7 TWIP steels: the second generation of advanced high strength steels

Twinning Induced Plasticity (TWIP) steels and Lightweight Steels with Induced Plasticity (L-IP) are the latest generation of Advanced High Strength Steels that are being developed for the automotive market. These steels are designed to provide the combination of very high tensile strengths and exceptional ductility, far above what is available with the current generation of AHSS.

In contrast to the ferrite based structure which characterizes the first generation AHSS, this latest generation consists of a face centered cubic austenite structure that is achieved through the use of very high levels of manganese. In the case of the recently introduced TWIP steels, the resultant material has a tensile strength of 1000 MPa with a total elongation well in excess of 50% (Cornette *et al.*, 2005). However, this combination of high strength and exceptional ductility comes at a significant cost. With manganese levels in excess of 20%, the cost of these steels is expected to approach that of some grades of stainless steel and aluminum, which presents a significant challenge for this material in the very cost sensitive automotive industry, and may ultimately be one of the limiting factors in its future success.

This latest generation of AHSS, like the dual phase steels that preceded it, is not a recent invention. A high manganese austenitic alloy similar to TWIP steels was discovered by Hadfield, perhaps as long ago as the early 1880s. Like many steel grades, there has been a long time between its discovery and its 're-discovery' and development into a product that may provide benefit to the automotive and other industries that could use a material with its uniquely high tensile strength and superior ductility. The unique properties of this steel are tied to the fact that it remains fully austenitic at all the temperatures that it has been evaluated at, and that it not only deforms

by the more conventional processes of layers slipping between each other and the movement of dislocations, but also by twinning inside of its grains. It has been reported that the boundaries from twinning function in a similar manner to grain boundaries, with respect to their ability to restrict the movement of dislocations (Cornette *et al.*, 2005). The seemingly magical mechanical properties of this steel and those of other common steels are shown in Table 2.8.

2.2.8 Overview

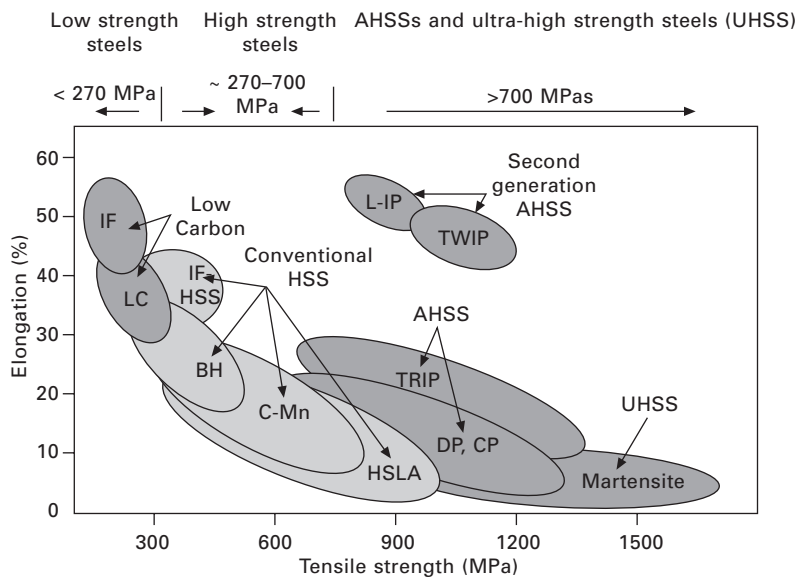
There is a wide range of steels available to the automotive designer and materials engineer for use in designing modern vehicle architectures. These steels provide a variety of strength levels and ductility that can meet most of the requirements for automotive structures and, when properly utilized, enable one to significantly reduce mass from what has been typically available in today's market. In order to make some sense of all these grades, a chart comparing these steels has commonly been used that graphically shows the relationship between strength and ductility. This graph, commonly called the 'banana chart' or 'ductility ladder' in the industry, is shown in Fig. 2.8 and has evolved over the years to the point that it is difficult to determine who came up with the original concept.

A chart such as Fig. 2.8 very effectively shows the positive relationship of tensile and elongation for the AHSS as compared with the conventional low carbon, bake hardenable, solid solution strengthened and precipitation hardened (HSLA) steels. In comparison, the first generation AHSS, consisting of TRIP, DP and CP steels, have higher elongation values for a given tensile strength than conventional HSLA steels. In stark contrast, materials that compose the second generation of AHSS, such as TWIP steels, greatly increase the ductility to tensile strength relationship to previously unheard of levels in commonly used carbon steels.

Table 2.8 TWIP steel properties compared to other HSSS Source: General Motors Corp., 2008

Grade	Yield strength (MPa, typical)	Tensile strength (MPa, typical)	Total elongation (typical, %)*	n-value
Low carbon IF steel	140	270	42	0.22
DP600	360	610	23	0.14
DP800	440	820	16	0.11
DP1000	650	1020	9	n/a
340 HSLA	360	450	24	0.13
420 HSLA	640	550	21	0.11
FeMn TWIP 1000	464	1009	>50	0.42

*Total elongation in 50 mm with an ISO #1 tensile bar.

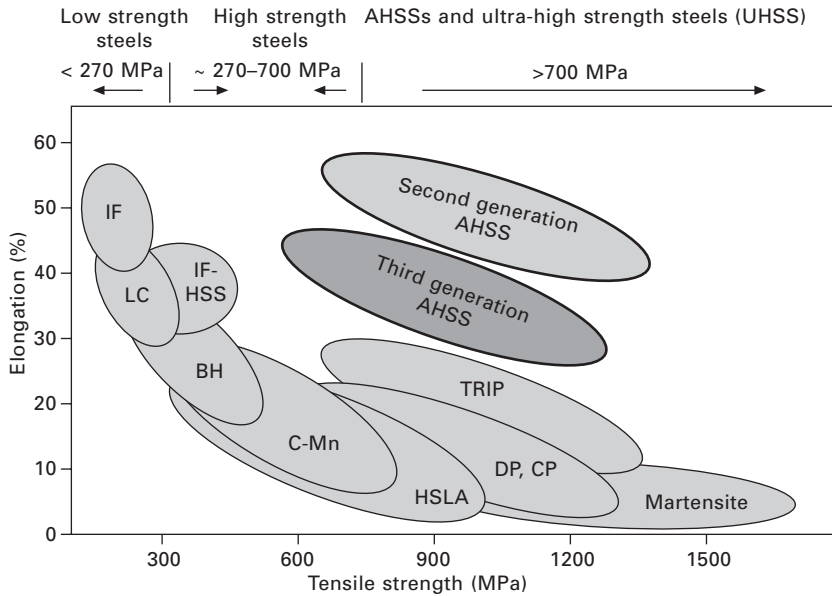


2.8 Automotive steel strength/ductility ladder.

2.3 Third generation advanced high strength steels

The American Iron and Steel Institute (AISI) initiated a program to investigate the types of steels that could be developed to fill in the gap in the ductility ladder between the first generation and second generation AHSS. The potential for this new, third generation of AHSS is being studied in the hope that it will be a more cost effective alternative to the second generation while maintaining a much higher level of ductility at similar strength levels to steels currently available with the first generation of AHSS. In terms of the 'infamous' banana chart, these steels are expected to fill the gap between the first and second generation AHSS and are shown in Fig. 2.9. There are three phases to the research: the first is a survey and evaluation of the latest trends, the second is the application of known strengthening mechanisms and investigation of the potential for modified base structures or novel or non-conventional strengthening mechanisms, and the third phase will consist of an evaluation of the potential processes to produce the structures and properties that were identified in the second phase. Some of the strengthening mechanisms under study, in addition to the more common mechanisms, include grain twinning, shear band formation, strain induced transformations such as found in the TRIP effect, and dislocation pinning.

In conjunction with these strengthening mechanisms, the AISI will also examine new base structure combinations including, but not limited to, duplex ferrite with austenite and new alloy approaches to produce leaner austenitic



2.9 Third generation of advanced high strength steels.

structures, ultra-rapid cooling, and also controlling the crystallographic texture of steel.

The goal of all this investigation and research is to develop new steels that will provide additional and very cost effective means of achieving the very challenging goals that automotive manufacturers have in meeting future fuel economy, emission and safety requirements for the next generation of automotive body structures in a cost effective manner compared to lightweight metals and composites (AISI, 2006).

2.4 Manufacturing and forming high strength steels

The major processes used to form and manufacture vehicles from high strength steels are similar to those used with conventional steels except that special techniques and guidelines have been developed by each automotive manufacturer to adapt to the special needs of these steels. The typical issues with forming high strength steels, such as springback, are well known but not entirely predictable, and there still exists some ‘art’ and ‘trial and error’ built into the process. Even so, much has been learned about how to manufacture parts from these steels and much has still to be learned. In addition to forming, joining high strength steels also presents its own set of challenges. While the most common process for joining steel in the automotive industry is spot

welding, other joining techniques such as adhesive bonding, laser assembly welding and MIG welding are also used in automotive manufacturing.

2.4.1 Forming high strength steels

Of all the processes used by automotive manufacturers to form steel sheets into parts, conventional stamping is the most commonly employed process. To a large extent, the reliance on stamping is related to the complex nature of the parts, the readily available infrastructure that supports stamping and its high volume capability that suits this industry. While stamping is the most common forming process, other processes such as roll forming, hot forming (or hot stamping as it is commonly referred to) and hydroforming are all used at various times. The following discussions will give the reader some background as to why the various processes are selected, some of their advantages and disadvantages and some examples of the types of parts that are formed with these technologies.

Stamping

Stamping has been the preferred method of forming parts in the automotive industry for decades. The industry's manufacturing infrastructure is largely based on stamping and the technologies necessary to make that process successful. There are several primary reasons why stamping has been so successful; stamping processes are able to make the complex shapes that are commonly required in the industry and stamping is compatible with the high volume that the industry requires.

Conventional stamping requires a set of dies that form the shape of the part, create the flanges that are necessary to join parts together, as well as trim, flange and punch any holes or openings that may be required. As a result, stamping processes generally require at least three dies; the forming die, the flanging and trim die, and the piercing die that adds any necessary holes. Depending on the complexity of the part, additional forming steps may be added such as pre-forming or doming the part to move metal to where it is needed before the forming die creates the shape of the part. This process can be used when forming very deep drawn parts and is most commonly employed with very formable low carbon steels. However, the technique is not commonly used with high strength steels, especially the advanced high strength steels. As mentioned in previous sections, the advanced high strength steels work harden very quickly. Pre-forming reduces the elongation and ductility of the steel and makes it difficult to move the steel into the desired shape in a second forming operation. As a result, it is common practice to form parts into the final shape, or as close to the final shape as possible, in the first stamping operation.

In its simplest form, a traditional set of line dies consists of a number of presses that are set together in a line such that steel blanks are fed into the first die, the part is stamped, and then the part is transferred to the second die, which is in a press next to the first, and the next process is performed in that press. This process continues through all the dies until the part is finished. Since there are a number of expensive dies involved in stamping, in order to be cost effective, this process must produce a large number of parts. In most cases, a line of stamping dies will produce between 10 and 14 parts per minute. This translates into the potential to produce more than 6000 parts in an 8-hour shift.

Another commonly used stamping process uses a progressive die. A progressive die is a single die that incorporates multiple forming operations in successive steps as the steel is progressively moved through each step between strokes. This process is most suited to small parts that do not have very deep forming operations but require multiple stages to make the desired shape. In a progressive die process, steel is fed directly from a coil into the tool, thereby eliminating the costs of blanking and transferring of blanks from a stack to the die. Another advantage is that many operations can be incorporated into that one process and there is no need to transfer parts between dies. The number of parts produced per minute can also be significantly higher than with traditional line dies, especially with small parts that are optimum for this process. Although the die sets can be expensive, this process can be less expensive in total cost compared to a conventional set of line dies.

Global formability

In order for stamping to be successful, a die must be designed with the knowledge of how metal flows and how the steel will react to applied strains. Today, that job is largely fulfilled by computer forming programs that evaluate part shape and formability of the steel, the die design, friction between the surface of the die and the steel, as well as how the metal flows in the die. These programs predict where the strains will be highest and where there is danger of excessive metal thinning that requires modifications to either die geometry or part shape. Metal flow in a die is influenced by many factors; strength of the steel, friction differences between the steel surface and the die surface, ductility of the steel, the ability of the steel to resist thinning, lubrication, strain rate sensitivity of the steel and how the metal is restrained from flowing into the die are but a few of the factors affecting formability.

A relatively simple way to determine if the selected steel grade has enough formability to make a part is to use a forming limit diagram. The forming limit diagram, also known as the Keeler–Goodwin diagram after its founders,

was developed as a method to plot strains on stamped parts and predict how close the part is to splitting (see Fig. 2.10).

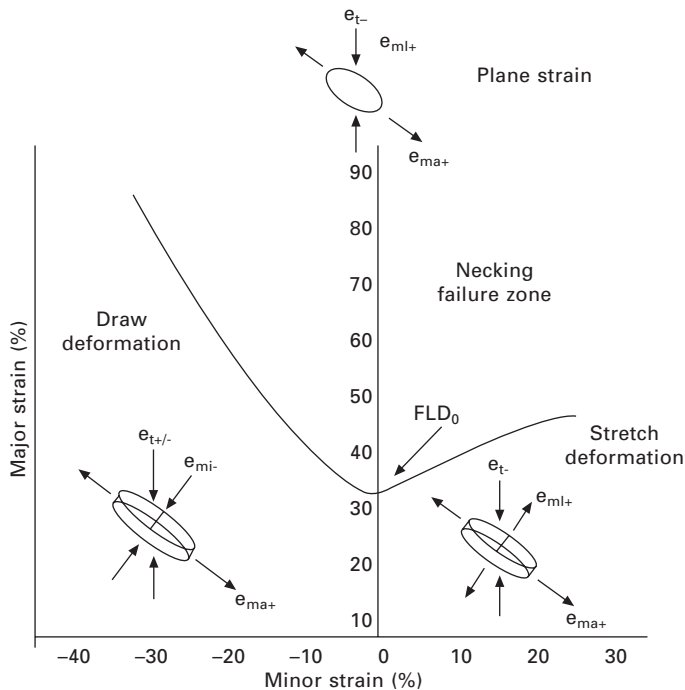
The forming limit diagram is a very useful, robust and relatively easy-to-apply tool. Since the shape of the curve is effectively constant with most sheet metals, the forming limit diagram is modified for the material of interest simply by moving the diagram up and down the y-axis using a very simple formula to calculate the y-intercept, which is known as the FLD_0 . That formula is based on the thickness of the steel and the strain hardening exponent, or n -value, which is the exponent on the following Power Law equation:

$$\sigma = K \epsilon^n \quad [2.1]$$

where σ = true stress
 ϵ = true strain
 K = strength coefficient at $\epsilon = 1.0$
 n = the strain hardening exponent

The FLD_0 is then calculated using the following formula:

$$FLD_0 = (23.3 + 14.1 t) \times n/0.21 \quad \text{where } t = \text{thickness (mm)} \quad [2.2]$$



2.10 Forming limit diagram.

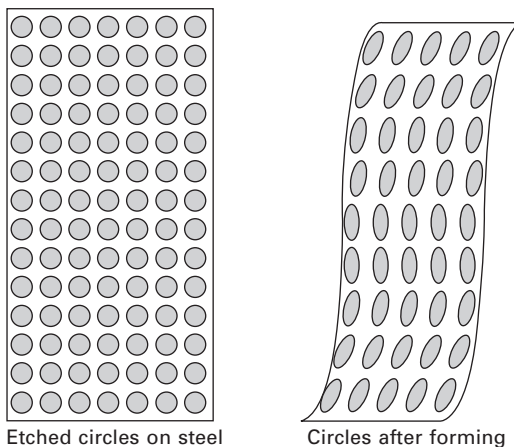
For most steels, the n -value ranges from 0 to about 0.3, with higher values being indicative of higher formability and improved ability to distribute strains and avoid necking.

This diagram is very effective when measuring global formability of sheet metal stampings. The strains present on a panel are determined by etching circles of known diameter on a steel blank before it is stamped. The circles are formed using templates made of thin films that have circles of known diameter etched imprinted over their entire surface (5 mm circles being common). This blank is placed into the forming die and then, under the same conditions as in production – i.e. same blank holding pressures, same ram speed, same lubrication, etc. – is stamped only in the forming die. The formed panel is then removed and the technician then can examine how the circles changed shape and calculate the forming strains at that location on the part. A diagram of the way the steel surface and the circles look before and after stamping is shown in Fig. 2.11.

These strains, which represent the in-plane major and minor forming strains, are plotted on the forming limit diagram such as is shown in Fig. 2.10 after the FLD_0 is calculated for the steel being tested. If strains at any location are above the solid line forming the forming limit diagram, that location is considered to be at risk for necking or even splits. Strains that are below this line are considered safe. There are many good books and papers written on sheet metal formability that can provide a working background for the interested engineer.

Local formability

Local formability, in contrast to global formability, generally relates to issues that are not predicted by the forming limit diagram. Examples of



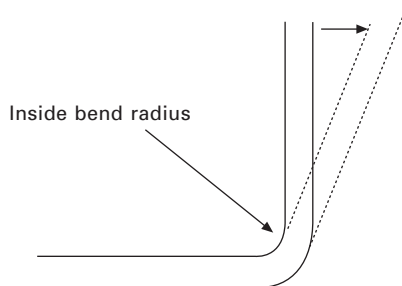
2.11 Examples of etched steel surface.

local formability issues include cracking on the outside radius of a bent flange, cracks on the edges of extruded holes, and cracking that occurs in areas of lower strain than would be predicted to cause cracking. Unlike conventional HSS such as HSLA and carbon–manganese grades, some of the AHSS, especially dual phase steels of 780 MPa and above, have shown a susceptibility to cracks in areas of low strain, especially at formed radii. These types of fractures have been called shear fractures and are currently the subject of extensive evaluation. Other AHSS, such as complex phase and TRIP steels, have shown greater resistance to stress fractures than have dual phase steels (Walp, 2006).

Springback

While all steels experience some degree of springback, the phenomenon is most severe in high strength steels. In many cases, springback is more of an issue than cracking and necking when forming high strength steels because it is very difficult to predict springback. An example of springback of a flange is shown in Fig. 2.12. There are a number of ways to compensate for springback. One method is to design the tool such that the flange is over bent during the stamping process with the intent that, after forming, the flanges will ‘springback’ to the desired location. This is good in theory, except that the absolute amount of springback is affected by residual stresses that may be in the part and other factors such as the radii of the die at the inside of the bend. In practice, it is easy to either under- or over-predict the amount of springback, resulting in a flange that is not in the proper design location. Worse yet, when springback causes the entire part to twist out of shape, it can be very difficult to determine the cause. All of these issues can result in a very long and drawn-out process of re-cutting the tool face to adjust springback in an attempt to achieve the proper final location of a flange or shape of a part.

The amount of springback can be improved in a simple flange by reducing the radii of the die, and hence the inside radii of the part flange. However,



2.12 Springback in high strength steels.

this must be done with the proper knowledge of the minimum bend radii that the material of choice can withstand before fracture. In addition, for many materials, flange direction in relation to the rolling direction of the steel can be critical. It is not uncommon for the minimum bend radii to be four times as large parallel to the rolling direction (i.e. longitudinal) as it is perpendicular (i.e. transverse) to the rolling direction. By convention, bend radii are reported as a function of not only the radius, but also the thickness of the steel and are expressed in the following formula:

$$\text{Bend radius} = r/t \quad [2.3]$$

where: r = radius in mm

t = thickness in mm

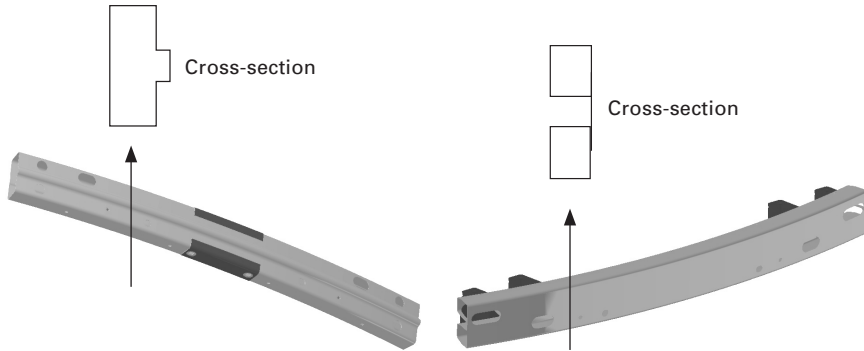
Prediction of springback is an area where a significant amount of study is being dedicated within the automotive industry. Steel companies, the Auto Steel Partnership and a number of research laboratories are studying springback prediction and modeling, and a detailed discussion would take a book entirely dedicated to this topic.

Roll forming

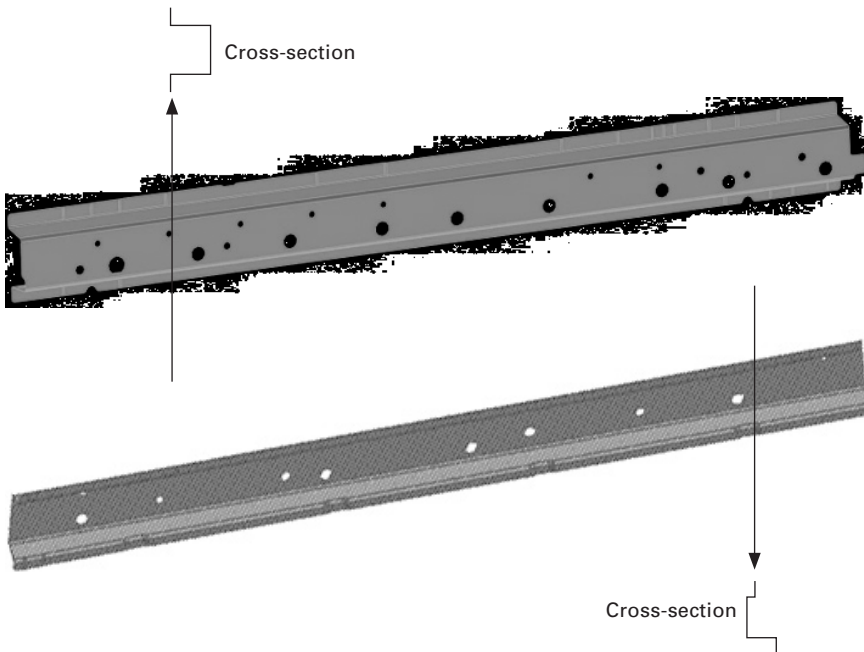
Roll forming is a process that is very applicable to high strength steels (especially steels of very high strength and low ductility such as cold rolled martensite), although almost any material can be roll formed. Roll forming utilizes a series of rolls that gradually form the steel into the required shape. Since this process is a continuous, coil fed, straight line forming process, part shape needs to be constant throughout the length of the part. Changes in section shape are not consistent with this process; however, there are a number of post roll forming processes that can bend a part and change its sweep. There are some superior examples where extremely high strength steels have been fabricated into some very complex sections using this process. Some example parts include bumper bars made out of DP1000 or cold rolled martensite, and rocker panels that have also been made of cold rolled martensite. Both are good examples of parts that are generally intended to resist deformation under all but the most severe loads. Figures 2.13 and 2.14 show some typical designs for roll formed parts.

Press hardening

Press hardening, or die quenching as it is also known, is a manufacturing method that generally provides the highest strength and lowest mass option for parts that are relatively complex in shape. In press hardening, a steel grade with sufficient hardenability, usually a carbon, manganese, boron



2.13 Examples of ultra high strength steel roll formed bumpers.



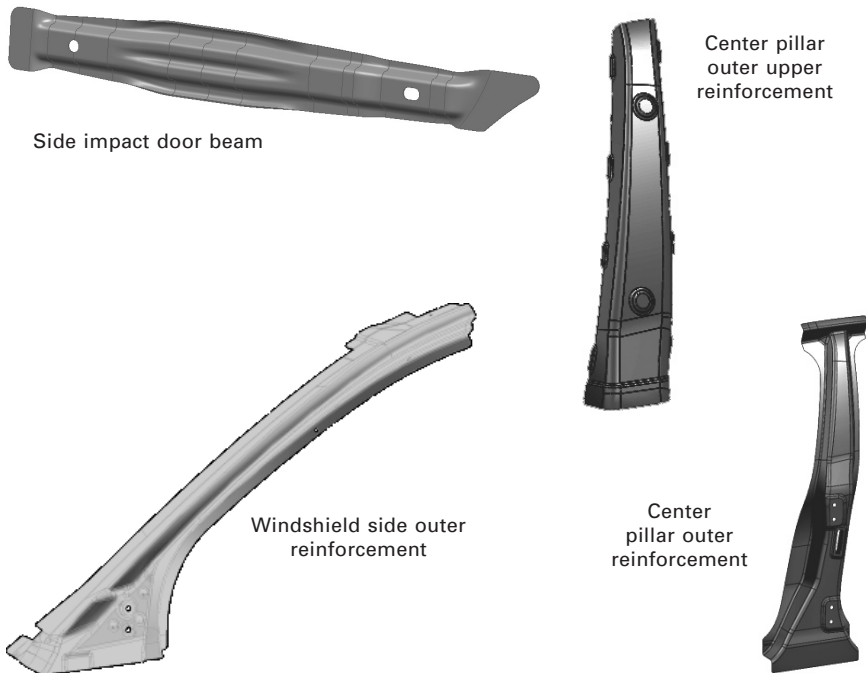
2.14 Examples of ultra high strength steel roll formed rockers.

steel alloy, is heated into the intercritical region, usually around 950°C , and then the part is transferred to a water-cooled die and immediately stamped and quenched into the final shape. The resultant microstructure is almost purely martensitic. This process results in parts that have tensile strengths of 1400–1500 MPa and has the advantage of being tolerant of complex shapes that can otherwise be formed only with much lower strength steels using conventional stamping processes.

Press hardening has greatly expanded in the number of its applications in the automotive industry since early 2000, and is now a process that is almost

routinely specified on a number of automotive applications such as door beams and center pillar reinforcements. The technique is used on parts that are critical to safety and frequently includes parts essential for the protection of passengers in side impact and/or roll over events. The parts produced by press hardening provide the highest strength among carbon steels currently in production for body structure stampings in the automotive industry. Some typical parts are shown in Fig. 2.15.

This process does have disadvantages that the automotive engineer must be aware of. Stampings from this process are covered with a heavy oxide scale and must be cleaned to facilitate welding and to provide a surface that is capable of providing suitable adhesion for automotive primers and paint. Removal of the oxide coating is usually accomplished by shot blasting, which not only adds additional cost, but also stress relieves the part and can contribute to wider dimensional variation. In order to avoid shot blasting, the steel industry is offering a product with an aluminum/silicon alloy coating that is highly resistant to oxidation at high temperatures. This coating eliminates the need for post-form cleaning, although it has its own set of challenges. The presence of this coating inhibits spot welding, which is already problematic due to the high alloy content of the steel. In addition, the coating alloys with



2.15 Examples of press hardened safety critical stampings.

iron in the steel to such an extent that the corrosion resistance that would be afforded by the coating is largely rendered ineffective.

As previously mentioned, steels used in this process must have sufficient hardenability such that they can achieve the high strength, martensitic microstructure with cooling rates that are practical to achieve in a water cooled die. With the required high alloy contents, weld cracks can be a concern and will be discussed at length in the next section on joining.

2.4.2 Joining high strength steels

Most of the methods commonly used to join lower carbon steels are also used to join high strength steels, although each of these methods possesses its own set of advantages and disadvantages that the automotive designer must understand for successful execution. The most common joining method for high strength steels is spot welding, just as it is for other steel grades that are commonly used in automotive body structures. Other joining methods such as arc welding, adhesive bonding and laser welding are also used, although arc welding is frequently limited because of the wide heat affected zone which exhibits significantly lower strength than the surrounding metal. Each of these methods is discussed briefly in the following paragraphs.

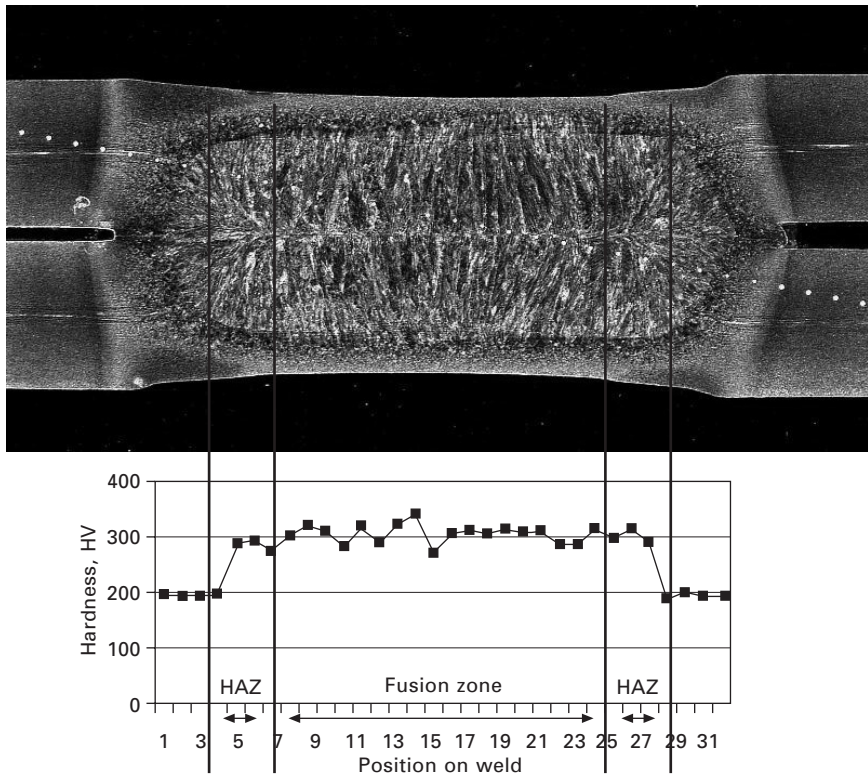
Spot welding

Automotive manufacturing plants are primarily facilitated for assembling vehicles with spot welds, and changes to high strength steel grades have had little effect on changing the industry's joining preferences. However, while the basic technology used for spot welding is little changed, improvement in weld controls and process enhancements has extended the ability to successfully spot weld steel grades with higher carbon equivalents in high volume processes common in the industry. Robotic welding, automatic weld feedback, sophisticated weld controllers and weld electrode tip dressing are but a few of the improvements in this joining method. Furthermore, the willingness to adapt weld cycles to changing materials and the detailed testing and evaluation of weld stacks have greatly extended the types and grades of steels that can be routinely welded with the very high quality levels that are required.

One of the most critical analysis tools available to the weld engineer when evaluating spot welds is to prepare and examine a metallurgical cross section. This technique will reveal critical information about the weld, the presence of weld cracks or microcracks, depth of weld penetration and the heat affected zone (HAZ). With the addition of other micro-analytical analysis techniques, the investigator can also determine hardness of the weld and adjacent areas, and the segregation of elements that may be detrimental to

the integrity of the weld. This type of information is invaluable, and weld development without access to this type of testing is very limited in what type of work can be done.

A cross-section of a weld between two DP600 steel sheets is shown in Fig. 2.16. The cross section has been mounted, polished and etched to show the grain structure of the weld and HAZ. In addition, a microhardness traverse across the weld clearly shows the hardness of the base metal, the HAZ, and the weld metal. There are a number of observations that can be made from this weld. The first is that the weld fusion zone is consistent and has excellent penetration into both steel sheets. Partial penetration or uneven penetration can suggest potential problems with welding conditions. Also, the hardness is consistent across the weld nugget and, as is clearly evident in the photomicrograph, the amount of weld electrode deformation of the weld is minimal. The HAZ is evident in both the photomicrograph and in the microhardness values, which show a sharp reduction in the hardness across this zone until the hardness of the base metal is reached. A weld such as is



2.16 Fusion zone and hardness of DP600 to DP600 spot welds. Source: general Motors Corp., 2008.

shown in Fig. 2.16 would be considered a good weld and would be predicted to perform well.

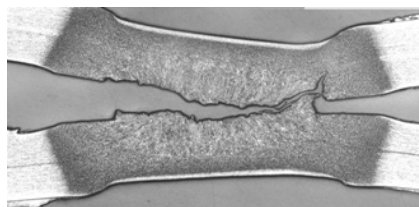
The performance of a weld is generally considered acceptable if the design load can be carried by the weld without fracture. However, this acceptance criterion is difficult to apply during an accident investigation since actual loads are difficult to estimate after the accident has occurred. From a practical perspective, it is preferred to have the weld button, or fusion zone of the weld, stay intact and force the fracture outside the weld. When this occurs, one can be sure that the weld did not fail. This type of fracture mode is called button pull-out and is shown in Fig. 2.17.

Another possible fracture mode is interfacial fracture. Interfacial fracture is said to occur when the fracture occurs through the fusion zone of the weld. This type of fracture mode can occur if the HAZ is small or does not exhibit significant softening, or the materials being welded are of very high strength. There may also be instances where there is a partially fused weld, or the weld conditions or materials being welded causes the weld metal to become brittle. This type of fracture can occur at lower strengths than the design load and is clearly not desirable. Fortunately, examination of the fracture surfaces can easily reveal the fracture mode and eliminate any question about the performance of the weld. The important point is that interfacial fracture, while not considered the preferred fracture mode, does not necessarily indicate that the weld did not meet the loads that it was designed to meet. This is an important point since interfacial fractures are more common with very high strength steels than they are with lower strength steels. However, it is salient to note that if the steel is thick enough, even low carbon steels can fracture interfacially.

In many automotive assembly operations, weld quality is evaluated by chisel impact of the weld which, with common steels, results in full perimeter weld metal pull-out. Under these conditions, the weld is known to have been stronger than the parent steel and, by definition, was an acceptable weld. However, with some AHSS, and in particular when the thickness of the steel is over 2.0 mm, it is not uncommon for the welds to fracture across the weld nugget itself. This creates inspection issues for the assembly



Button pull-out



Interfacial fracture

2.16 Weld fracture modes.

plant since it may not be clearly evident if the weld metal was properly fused without running a time-consuming metallurgical mount of the weld. However, in order to avoid potential legal responsibility, it is imperative that the manufacturer have proof that the weld met all applicable requirements and that the weld carried the necessary loads before it fractured. This may motivate manufacturers to utilize other methods to verify the condition of welds of these types of steels, such as the use of ultrasonic evaluation.

In real world applications, welds can also fracture in mixed modes, where there may be varying degrees of interfacial fracture and button pull-out. In the final analysis, either fracture mode can be acceptable in terms of the load that was carried, and in the end, engineering specifications should consider these fracture modes and specify what is acceptable. This is especially important when spot welding AHSS.

There are a number of formulae developed to assess cracking susceptibility (Matsuda, 1990; Olson *et al.*, 1993), with each one containing different elements and contributions to cracking. For many steels, such as HSLA and leaner dual phase steels, the carbon equivalent (CE) formula (Saito, 1983), developed at Nippon Steel, has been found by some to have a good relationship between chemical composition and weld-fracture from cross-tension tests. Using this formula, with normal levels of residual phosphorus, sulfur and silicon commonly found in boron steels, a carbon equivalent of 0.36 is not unusual. Testing has shown that, when the carbon equivalent of steel was higher than 0.24, weld interfacial fractures were generally observed.

$$\begin{aligned}\text{Carbon equivalent} = \%C + \%Mn/20 + \%Si/30 \\ + 2 (\%P) + 4 (\%S)\end{aligned}\quad [2.4]$$

More recent evaluations of higher strength dual phase steels indicate that this formula, which does not include a number of alloying elements used in some of these grades, may not be the most accurate in its predictions for all alloy compositions and strength levels. The investigator would be prudent to evaluate a number of different alloys with different chemistries before applying any formula for weldability and, even then, to follow accepted practices to evaluate weld quality such as microstructural evaluations.

Other welding methods

While spot welding is the most common method used to join automotive body structures, other techniques such as metal inert gas welding (MIG), laser assembly welding, structural adhesive bonding and laser blank welding are also employed. MIG welding is a type of gas metal arc welding (GMAW) that utilizes a consumable electrode that makes a weld under an inert or semi-inert gas shield. The process is commonly used in automotive manufacturing, but has its limitations when joining many grades of advanced and ultra, high

strength steels. The relatively high heat input required to fuse the electrode material and the work piece can result in a large heat affected zone as compared to resistance spot welding. As a result, this technique needs to be carefully studied with respect to the alloys being joined and to the amount of softening that is occurring in the HAZ. Therefore, techniques that limit heat input such as localized rather than continuous welds, weld speed, shielding gas, and the size of the weld need to be considered along with the structural requirements of the joint. The sensitivity of many of the newer advanced and ultra high strength steels to HAZ softening should lead one to perform careful evaluations of the alloy, weld stack and welding practice before this process is selected. It should be noted, however, that this technique has a long and positive performance history in welding relatively heavy gauge low carbon, HSLA and solid solution strengthened steels.

Adhesive bonding

Adhesive bonding of automotive structural joints is a technique that is receiving a lot of attention. The development of new generations of adhesives that combine high strength without the brittleness of conventional structural adhesives has enabled the use of increased structural bonding and has opened up new opportunities for the automotive designer. These new adhesives, commonly referred to as crash toughened adhesives, use synergistic rubber toughening to create particles in the adhesive that exhibit high fracture toughness. This reduces the tendency for fracture during impact events and therefore improves energy absorption. Another critical improvement with this new generation of adhesives is the higher working temperature range that better suits the operating temperature extremes in which automobiles need to operate.

The use of these adhesives creates the opportunity for significant weight savings through the reduction of weld flange size and improvement in the structural efficiency of joints. At this time, most crash toughened adhesives are used to augment conventional spot welds; however, the opportunities for these adhesives to reduce or even replace spot welding is a major area of interest. An entirely adhesive bonded structure may be years away from reality, but there are many talented engineers working on this challenge and the use of structural adhesives in joining structural components is likely to continue to grow.

2.5 Designing with steels for lightweighting automotive structures

In an environment where fuel economy, safety and emissions are becoming so critically important, the ultimate goal for the automotive engineer is to

develop an efficient design that incorporates the right material on each part such that the overall material and design work together to enable a highly efficient vehicle architecture. Given the overall critical nature of design, no discussion of the materials used to lightweight automotive designs would be complete without at least some discussions on how those materials are effectively incorporated into a vehicle structure.

In order to design efficient vehicle body structures with the lowest potential mass, the design of each part of the vehicle, how these parts function as a subsystem and ultimately, as an overall vehicle, are extremely critical to overall efficiency. The complex interactions between individual parts, these parts and their subsystems and between each subsystem will ultimately determine how successful the entire design is in terms of structural and mass efficiency.

The role a material plays in overall vehicle performance, while being critical to an efficient design, is not as important as the part and system designs that make up the vehicle. In other words, overall vehicle design and structural load path efficiency are more critical than the materials that are selected for each of the parts in that vehicle. To look at this in another way, an inefficient structural design cannot be transformed into an efficient design through the use of the latest and greatest materials that are available. However, excellent material selection can make a really good design exceptional, and that should be the goal of every automotive design.

One of the first things automotive engineers need to accomplish when designing new vehicle architectures is to develop a philosophy of how vehicle loads and crash energy will be managed and how all the major components and subsystems will be ‘packaged’ within the allotted space. Frequently, it is the amount of space available for a load carrying part or subsystem that will ultimately determine how efficient that part and/or subsystem is. For the automotive designer, the strength of components and their ability to carry and distribute load is critical. In order to better understand how this works, let us look at a simplified vehicle design such as in Fig. 2.18 to see how loads could be transferred through the architecture.

The body structure in Fig. 2.18 represents most of the major components in a vehicle structure. The number of critical body structure parts is somewhat difficult to identify with great precision since it is common practice to break up many of the larger parts into smaller parts that are more manufacturable. While this number can vary between manufacturers depending upon their design and manufacturing philosophies, of the 400–450 parts that typically comprise a body structure, there are in the order of 40 to 50 major components. This figure does not include the closure panels: hoods (bonnet), fenders, doors, and rear decklid (boot). These panels are generally not considered critical to the vehicle structure. The remaining parts are comprised mostly of miscellaneous reinforcements and brackets that may be critical to vehicle performance, but their discussion is beyond the scope of this chapter.

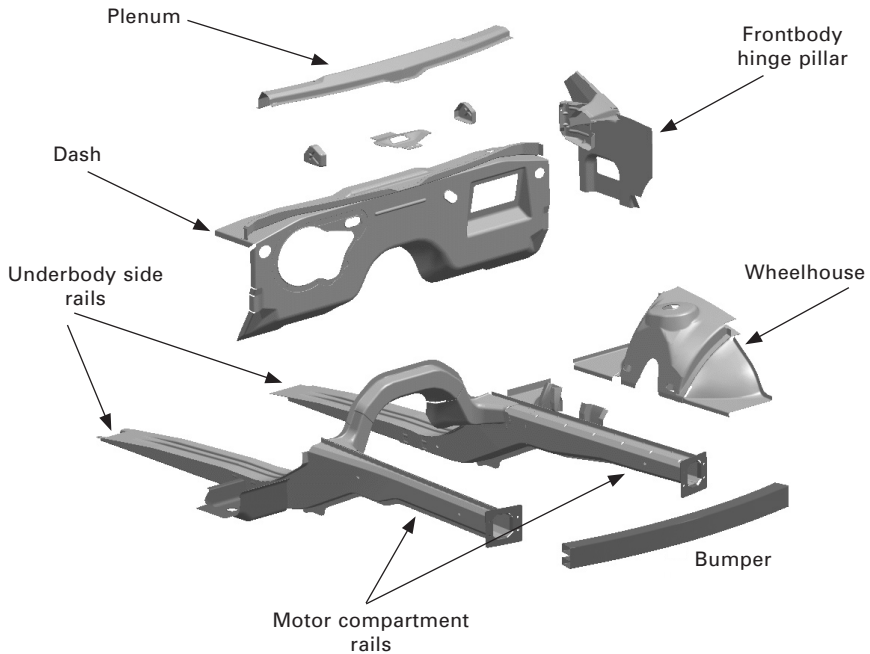


2.18 Simplified vehicle structure.

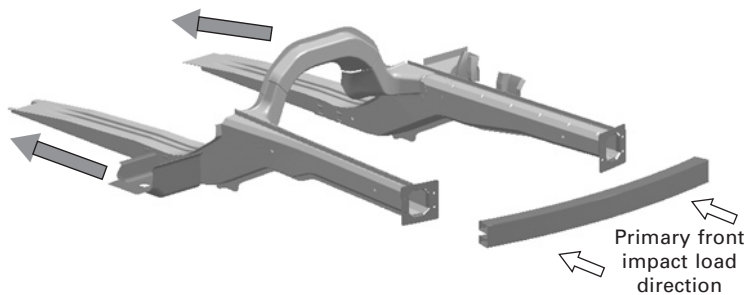
A typical front end structure is shown in Fig. 2.19. This structure consists of the primary load carrying members: bumper, motor compartment rails and underbody side rails. Additional parts consist of the wheelhouse, dash, plenum and front body hinge pillar. While these parts are important to the overall vehicle structure and do contribute to energy absorption, the primary load path for energy from a front end collision is through the bumper, to the motor compartment rails, the engine cradle (not shown) and underbody side rails as shown in Fig. 2.20.

In this simplified view, the bumper bar experiences the initial load of impact and transfers load to the motor compartment rails; any remaining energy is transferred to the underbody side rails. The function of the bumper bar is to take the high loads from impact and, to the extent possible, transfer those loads to the motor compartment rails. The bumper bar is designed to resist deformation, and therefore is made from very high strength steel. Steels with high tensile strength are preferred for the bumper, so the highest strength dual phase steels and martensitic steels are generally preferred. Roll forming these steels to the proper shape is an effective and low cost manufacturing process.

In contrast, the role of the motor compartment rails is to absorb energy and reduce the overall amount of energy transferred to the occupants. In order to absorb significant amounts of energy, the rails are designed to undergo significant, but controlled, deformation. Traditionally, motor compartment rails have been manufactured from conventional high strength steels, with precipitation hardened and carbon–manganese steels of around 300–350 MPa yield strength being very common. The ability for dual phase steels to absorb significantly higher energies than conventional steels at the same yield strength has led to these steels becoming more common in this application. Dual phase steel with a tensile strength of 590 MPa and a yield strength of

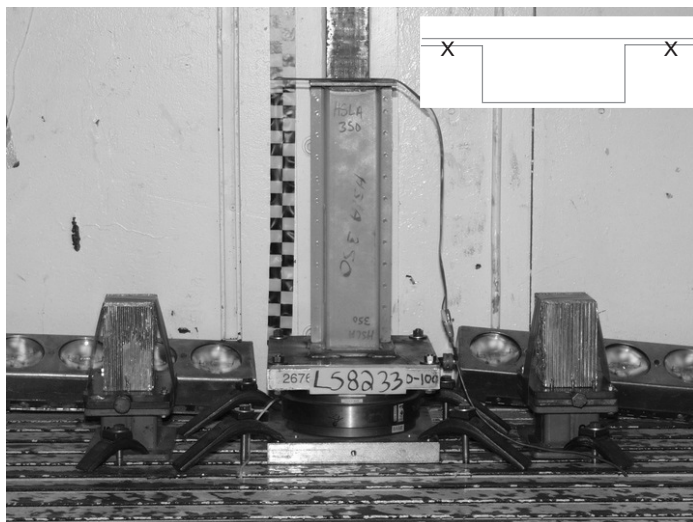


2.19 Front end structure.



2.20 Front end structure load direction.

340 MPa, commonly referred to as dual phase 600, or just DP600, has been successfully used in the manufacturing of motor compartment rails and is now in full production by a number of vehicle manufacturers from Europe, Asia and North America. With proper designs, DP800 grades have demonstrated their ability to carry even higher loads and also show great promise in these types of applications. In order to absorb the most energy, engineers commonly try to design these rails to crush like an accordion. That is, they want the rails to form folds as they crush axially, which maximizes the amount of absorbed energy. In Fig. 2.21, a rail section before and after axial crush is



(a)



(b)

2.21 Axial crush of a motor compartment rail section (a) motor compartment section before crush testing (b) motor compartment section after crush testing.

shown. In the lower photograph, the folds in the rail after testing are clearly evident in the circled area. These folds absorb significant amounts of energy from bending and unbending during deformation and can be effectively computer modeled. As previously mentioned, simulations and testing have shown that dual phase steels absorb more energy than conventional high strength steels. For equivalent yield strengths at approximately 340 MPa, the corresponding dual phase steel at 590 MPa tensile strength will absorb

10–15% more energy than a corresponding microalloyed steel at 410 MPa yield tensile strength (Yan *et al.*, 2005). Advantages such as these are key enablers for lightweighting automotive structures.

The underbody side rails in Figs. 2.19 and 2.20, in contrast to the motor compartment rails, are intended to resist buckling. This is important because these rails are directly under the passenger compartment where deformation is not desirable. Maintaining the passenger space with as little deformation as possible is highly desirable and is a key strategy to prevent significant injury. This concept is referred to in the industry as the ‘safety cage’, or an area around the passengers in which most of the structure is designed for protecting the interior volume of the vehicle and reducing the potential for serious injury.

Nowhere in the vehicle is the concept of the ‘safety cage’ more evident than in the side structure of the vehicle. In the side structure, as shown in Fig. 2.22, there is very little or no available crush space to absorb energy without intruding on the passenger compartment. In side impact, significant intrusion into this safety zone for the passenger is something that automotive designers try to limit. This area is so critical for passenger safety that in many regions around the world, regulators and safety groups have adopted standards to measure vehicle performance against side intrusion.

The complexity of the body side structure and the number of parts and subsystems that need to function together as a complete system are evident from the diagram. The process of designing the side structure, materials selection and tuning the performance of the subsystem such that it provides the proper performance is extremely difficult and requires a team of very experienced and talented engineers. While there is no way to perform an adequate review of side structure design and load management in a book such as this, a high level review of the major loads and potential material selection philosophies is possible.

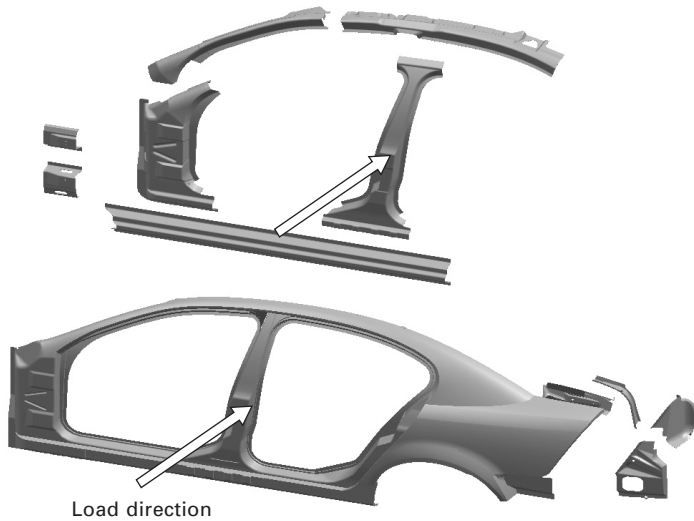
The load direction in side impact is principally through the center pillar of the vehicle, or B-pillar as it is commonly called. In contrast, the outer ‘skin’ of a vehicle, which is shown in Fig. 2.23, is primarily comprised of very thin, low carbon and bake hardenable steels and, in most cases, is not a major contributor to the overall structure of the vehicle.

However, the parts that comprise the inner structure of the vehicle: the B-pillar outer reinforcement, the rocker outer and the roof rails, are the major load carrying members. As mentioned earlier, it is the function of the side structure to oppose the crash force and to not significantly deform such that the passenger space inside the vehicle is compromised. As a result, these types of parts should be made of the highest strength steels that are manufacturable into the shapes that are required. In particular, the B-pillar outer reinforcement and the rocker outer are the two members that carry the highest loads and are arguably the most important members for side



2.22 Bodyside structure.

impact. Since these parts are designed to resist crushing or to crush only in pre-determined areas, for all the reasons previously discussed, they are made of the highest strength that can be formed into the necessary shapes. For the B-pillar outer reinforcement, the highest strength steel is martensite, but forming martensitic steels at room temperature would be impossible for the shapes that are common to these types of parts. As a result, these parts are more frequently being made from hot stamped boron steel. With this process, the tensile strength of the final part is commonly around 1400 MPa, with a corresponding yield strength close to 1000 MPa. From a performance perspective, when high loads need to be managed and deformation must be



2.23 Load direction in side impact.

limited, hot stamped parts are generally considered the best option from a mass and performance perspective.

The roof rails also play an important role in side impact. As force is transferred from the B-pillar on impact, the loads are transferred to the rocker and to the roof side rails. Significant intrusion into the upper passenger compartment would compromise headspace and cause significant potential for occupant injury. As a result, press hardened steels need to be considered as possible materials in this type of application as well. This area is so critical that automotive manufacturers have been incorporating side curtain airbags in a number of vehicles to help protect the passenger from severe trauma.

However, there are many more nuances to side structure design than the simple analysis provided above. There are strategies designed to modify materials and section strength in these areas such that more load is transferred into the underbody and away from the upper side structure. This lowers the potential force that can be transferred to an occupant's head and thorax, and transfers that load into the auto's underbody, where it can be harmlessly absorbed by crushing other less critical components. In such a strategy, the designs and materials for these components will be adjusted to move the loads to areas where they present less danger to vehicle occupants.

In addition to the side structure, the roof structure, as previously shown in Fig. 2.22, also is utilized in side impacts where the force is high enough to travel into the upper vehicle structure. Here, forces are transferred from the B-pillar reinforcement to the roof side rails, and ultimately, if loads are high enough, the center roof bow can come under load. In some designs, this roof bow is being designed with high strength steels in order to support the

roof side rails and to ultimately transfer load to the other side of the vehicle and away from the primary load path.

There are additional load paths that can be important in some crash events. For rear crashes, the rear bumper and longitudinal rails perform much the same function as the front motor compartment rails. These rear rails perform double duty in that they not only protect the passengers, but they also protect the fuel tank from high loads, deformation, and ultimately, from the potential loss of fuel. In the case of a rollover, the upper and side structures provide protection just as they do in side impacts, except that the loading directions are very different from the side impact events. The high strength roof side rails and B-pillars prevent collapse of the roof and protect interior passenger space.

2.6 Conclusion

The complexities facing an automotive engineer are daunting. The difficulties of designing the parts of a vehicle to function together to meet the myriad of requirements that modern vehicles must meet is extremely complex. Because of this, the overall potential for success of a vehicle architecture is determined far before the first parts are made and the first prototype vehicle is assembled. Architectural design, energy management and efficient part designs are the cornerstones of lightweight, efficient designs. However, to optimize a design, proper material selection is necessary for the part and the vehicle that it is a component of, in order for it to function to its optimum design capability. It has been estimated that the weight reduction potential through material substitution, based on some work in 1980 (Hsia and Kidd, 1980), was in the range of 10–30%. These numbers are probably still valid given the continual advancements in steel development.

While the mass savings potential by switching from steel to aluminum used to be in the area of 50%, with optimum designs and properly using the first generation of steels, that number is now far less than that with the currently available AHSS. There are a number of design examples where an efficient steel design nearly matches an aluminum design for the same part function, and this can be accomplished with much lower cost than the ‘lightweight metal’ alternatives. In the end, all materials – steel, aluminum, magnesium, cast iron and composites – have attributes that can, and should, be utilized to their fullest. To do less is to produce products that are not optimized and may not use our precious resources as effectively as they should. To that end, the latest generation of advanced high strength steels, and the new materials that are yet to be developed, will take automotive design to the next level and beyond.

The process of designing vehicle architecture is very complex and time consuming, and as such is way beyond the scope of this chapter. However,

combining the aspects of material selection, energy management in vehicle architecture, and joining and manufacturing considerations such as have been presented, gives the aspiring engineer a good introduction into the world of engineering for optimum lightweight automotive structures.

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