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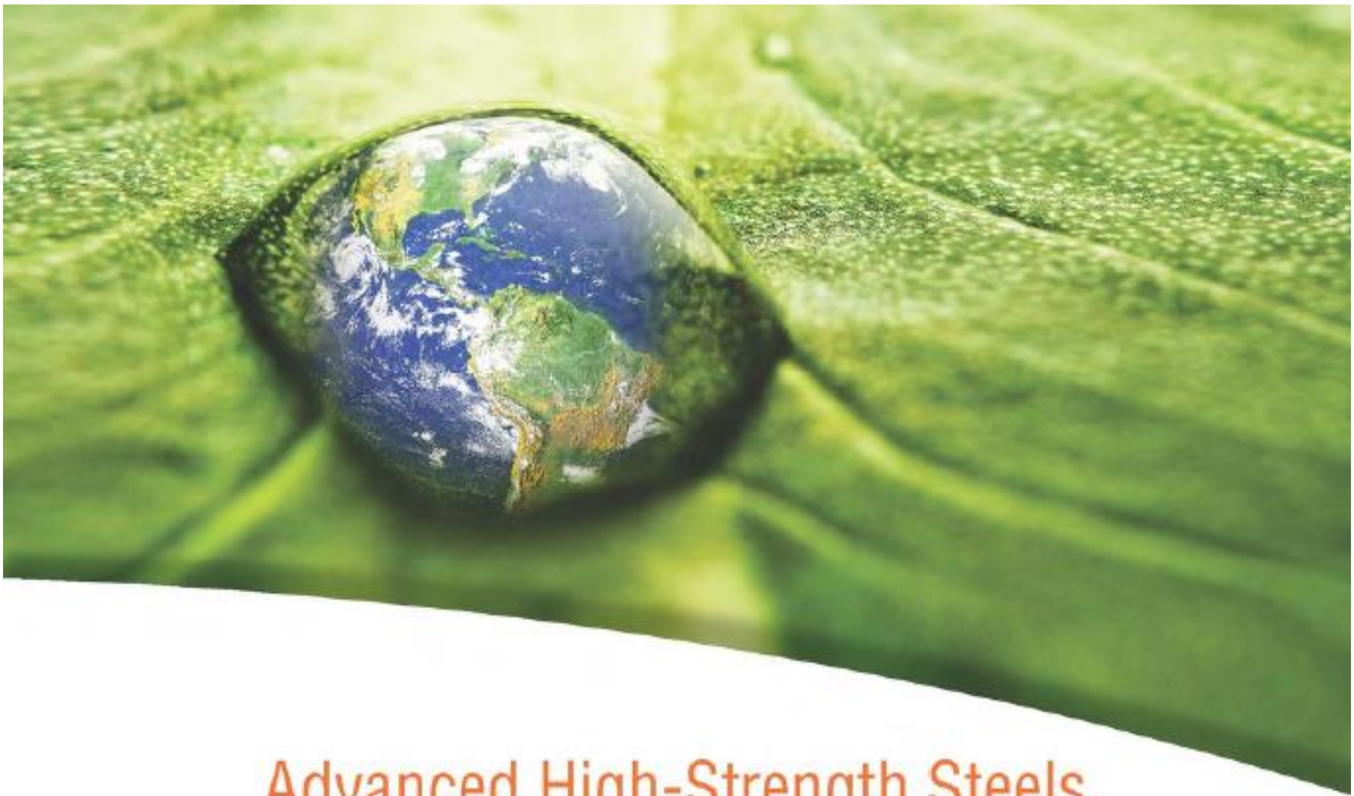


Advanced High-Strength Steels Application Guidelines Version 6.0

Technical Editors:

Stuart Keeler, Sc.D. Mechanical Metallurgy
Menachem Kimchi, M.Sc. Welding Engineering
Peter J. Mooney, Managing Director, 3S-Superior Stamping Solutions, LLC

WorldAutoSteel

SECTION 2 – METALLURGY OF AHSS

2.A. Defining Steels

Automotive steels can be classified in several different ways. One is a metallurgical designation providing some process information. Common designations include low-strength steels (interstitial-free and mild steels); conventional HSS, such as bake hardenable and high-strength, low-alloy steels (HSLA); and Advanced High-Strength Steels, or AHSS (for example, dual phase and transformation-induced plasticity steels). Additional higher strength steels for the automotive market include hot-formed, postforming heat-treated steels, and steels designed for unique applications that have improved edge stretch and stretch bending characteristics.

A second classification method important to part designers is strength of the steel. This document will use the general terms HSLA and AHSS to designate all higher strength steels. This classification system has a problem with the on-going development of the many new grades for each type of steel. Therefore, a DP or TRIP steel can have strength grades that encompass two or more strength ranges.

A third classification method presents various mechanical properties or forming parameters of different steels, such as total elongation, work hardening exponent (n-value), or hole expansion ratio (lambda - λ). As an example, Figure 2.A-1 compares total elongations – a steel property related to formability – to the tensile strength for the current types of steel. These properties are important for press shop operations and virtual forming analyses.

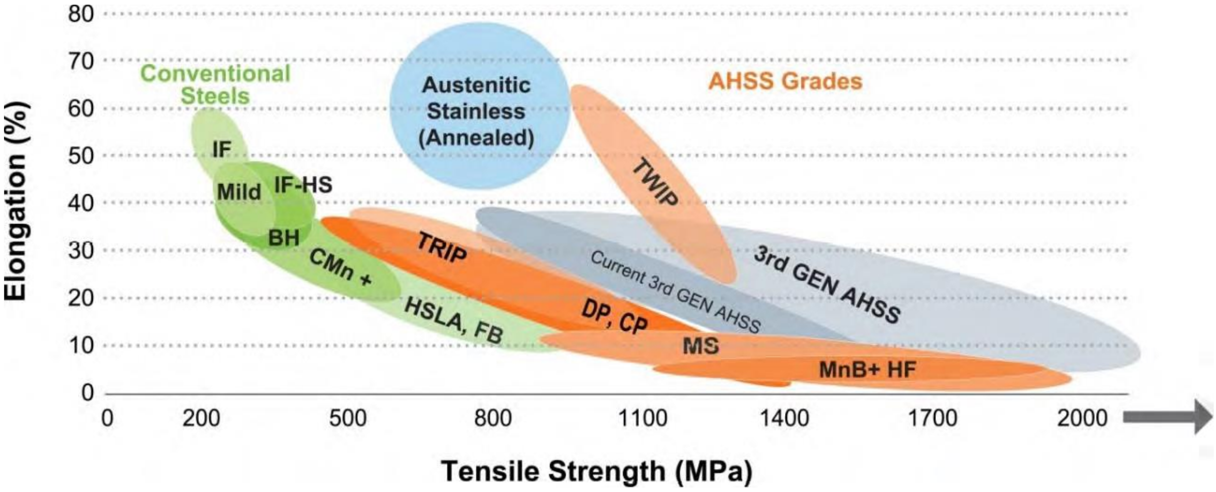


Figure 2.A-1: Global Formability Diagram for Today's AHSS Grades (includes comparison of traditional low-strength and high-strength steels).[W-1]

The principal difference between conventional HSLA steels and AHSS is their microstructure. Conventional HSLA steels are single-phase ferritic steels with a potential for some pearlite in C-Mn steels. AHSS are primarily steels with a multiphase microstructure containing one or more phases other than ferrite, pearlite, or cementite - for example martensite, bainite, austenite, and/or retained austenite in quantities sufficient to produce unique mechanical properties. Some types of AHSS have a higher strain hardening capacity resulting in a strength-ductility balance superior to conventional steels. Other types have ultra-high yield and tensile strengths and show a bake hardening behavior.

Since the terminology used to classify steel products varies considerably throughout the world, this document uses the WorldAutoSteel format to define the steels. Each steel grade is identified by metallurgical type, minimum yield strength (in MPa), and minimum tensile strength (in MPa). As an example, DP 500/800 means a dual phase steel with 500 MPa minimum yield strength and 800 MPa minimum ultimate tensile strength. The ULSAB-AVC programme[W-1] first used this classification system.

2.B. Metallurgy of AHSS

Manufacturers and users of steel products generally understand the fundamental metallurgy of conventional low- and high-strength steels. Section 2.B. provides a brief description of these common steel types. Since the metallurgy and processing of AHSS grades are somewhat novel compared to conventional steels, they are described here to provide a baseline understanding of how their remarkable mechanical properties evolve from their unique processing and structure. All AHSS are produced by controlling the chemistry and cooling rate from the austenite or austenite plus ferrite phase, either on the runout table of the hot mill (for hot-rolled products) or in the cooling section of the continuous annealing furnace (continuously annealed or hot-dip coated products). Research has provided chemical and processing combinations that have created many additional grades and improved properties within each type of AHSS.

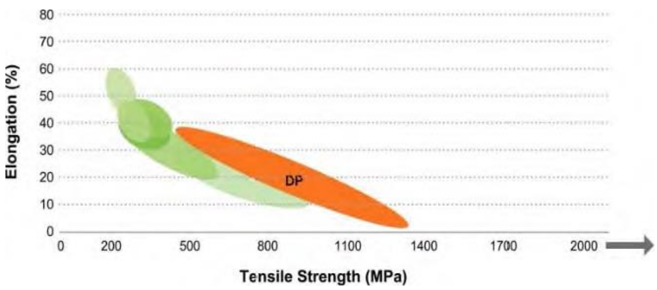
2.B.1. Dual Phase (DP) Steel

DP steels consist of a ferritic matrix containing a hard martensitic second phase in the form of islands.

Increasing the volume fraction of hard second phases generally increases the strength. DP (ferrite plus martensite) steels are produced by controlled cooling from the austenite phase (in hot-rolled products) or from the two-phase ferrite plus austenite phase (for continuously annealed cold-rolled and hot-dip coated products) to transform some austenite to ferrite before a rapid cooling transforms the remaining austenite to martensite. Due to the production process, a small amount of other phases (bainite and retained austenite) may be present.

Depending on the composition and process route, steels requiring enhanced capability to resist cracking on a stretched edge (as typically measured by hole expansion capacity) can have a microstructure containing significant quantities of bainite.

Figure 2.B-1 shows a schematic microstructure of DP steel, which contains ferrite plus islands of martensite. The soft ferrite phase is generally continuous, giving these steels excellent ductility. When these steels deform, strain is concentrated in the lower-strength ferrite phase surrounding the islands of martensite, creating the unique high initial work-hardening rate (n-value) exhibited by these steels. Figure 2.B-2 is an actual micrograph showing the ferrite and martensite constituents.



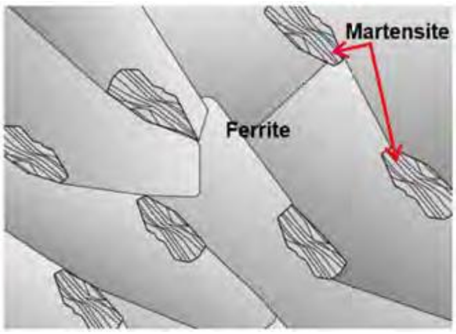


Figure 2.B-1: Schematic shows islands of martensite in a matrix of ferrite.

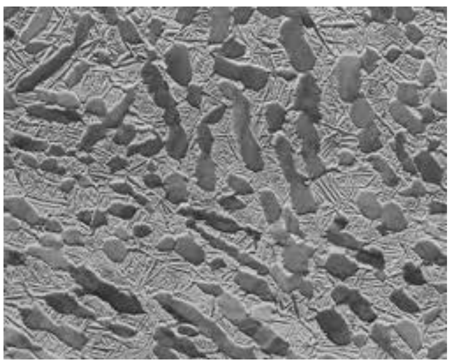


Figure 2.B-2: Micrograph of DP steel.

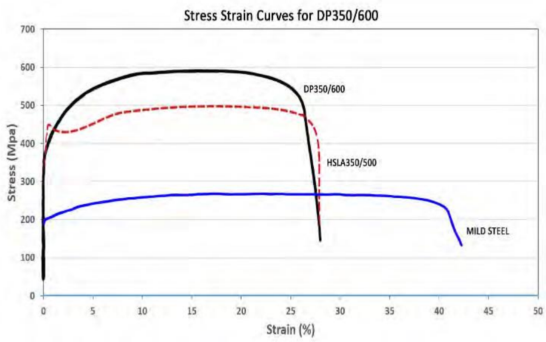


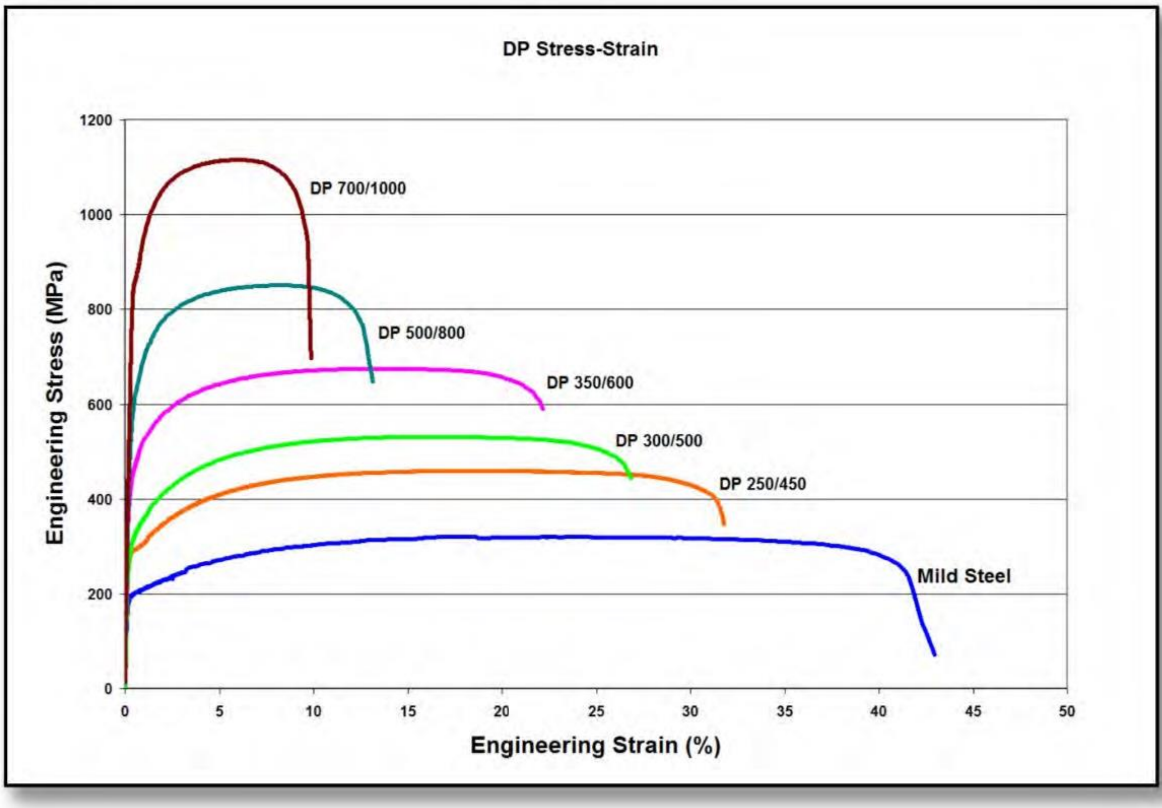
Figure 2.B-3: The DP 350/600 with higher TS than the HSLA 350/450[K-1]

The work hardening rate plus excellent elongation creates DP steels with much higher ultimate tensile strengths than conventional steels of similar yield strength. Figure 2.B-3 compares the engineering stress-strain curve for HSLA steel to a DP steel curve of similar yield strength. The DP steel exhibits higher initial work hardening rate, higher ultimate tensile strength, and lower YS/TS ratio than the HSLA with comparable yield strength. Additional engineering and true stressstrain curves for DP steel grades are located in Figure 2.B-4.

DP and other AHSS also have a bake hardening effect that is an important benefit compared to conventional higher strength steels. The bake hardening effect is the increase in yield strength resulting from elevated temperature aging (created by the curing temperature of paint bake ovens) after pre-straining (generated by the work hardening due to deformation during stamping or other manufacturing process). The extent of the bake hardening effect in AHSS depends on an adequate amount of forming strain for the specific chemistry and thermal history of the steel. Additional bake hardening information is located in Section 2.D.8. – Bake Hardening and Aging.

In DP steels, carbon enables the formation of martensite at practical cooling rates by increasing the hardenability of the steel. Manganese, chromium, molybdenum, vanadium, and nickel, added individually or in combination, also help increase hardenability. Carbon also strengthens the martensite as a ferrite solute strengthener, as do silicon and phosphorus. These additions are carefully balanced, not only to produce unique mechanical properties, but also to maintain the generally good resistance spot welding capability. However, when welding the higher strength grades (DP 700/1000 and above) to themselves, the spot weldability may require adjustments to the welding practice. Examples of current production grades of DP steels and typical automotive applications are shown below:

DP 300/500	Roof outer, door outer, body side outer, package tray, floor panel
DP 350/600	Floor panel, hood outer, body side outer, cowl, fender, floor reinforcements
DP 500/800	Body side inner, quarter panel inner, rear rails, rear shock reinforcements
DP 600/980	Safety cage components (B-pillar, floor panel tunnel, engine cradle, front sub-frame package tray, shotgun, seat),
DP 700/1000	Roof rails
DP 800/1180	B-pillar upper



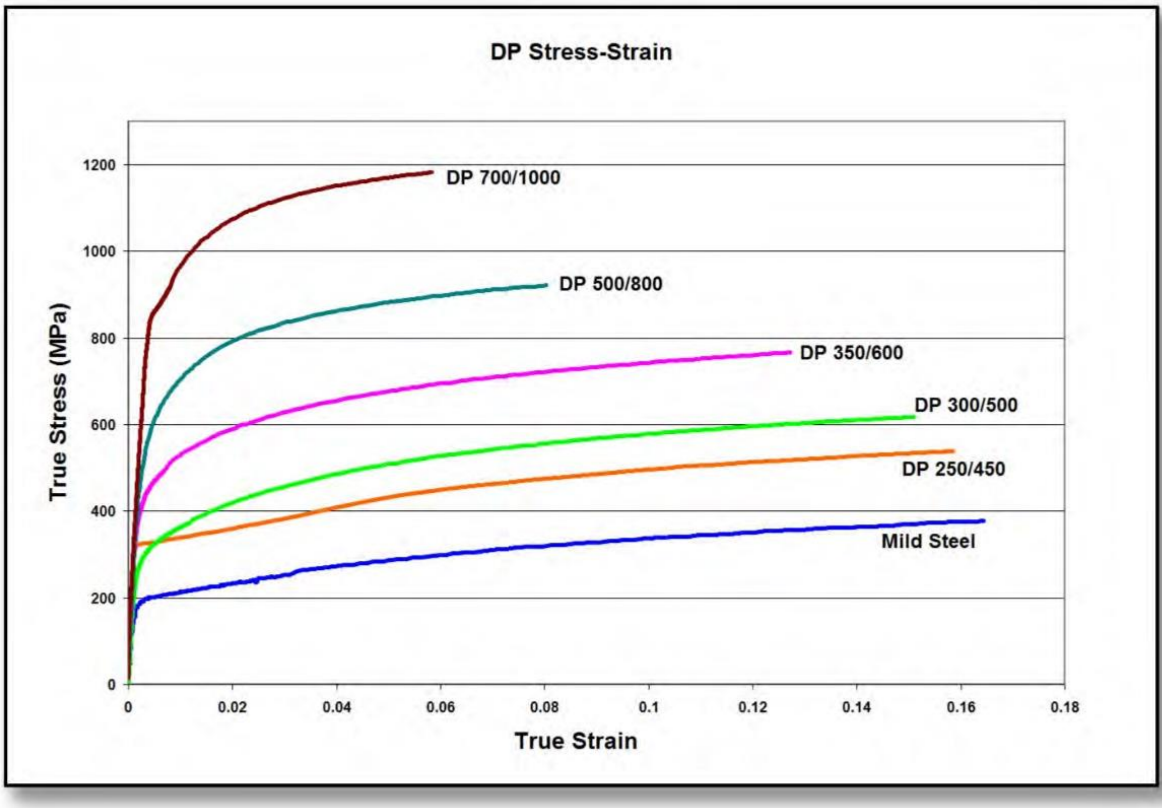
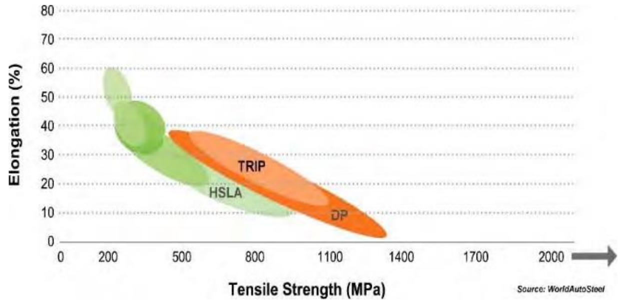


Figure 2.B-4: Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curves for a series of DP steel grades.[S-5, V-1]
Sheet thicknesses: DP 250/450 and DP 500/800 = 1.0mm. All other steels were 1.8-2.0mm.

2.B.2. Transformation Induced Plasticity (TRIP) Steel

The microstructure of TRIP steels is retained austenite embedded in a primary matrix of ferrite. In addition to a minimum of five volume percent of retained austenite, hard phases such as martensite and bainite are present in varying amounts. TRIP steels typically require the use of an isothermal hold at an intermediate temperature, which produces some bainite. The higher silicon and carbon content of TRIP steels also result in significant volume fractions of retained austenite in the final microstructure. Figure 2.B-5 shows a schematic of TRIP steel microstructure. Figure 2.B-6 is a micrograph of TRIP 690. Figure 2.B-7 compares the engineering stress-strain curve for HSLA steel to a DP steel curve of similar yield strength.

During deformation, the dispersion of hard second phases in soft ferrite creates a high work hardening rate, as observed in the DP steels. However, in TRIP steels the retained austenite also progressively transforms to martensite with increasing strain, thereby increasing the work hardening rate at higher strain levels. This is illustrated in Figure 2.B-8, where the engineering stress-strain behavior of HSLA, DP and TRIP steels of approximately similar yield strengths are compared. The TRIP steel has a lower initial work hardening rate than the DP steel, but the hardening rate persists at higher strains where work hardening of the DP begins to diminish. Additional engineering and true stress-strain curves for TRIP steel grades are located in Figure 2.B-9.



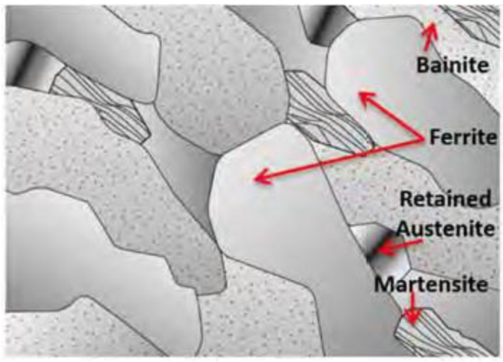


Figure 2.B-5: Bainite and retained austenite are additional phases in TRIP steels

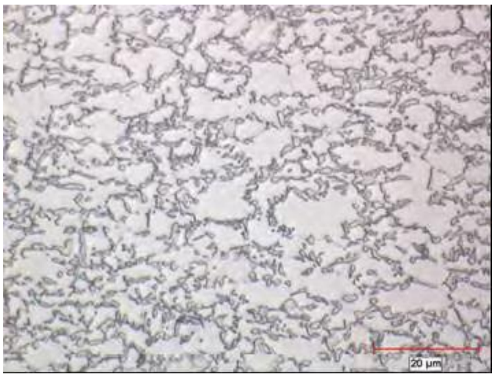


Figure 2.B-6: Micrograph of TRIP 690 steel

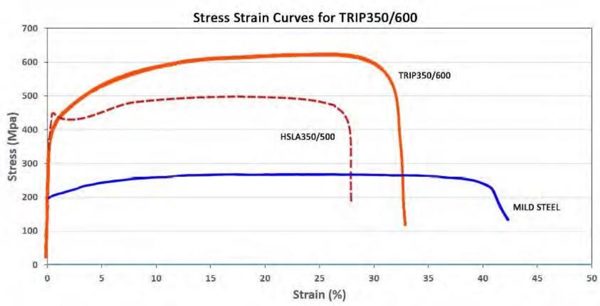


Figure 2.B-7: TRIP 350/600 compared to similar yield strength HSLA.

The work hardening rates of TRIP steels are substantially higher than for conventional HSS, providing significant stretch forming. This is particularly useful when designers take advantage of the high work hardening rate (and increased bake hardening effect) to design a part utilizing the as-formed mechanical properties. The high work hardening rate persists to higher strains in TRIP steels, providing a slight advantage over DP in the most severe stretch forming applications.

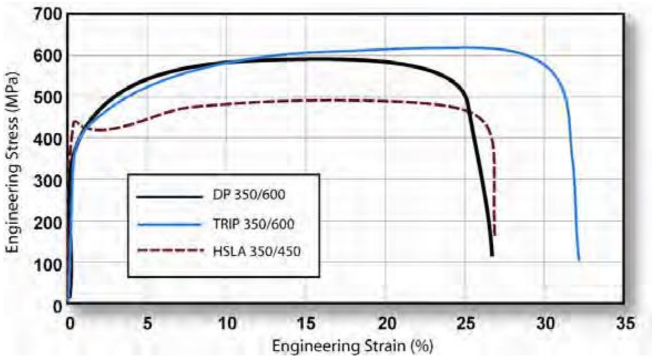


Figure 2.B-8: TRIP 350/600 with a greater total elongation than DP 350/600 and HSLA 350/450[K-1]

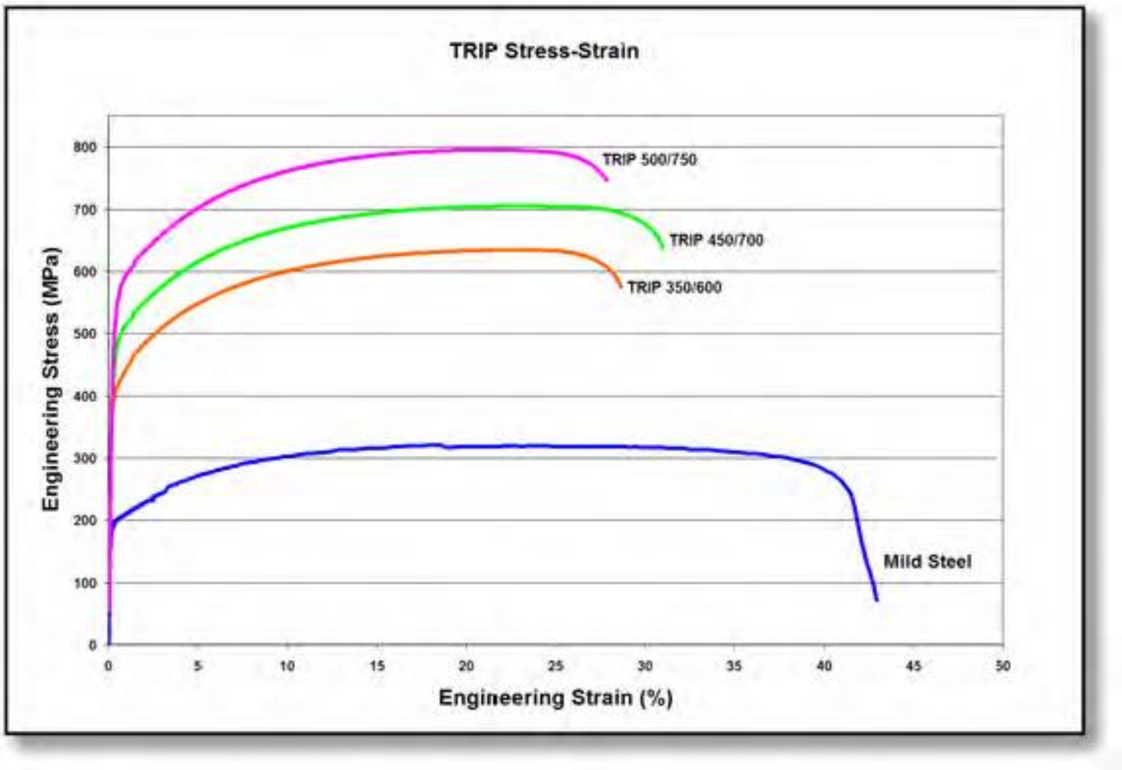
TRIP steels use higher quantities of carbon than DP steels to obtain sufficient carbon content for stabilizing the retained austenite phase to below ambient temperature. Higher contents of silicon and/or aluminium accelerate the ferrite/bainite formation. These elements assist in maintaining the necessary carbon content within the retained austenite. Suppressing the carbide precipitation during bainitic transformation appears to be crucial for TRIP steels. Silicon and aluminium are used to avoid carbide precipitation in the bainite region.

The strain level at which retained austenite begins to transform to martensite is controlled by adjusting the carbon content. At lower carbon levels, the retained austenite begins to transform almost immediately upon deformation, increasing the work hardening rate and formability during the stamping process. At higher carbon contents, the retained austenite is more stable and begins to transform only at strain levels beyond those produced during forming. At these carbon levels, the retained austenite persists into the final part. It transforms to martensite during subsequent deformation, such as a crash event.

TRIP steels therefore can be engineered or tailored to provide excellent formability for manufacturing complex AHSS parts or exhibit high work hardening during crash deformation for excellent crash energy absorption. The additional alloying requirements of TRIP steels degrade their resistance spot-welding behavior. This can be addressed somewhat by modification of the welding cycles used (for example, pulsating welding or dilution welding).

Current production grades of TRIP steels and example automotive applications:

TRIP 350/600	Frame rails, rail reinforcements
TRIP 400/700	Side rail, crash box
TRIP 450/800	Dash panel, roof rails
TRIP 600/980	B-pillar upper, roof rail, engine cradle, front and rear rails, seat frame



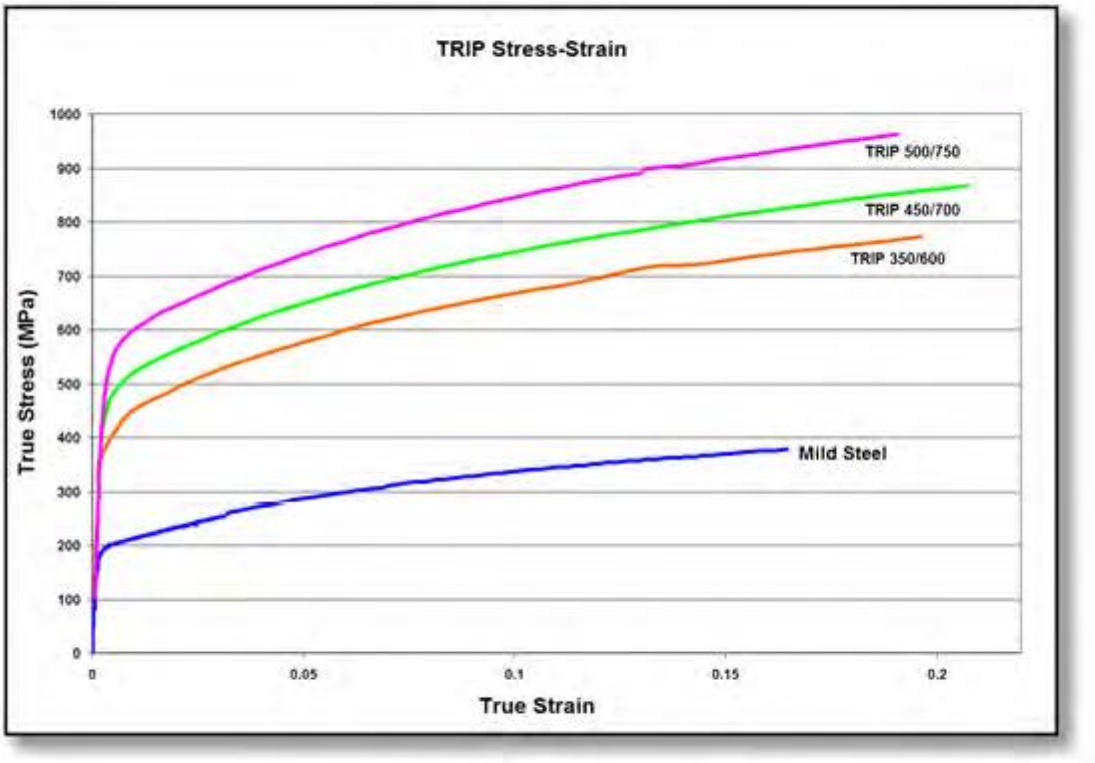
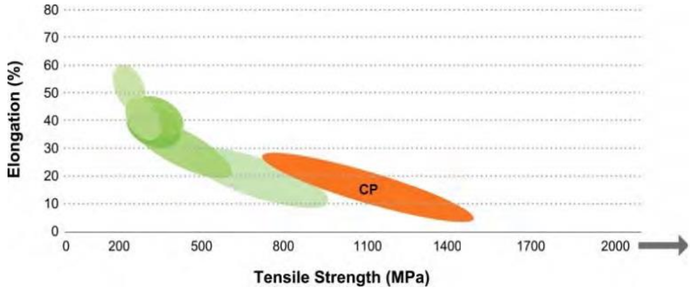


Figure 2.B-9: Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curves for a series of TRIP steel grades.[V-1]
Sheet thickness: TRIP 350/600 = 1.2mm, TRIP 450/700 = 1.5mm,
TRIP 500/750 = 2.0mm, and Mild Steel = approx. 1.9mm

2.B.3. Complex Phase (CP) Steel



CP steels typify the transition to steel with very high ultimate tensile strengths. The microstructure of CP steels contains small amounts of martensite, retained austenite and pearlite within the ferrite/bainite matrix. An extreme grain refinement is created by retarded recrystallization or precipitation of microalloying elements like Ti or Nb. Figure 2.B-10 shows a schematic of CP steel microstructure. Figure 2.B-11 shows the grain structure for hot rolled CP 800/1000. Figure 2.B-12 compares the engineering stress-strain curve for HSLA steel to a CP 1000/1200 steel curve.

In comparison to DP steels, CP steels show significantly higher yield strengths at equal tensile strengths of 800 MPa and greater. CP steels are characterized by high energy absorption, high residual deformation capacity and good hole expansion. Engineering and true stress-strain curves for CP steel grades are located in Figure 2.B-13.

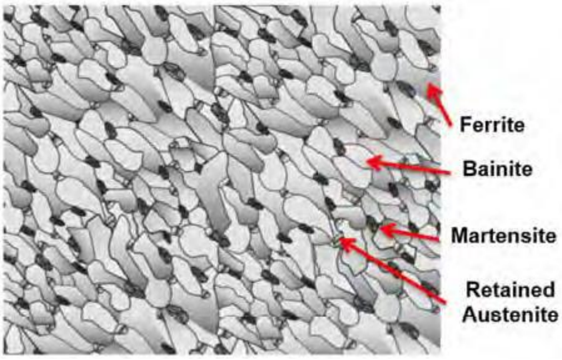


Figure 2.B-10: Schematic of CP steel microstructure.

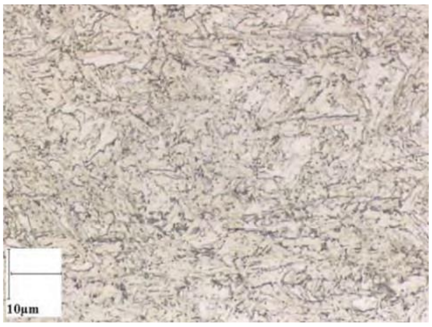


Figure 2.B-11: Micrograph of CP 800/1000 hot rolled steel.

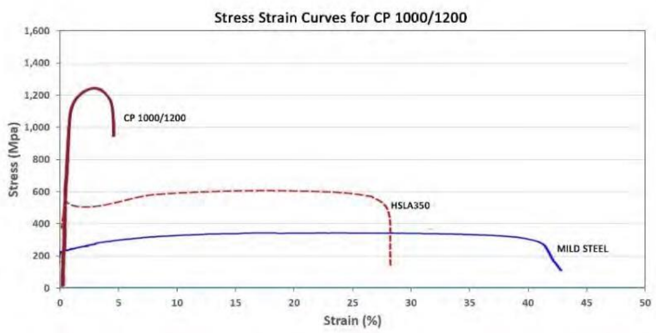
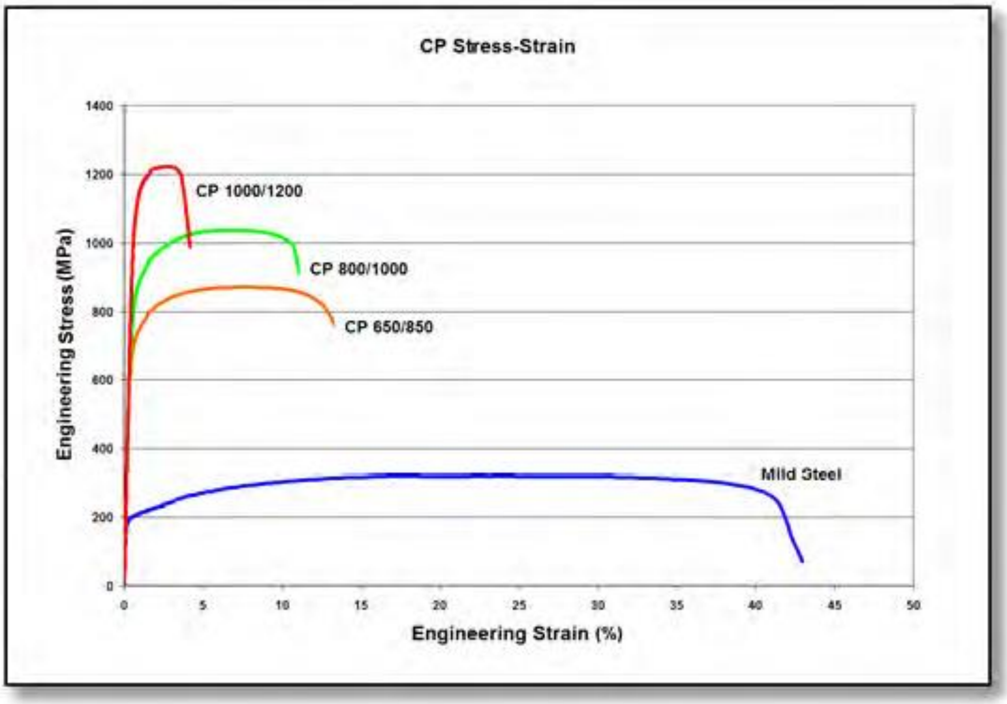


Figure 2.B-12: CP 1000/1200 compared to HSLA.

Current production grades of CP steels and example automotive applications:

CP 600/900	Frame rails, B-pillar reinforcements
CP 680/780	Frame rails, chassis components, transverse beams
CP 750/900	B-pillar reinforcements, tunnel stiffener
CP 800/1000	Rear suspension brackets, fender beam
CP1000/1200	Rear frame rail reinforcements, rocker outer
CP1050/1470	Rocker panels, bumper beams



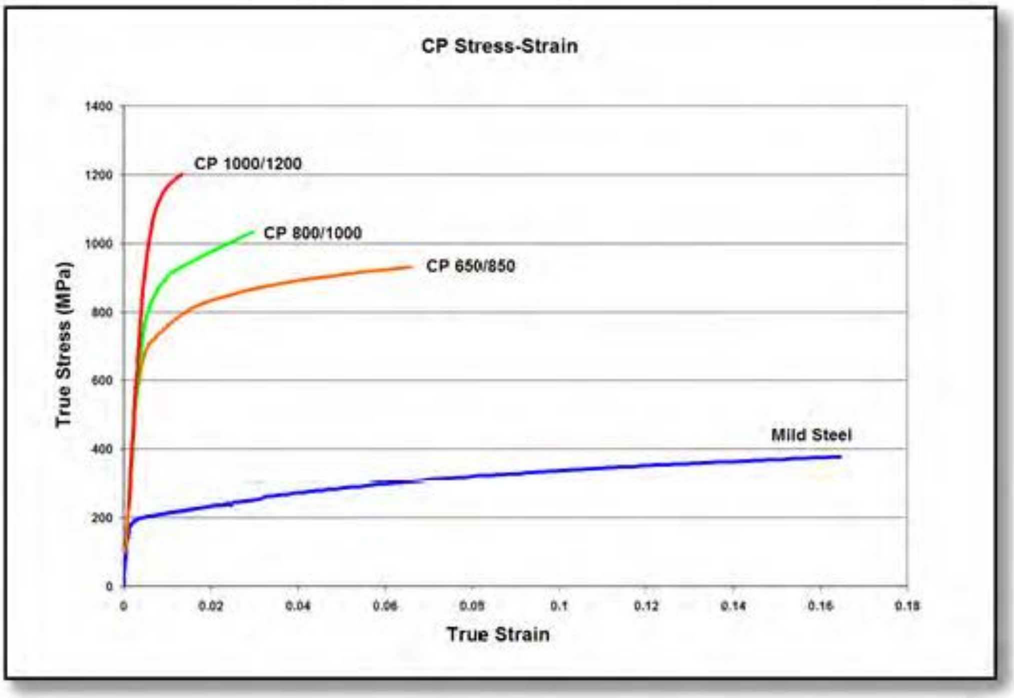
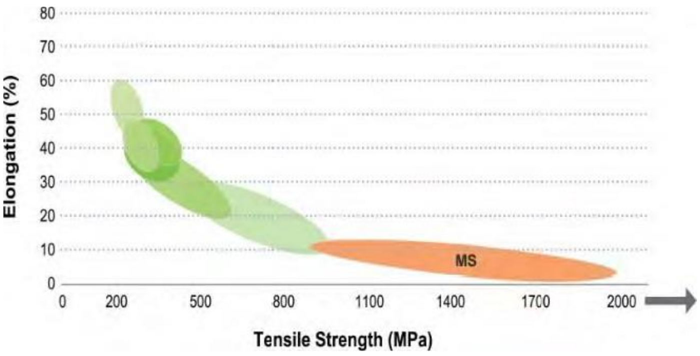


Figure 2.B-13: Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curves for a series of CP steel grades.[V-1] Sheet thickness: CP650/850 = 1.5mm, CP 800/1000 = 0.8mm, CP 1000/1200 = 1.0mm, and Mild Steel = approx. 1.9mm.

2.B.4. Martensitic (MS) Steel

To create MS steels, the austenite that exists during hot-rolling or annealing is transformed almost entirely to martensite during quenching on the run-out table or in the cooling section of the continuous annealing line. The MS steels are characterized by a martensitic matrix containing small amounts of ferrite and/or bainite (note Figure 2.B-14 and 2.B-15). Within the group of multiphase steels, MS steels show the highest tensile strength level. This structure also can be developed with postforming heat treatment. MS steels provide the highest strengths, up to 1700 MPa ultimate tensile strength. MS steels are often subjected to postquench tempering to improve ductility, and can provide adequate formability even at extremely high strengths. Figure 2.B.-16 shows MS950/1200 compared to HSLA. Engineering and true stress-strain curves for MS steel grades are located in Figure 2.B-17.

Adding carbon to MS steels increases hardenability and strengthens the martensite. Manganese, silicon, chromium, molybdenum, boron, vanadium, and nickel are also used in various combinations to increase hardenability. MS steels are produced from the austenite phase by rapid quenching to transform most of the austenite to martensite.



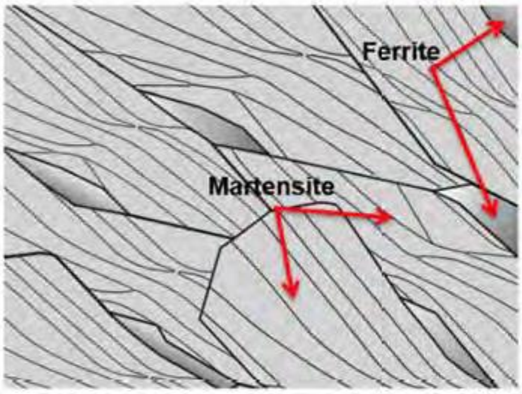


Figure 2.B-14: Schematic of Martensitic steel microstructure.

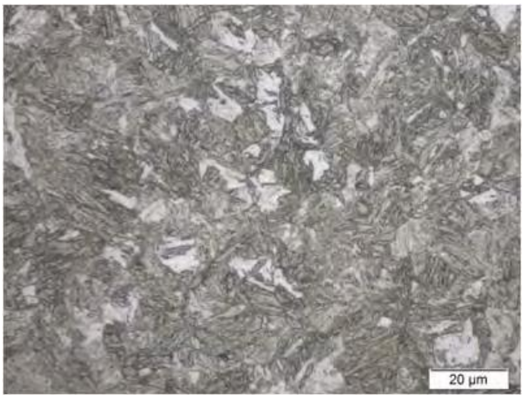


Figure 2.B-15: Microstructure for MS 950/1200.

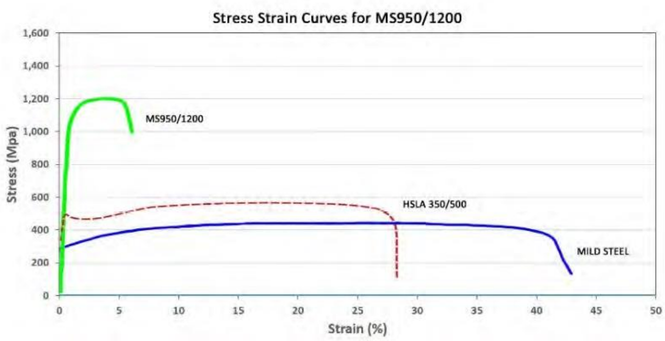


Figure 2.B.-16: MS950/1200 steel compared to HSLA.

Current production grades of MS steels and example automotive applications:

MS 950/1200	Cross-members, side intrusion beams, bumper beams, bumper reinforcements
MS 1150/1400	Rocker outer, side intrusion beams, bumper beams, bumper reinforcements
MS 1250/1500	Side intrusion beams, bumper beams, bumper reinforcements

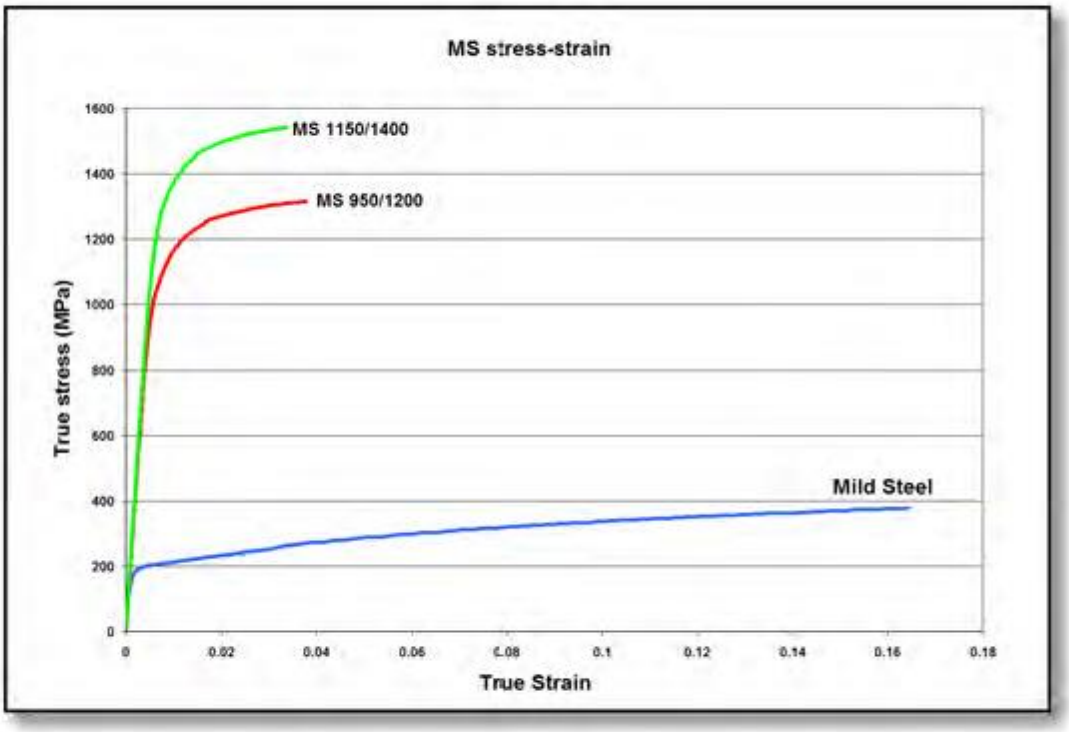


Figure 2.B-17: Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curves for a series of MS steel grades[S-5]. All Sheet thicknesses were 1.8-2.0 mm.

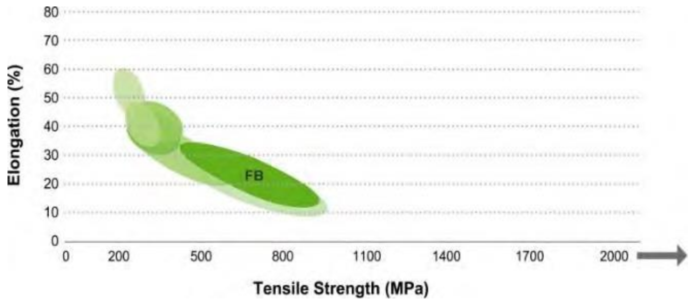
2.B.5. Ferritic-Bainitic (FB) Steel

FB steels sometimes are utilized to meet specific customer application requirements that require Stretch Flangeable (SF) or High Hole Expansion (HHE) capabilities for improved edge stretch capability.

FB steels have a microstructure of fine ferrite and bainite. Strengthening is obtained by both grain refinement and second phase hardening with bainite. Figure 2.B-18 is a schematic of Ferritic-Bainitic steel micro-structure. Figure 2.B-19 is a micrograph of FB 450/600. FB steels are available as hot-rolled products.

The primary advantage of FB steels over HSLA and DP steels is the improved stretchability of sheared edges as measured by the hole expansion test (λ). Compared to HSLA steels with the same level of strength, FB steels also have a higher strain hardening exponent (n-value) and increased total elongation. Figure 2.B.-20 compares FB 450/600 with HSLA 350/500 steel. Engineering and true stress-strain curves for FB steel grades are located in Figure 2.B.21.

Because of their good weldability, FB steels are considered for tailored blank applications. These steels also are characterized by both good crash performances and good fatigue properties.



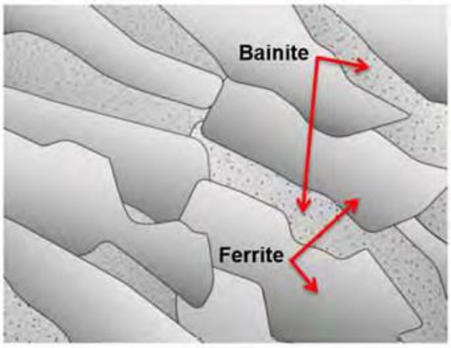


Figure 2.B-18: Schematic of Ferritic-Bainitic steel microstructure.

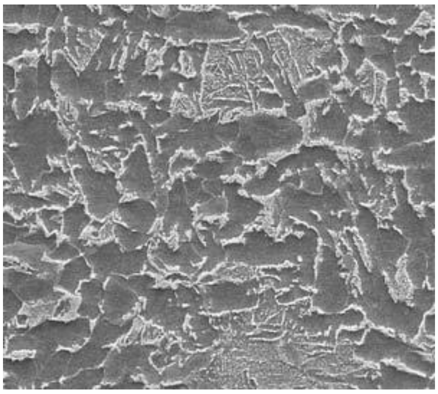


Figure 2-19: Micrograph of FB 450/600.

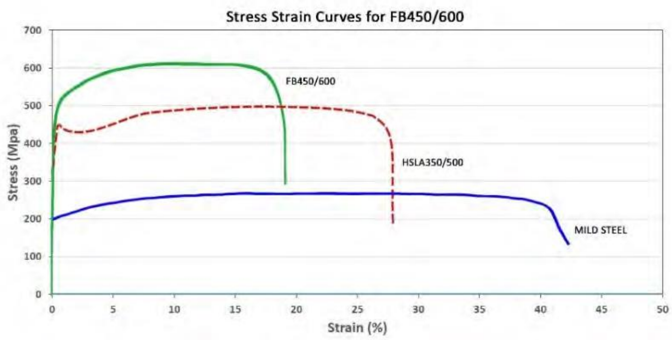
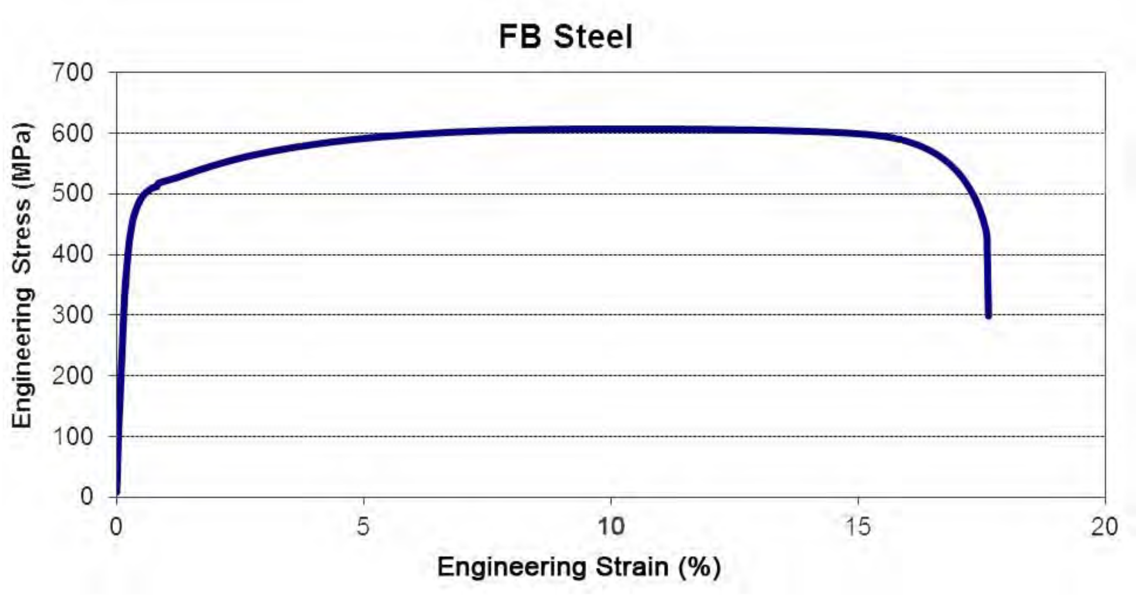


Figure 2.B-20 FB 450/600 compared to HSLA 350/500 steel.

Current production grades of FB steels and example automotive applications:

FB 330/450	Rim, brake pedal arm, seat cross member, suspension arm
FB 450/600	Lower control arm, rim, bumper beam, chassis parts, rear twist beam



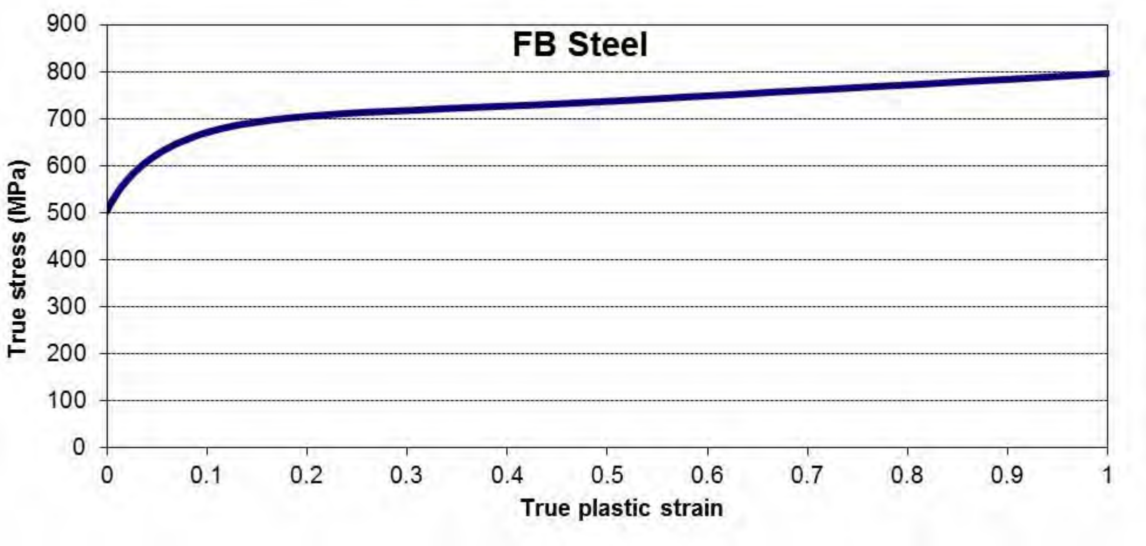
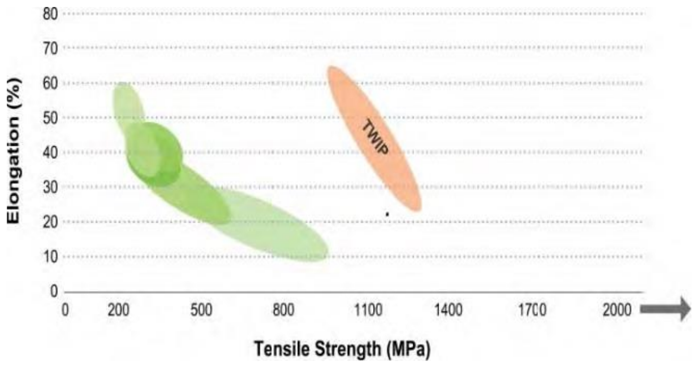


Figure 2.B-21: Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curve for FB 450/600.[T-10]

2.B.6. Twinning-Induced Plasticity (TWIP) Steel

TWIP steels[C-4] have a high manganese content (17-24%) that causes the steel to be fully austenitic at room temperatures. A large amount of deformation is driven by the formation of deformation twins. This deformation mode leads to the naming of this steel class. The twinning causes a high value of the instantaneous hardening rate (n-value) as the microstructure becomes finer and finer. The resultant twin boundaries act like grain boundaries and strengthen the steel. Figure 2.B.-22 provides a schematic of TWIP steel. Figure 2.B.-23 shows the as annealed microstructure for a TWIP steel.

TWIP steels combine extremely high strength with extremely high stretchability. The n-value increases to a value of 0.4 at an approximate engineering strain of 30% and then remains constant until both uniform and total elongation reach 50%. The tensile strength is higher than 1000 MPa. Figure 2.B.-24 compares TWIP 750/1000 to HSLA steel. Engineering and true stress-strain curves for TWIP steel grades are located in Figure 2.B-25.



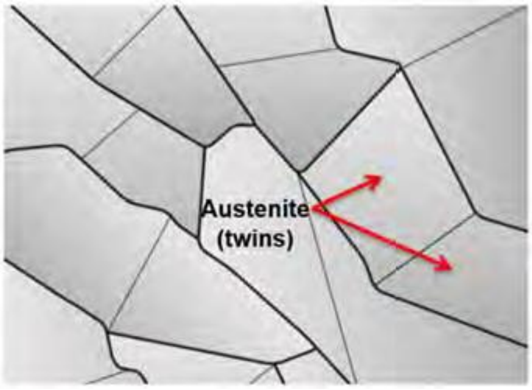


Figure 2.B.-22: Schematic of TWIP steel.

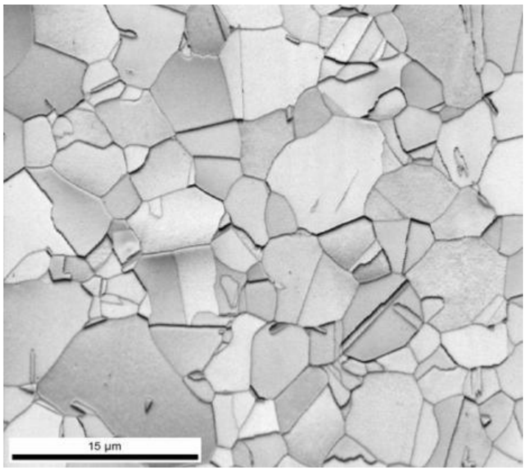


Figure 2.B-23: Photomicrograph of TWIP steel as annealed.

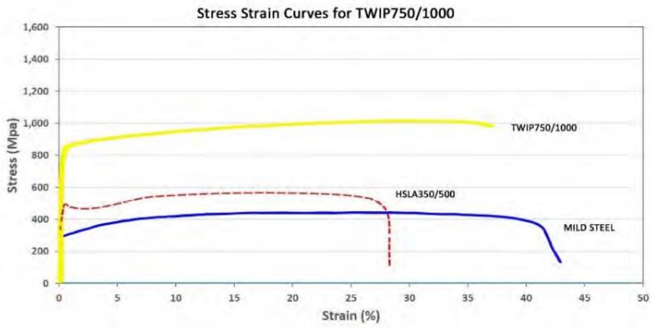


Figure 2.B-24: TWIP 750/1000 compared to HSLA steel.

Current production grades of TWIP steels and example automotive applications:

TWIP 500/900	A-Pillar, wheelhouse, front side member
TWIP 500/980	Wheel, lower control arm, front and rear bumper beams, B-pillar, wheel rim
TWIP 600/900	Floor cross-member, wheelhouse
TWIP 750/1000	Door impact beam
TWIP 950/1200	Door impact beam

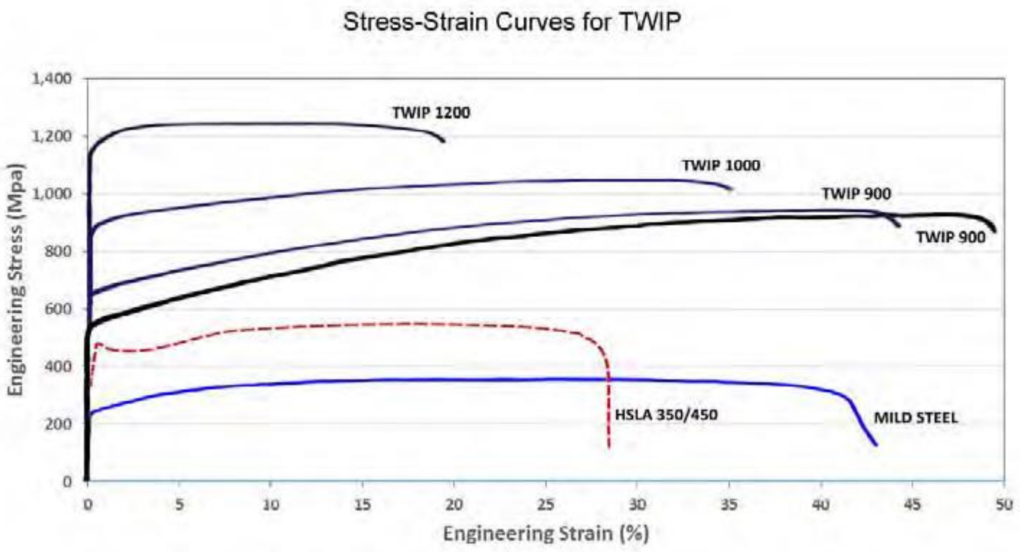
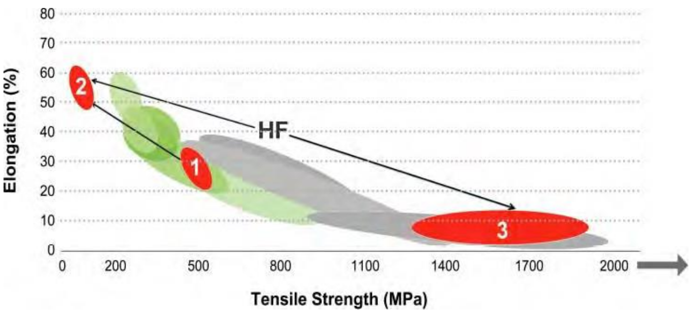


Figure 2.B-25: Engineering stress-strain curve for TWIP[P-2]

2.B.7. Hot-Formed (HF) Steel



The implementation of press-hardening applications and the utilization of hardenable steels are promising alternatives for optimized part geometries with complex shapes and no springback issues. Boron-based hot-forming steels (between 0.001% and 0.005% boron) have been in use since the 1990s for body-in-white construction. A typical minimum temperature of 850 °C must be maintained during the forming process (austenitization) followed by a cooling rate greater than 50 °C/s to ensure that the desired mechanical properties are achieved. Two types of press-hardening or hotforming applications are currently available:

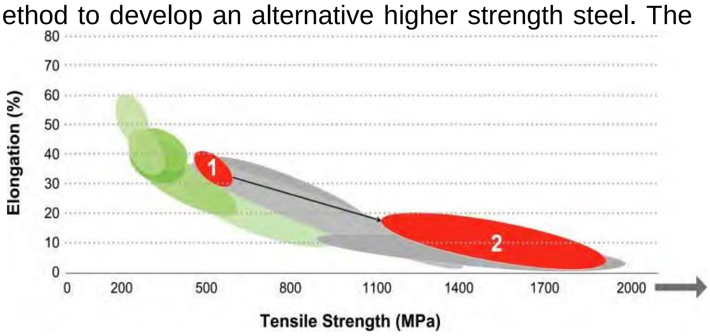
- Direct Hot-Forming
- Indirect Hot-Forming

During Direct Hot-Forming, all deformation of the blank is done in the high temperature austenitic range followed by quenching. Indirect Hot-Forming preforms the blank at room temperature to a high percentage of the final part shape followed by additional high temperature forming and quenching. The final microstructure of HF steel is similar to Martensite. Stress-strain curves after quenching are similar to martensitic (MS) steels shown in Figure 2-13.

Additional information on Hot-Forming is located in Section 3.B.5 – Hot-Forming Modes. Current production grades of HF steels and automotive applications:

HF 340/480	As-received room temperature
HF 1050/1500	Heat treated after forming A-pillar, B-pillar, cross beam
HF 1200/1900	Heat treated after forming

2.B.8. Post-Forming Heat-Treatable (PFHT) Steel



Post-forming heat treatment is a general method to develop an alternative higher strength steel. The major issue holding back widespread implementation of HSS typically has been maintaining part geometry during and after the heat treatment process. To address distortion problems, the part is fixtured, then heated (via furnace or induction) followed by immediate quenching. This has been a more effective solution for production applications because, the stamping is formed at a lower strength (ellipse 1) and then raised to a much higher strength by heat treatment (ellipse 2).

Another process is air-hardening of alloyed tempering steels that feature very good forming properties in the soft-state (deep-drawing properties) and high strength after heat treatment (air-hardening). Apart from direct application as sheet material, air-hardening steels are suitable for tube welding. These tubes are excellent for hydroforming applications.

A third option is in-die quenching. A version of Indirect Hot-Forming completes all forming of the part at room temperature, heats the part to about 850-900 ºC, and then uses a water cooled die to quench the part to martensite. This process is called Form Hardening.

Current production grades of PFHT steel and example automotive applications:

PFHT 340/480	As-received room temperature
PFHT 1050/1500	Heat treated after forming
PFHT 1200/1900	Heat treated after forming

2.B.9. Special Processed Steels

The microstructures of DP, TRIP and other AHSS have islands or particles of different phases. One example is the martensite islands. When forming steels, these particles cause localization of strain during edge stretching, stretch-bending over tight radii, or other deformation modes whereby strain can localize to generate high peak strains. These steels then are subject to failure at deformations less than that predicted by the properties. Steel companies have been conducting extensive research to develop specialized steels for such applications that minimize the negative effect of these phases or particles.
More information is contained in Section 3.B.3 – Deformation Limits.

2.B.10. Evolving AHSS Types

In response to automotive demands for additional AHSS capabilities, research laboratories in the steel industry and academic institutions continue to search for new types of steel or modification of existing types. The goal of the primary research (Enhanced Multiphase Products) is improving formability for a given strength range while reducing the cost and welding problems associated with steels having a high percent of austenite. Other examples of these developing steels are ultrafine (nano) grain, low density, and high Young's modulus steels.

As an example, the Figure 2.B-26 shows multiple pathways with different AHSS grades, which are being modified to achieve vastly improved ductility.

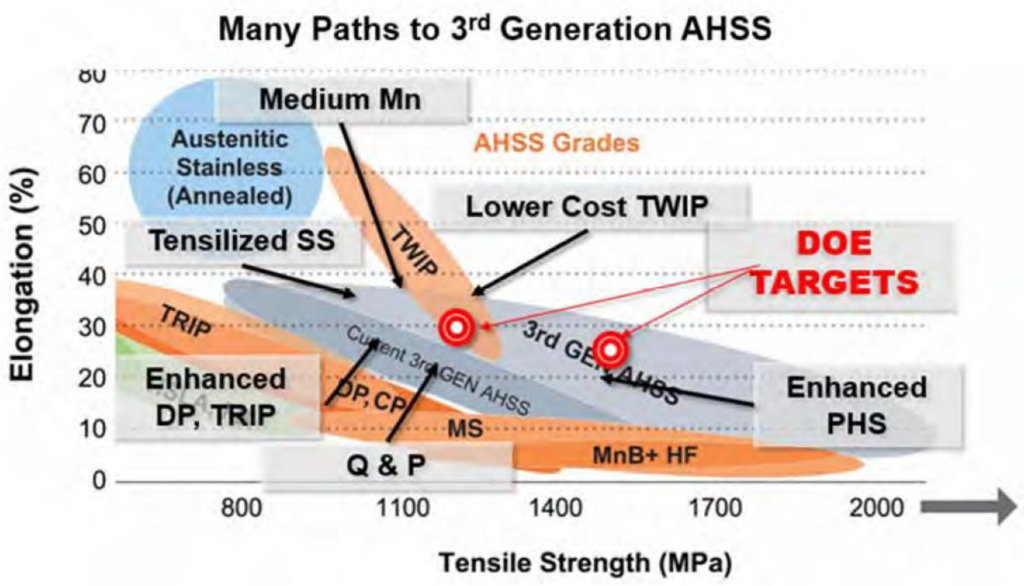


Figure 2.B.26: There are many pathways to achieve improved ductility with Gen 3 steels. Laboratory elongation data approach 2 to 3 times the values commonly reported for DP steels.[W-10]

TPN – Three-Phase Steel with Nano-Precipitation

A new family of high-performance cold forming steels consists of a ferritic matrix containing bainite, residual austenite and nano-precipitations. During the forming, a high percentage of retained austenite is converted to martensite. This work-induced transformation has a positive effect on the hardening behavior of the material to create a good combination of high formability and high strength.
Due to their high resistance to local thinning, these grades allow component geometries that are very difficult to achieve with other high-strength steels of the same strength class. The following nanoprecipitation grades are produced for automotive applications.

TPN 680/780: HR660Y760T-TP	B-pillar, Crossmember, longitudinal members, side panel reinforcement
TPN 750/900: HR730Y880T-TP	B-pillar, Crossmember, longitudinal members, bumper, side panel reinforcement

Q&P – Quenching and Partitioning

Q&P steels are a series of C-Si-Mn, C-Si-Mn-Al or other likely compositions subjected to the quenching and partitioning (Q&P) heat treatment process. With a final microstructure of ferrite (in the case of partial austenitization), martensite and retained austenite, Q&P steels exhibit an excellent combination of strength and ductility, which permitted their use in a new generation of advanced high strength steels (AHSS) for automobiles. Q&P steels are suitable for cold stamping for those structure and safety parts of automotive with relatively complicated shape to improve fuel economy while promoting passenger safety.

2.C. Conventional Low- and High-Strength Automotive Sheet Steels

2.C.1. Mild Steels

Mild steels have an essentially ferritic microstructure. Drawing Quality (DQ) and Aluminium Killed (AKDQ) steels are examples of mild steels and often serve as a reference base because of their widespread application and large production volume over the past decades.

2.C.2. Interstitial-Free (IF) Steels (Low Strength and High Strength)

IF steels have ultra-low carbon levels designed for lower yield strengths and higher work hardening exponents (n-values). These steels have more stretchability than Mild steels. The IF-HS grades utilize a combination of elements for solid solution strengthening, precipitation of carbides and/or nitrides, and grain refinement. Another common element added to increase strength is phosphorous (another solid solution strengthener). The higher strength grades of IF steel are widely used for both structural and closure applications.

2.C.3. Bake Hardenable (BH) Steels

BH steels have a basic ferritic microstructure and solid solution strengthening. A unique feature of these steels is the chemistry and processing designed to keep carbon in solution during steelmaking and then allowing this carbon to come out of solution during paint baking or several weeks at room temperature. This increases the yield strength of the formed part for increased dent resistance without reduction in formability. Common applications are automotive outer body panels where increased dent resistance is required.

2.C.4. Carbon-Manganese (CM) Steels

CM steels utilize solid solution strengthening for higher strength.

2.C.5. High-Strength Low-Alloy (HSLA) Steels

HSLA steels increase strength primarily by micro-alloying elements contributing to fine carbide precipitation, substitutional and interstitial strengthening, and grain-size refinement. HSLA steels are found in many body-in-white and underbody structural applications where strength is needed for increased in-service loads.

2.D. Understanding Mechanical Properties

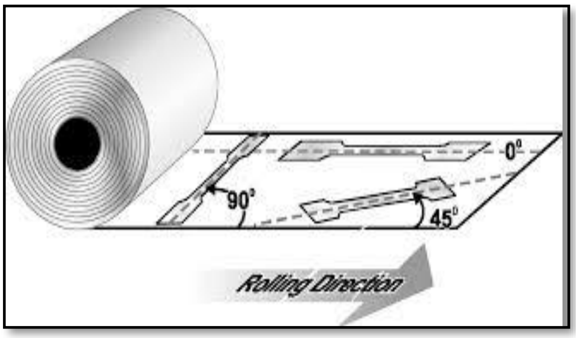


Figure 2.D-1: Typical tensile test specimen orientation as taken from coil.[M-5]

For decades, the single phase ferritic mild and high-strength low-alloy steels were commonly known by yield strength, tensile strength, and total elongation – usually tested in the longitudinal (0°) transverse (90°) and 45° position relative to the rolling direction (see Figure 2.D-1). Often hardness readings were included, but hardness readings are of little use in assessing formability requirements for steel and are best used to quantify the durability of tooling used to roll, stamp, and trim steel. Sometimes work hardening exponents (n-values) and anisotropy ratios (r-values) were specified to attain improved and consistent formability. The formability limits of different grades of conventional mild and HSLA steels were learned by correlating press performance with as-received mechanical properties.

Today the AHSS are more complex with press performance capabilities modified by changing chemistry, annealing temperature, amount of deformation, time, and even deformation path. By developing new microstructures, these steels become "Designer Steels" with properties tailored not only for initial forming of the stamping but in-service performance requirements for crash resistance, energy absorption, fatigue life, and other needs. An extended list of properties is now needed to evaluate total performance with virtual forming prior to cutting the first die, to ensure ordering and receipt of the correct steel, and to enable successful troubleshooting if problems occur.

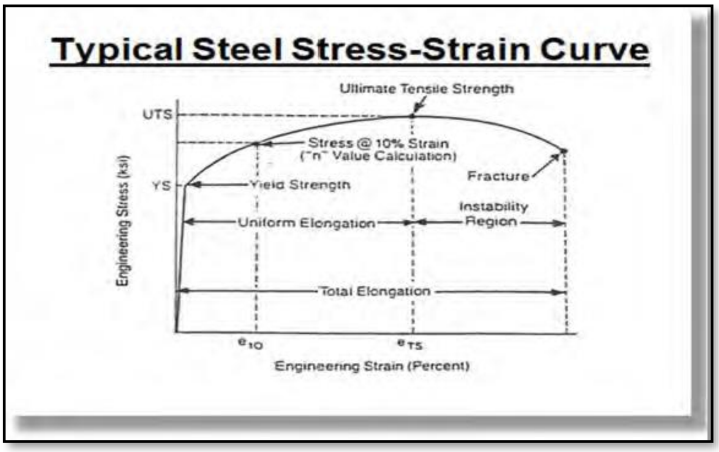
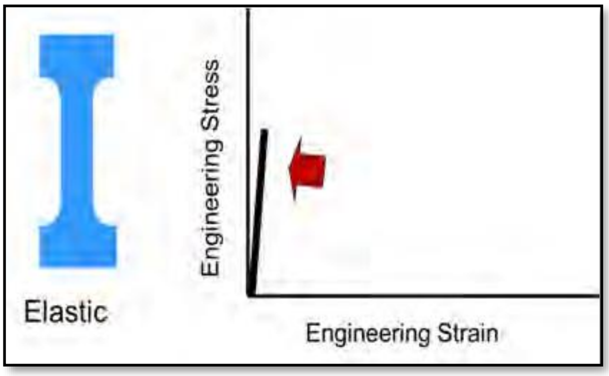


Figure 2.D-2: Typical engineering stress-strain curve showing some of the key formability parameters

As the use of formability parameters is spreading out from OEMs to the tier suppliers, it becomes even more important that all levels of suppliers and users understand both how to measure the parameters and how they affect the forming process. This section provides a short introduction to these parameters. Many of these parameters are measured during a tensile test, which commonly provides an engineering stress-strain curve (Figure 2.D-2). The following section explains each of the tensile test parameters.

2.D.1. Elastic Stresses – Young's Modulus

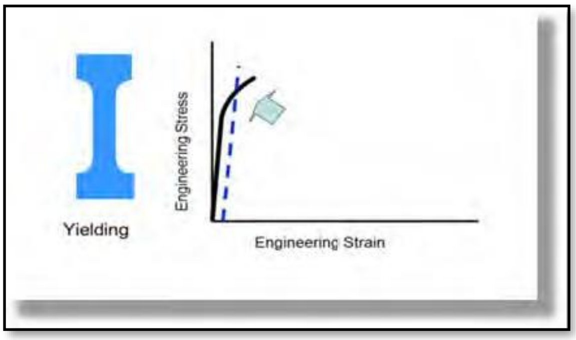


The first deformation of a stamping is created by the external forces of the tooling pulling or pushing) the atoms in the atomic cell away from their neutral state. At the atomic level, these forces are called elastic stresses and the deformation elastic strain. These forces within the atomic cell are extremely strong, creating small magnitudes of elastic strain for high values of elastic stress. The curve of elastic stress plotted against elastic strain is called Young's modulus or elastic modulus. For steel this is a steep straight line for most of its length – often called proportional straining. This elastic strain becomes non-proportional with the onset of plastic (permanent) deformation.

The slope of the modulus line depends on the atomic structure of the metal. Most steels have an atomic unit cell of nine iron atoms – one on each corner of the cube and one in the center of the cube. This is labeled BCC or Body Centered Cubic. The common value for the slope of steel is 210 GPa (30 million psi). In contrast, aluminum and many other non-ferrous metals have 14 atoms – one on each corner of the cube and one on each face of the cube. This is labeled FCC or Face Centered Cubic. The common number for the slope of aluminum is 70 GPa (10 million psi). Removing the forming forces to zero causes the atomic spacing to return back to its initial dimensions. The elastic stresses and elastic strain are now at zero. This return to initial dimensions is called springback – a major factor in achieving consistent stamping shape and dimensions**.** The amount of springback is inversely proportional to the modulus of elasticity. Therefore, for the same yield stress, steel with three times the modulus of aluminum will have one-third the amount of springback.

Springback deformation usually cannot return the stamping back to its zero elastic stress state due to plastic deformation. The elastic stress remaining in the stamping is called the residual or trapped stress. Any additional change to the stamping conditions (blank trim, hole punching, bracket welding, reshaping, or other plastic deformation) will change the amount of residual stresses and therefore potentially change the stamping shape and dimensions.

2.D.2. Yield Strength vs. Yield Stress



After elongating by elastic deformation, regions of the metal will begin adding plastic (permanent) deformation to sheet metal. Instead of a sharp change from elastic to plastic deformation, a gradual transition occurs. Two measurement techniques are used to assign a yield strength (Figure 2.D-3). The first is drawing a line parallel to the modulus line at an offset strain of 0.2%. The intersection stress becomes the yield strength. The second technique is drawing a vertical line at the 0.5% strain value until it crosses the stress-strain curve. The yield strengths of the two techniques are nearly equal.

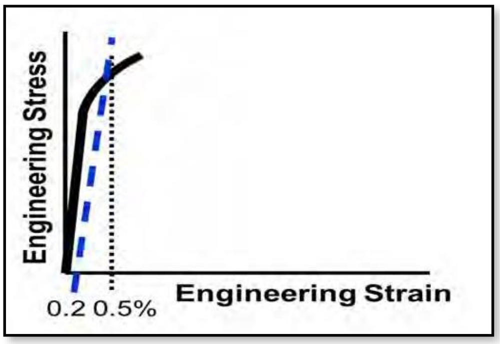


Figure 2.D-3: Determining yield strength with a line parallel to the modulus line and offset by 0.2% or a vertical line offset by 0.5%.

Some metals have yield point elongation (YPE) or Lüder's bands. This occurs when a band of deformation breaks free from being pinned by interstitial carbon atoms and other restrictive features of the microstructure. The stress drops immediately and is called the upper yield stress (Figure 2.D-4). The stress drops to the lower yield stress. Deformation continues at approximately a constant stress until the entire tensile sample has yielded and the sample begins to work harden.

Since springback is proportional to the yield strength of the steel, knowing the yield strength allows some estimation of relative springback (Figure 2.D-5). In this figure compared to mild steel, HSLA can attain four times more springback and MS AHSS can attain eight times more springback due to increased yield strength.

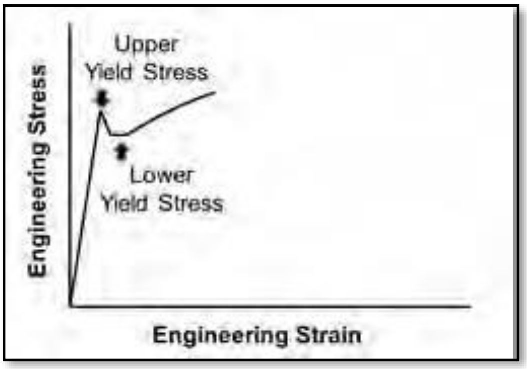


Figure 2.D-4: Defining upper/lower yield stress.

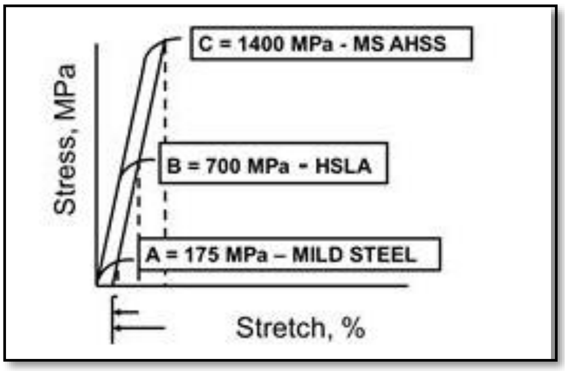
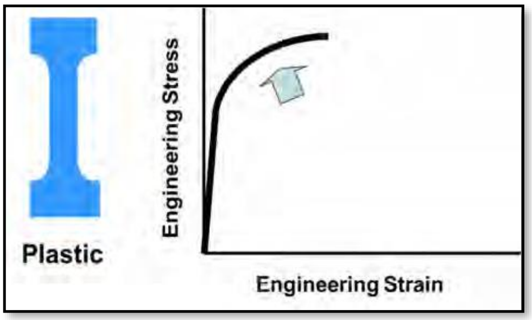


Figure 2.D-5: The springback is proportional to the yield strength.

2.D.3. Work Hardening – n-value



Deformation in the plastic region causes the metal to work harden, which has both advantages and disadvantages. The metal in the area of greater deformation is strengthened by work hardening to reduce the formation of strain gradients (localization of strain) observed in Figure 2.D-6. Assume the design of the die caused the stamping to greatly increase deformation in one zone relative to the remainder of the stamping. Without work hardening, this deformation zone would become thinner as the metal is stretched to create more surface area. This thinning increases the local surface stress to cause more thinning until the metal reaches its forming limit. With work hardening the reverse occurs. The metal becomes stronger in the higher deformation zone and reduces the tendency for localized thinning. The surface deformation becomes more uniformly distributed.

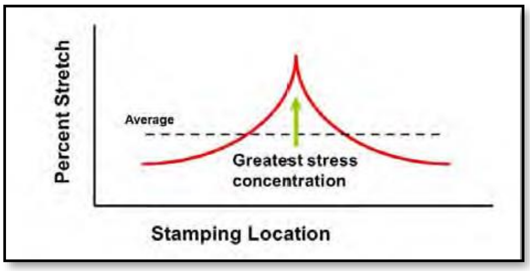


Figure 2.D-6: Strain gradients grow in high stress areas of the stamping.

For sheet metal forming the work hardening is commonly defined by the power law equation:

$$\sigma_T = K\,\epsilon^n$$

The work hardening exponent (n-value) is the measure for comparing stretching capability of various metals. For decades conventional steels (mild steels, HSLA, etc) had an n-value that was constant with deformation. The n-value measurements commonly were made from 10% to 20% elongation. A more robust measurement is 10% elongation to elongation at maximum load. This avoids elongation measurements for tests that have an onset of necking less than 20% and includes measurement data for metals that have maximum loads in excess of 20%. Although the yield strength, tensile strength, yield/tensile ratio and percent elongation are helpful when assessing a steels formability, it is the n-value along with steel thickness that determines the position of the forming limit curve (FLC) on the forming limit diagram (FLD) (to be discussed further in Section 3.B.3 – Deformation Limits). The n-value, therefore, is the mechanical property that one should always analyze when global formability concerns exist. That is also why the n-value is one of the key material related inputs used in virtual forming simulations.

Today many of the AHSS grades have n-values that change value with increased deformation (or engineering strain). For example, Figure 2.D-7 compares the instantaneous n-value of a DP350/600 with a conventional HSLA350/450 grade where the DP steel has a relatively high n-value at lower strain levels, then drops to a range very similar to the conventional HSLA grade after about 7-8% strain. The actual strain gradient of the two steels will be very different due to this initial higher work hardening rate of the dual phase steel. As a result of this unique characteristic of certain AHSS grades with respect to n-value, many OEM's and Tier suppliers create steel specifications for these grades that have one minimum n-value, typically in the 4-6% strain range and a second lower minimum n-value at 10% to the end of uniform elongation. Plots of n-value against strain (instantanous n-values) are helpful in defining the stretchability of these newer steels. The work hardening also plays an important role in determining the amount of total stretchability as measured by various deformation limits (see Section 3.B.3 – Deformation Limits).

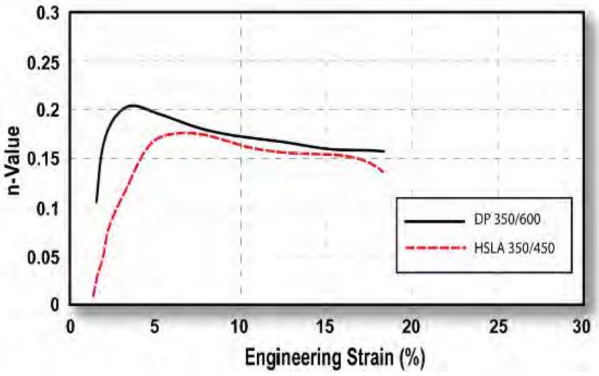


Figure 2.D-7: Instantaneous n-values versus strain for DP 350/600 and HSLA 350/450 steels.[K-1]

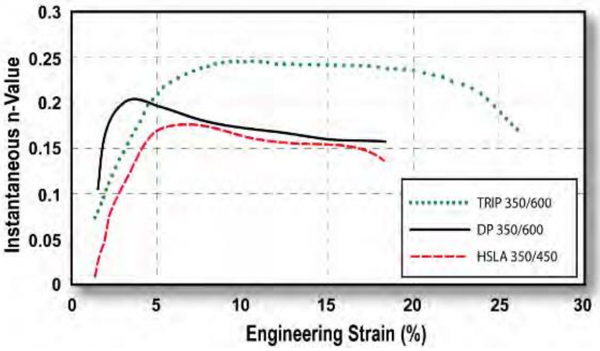


Figure 2.D-7: Instantaneous n-values versus strain for DP 350/600, TRIP 350/600 and HSLA 350/450 steels.[K-1]

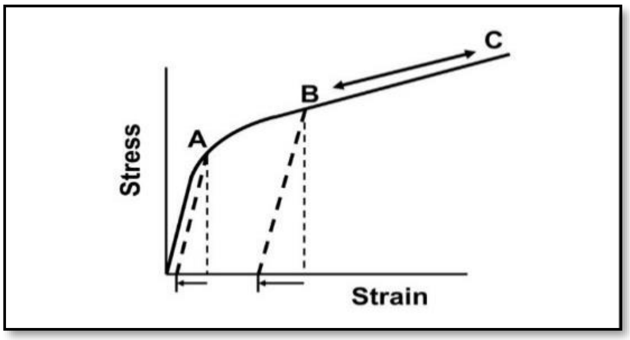


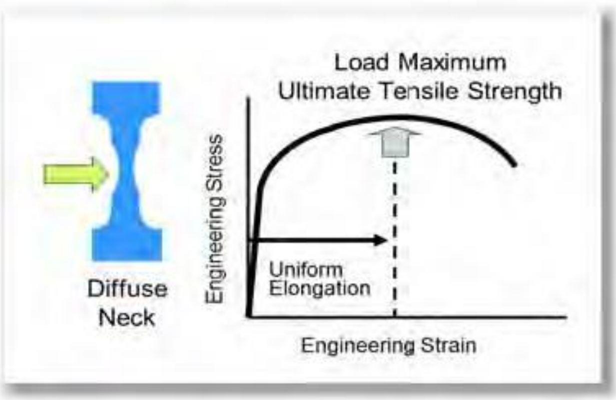
Figure 2.D-8: Deformation of the steel causes the stress at each location in the stamping to change due to work hardening. The resultant stress is called flow stress.

Among the AHSS grades available, DP exhibits the greatest initial work hardening rate at strains below 8%. Whereas DP steels perform well under global formability conditions, TRIP steels offer additional advantages derived from a unique, multiphase microstructure that also adds retained austenite and bainite to the DP microstructure. During deformation, the retained austenite is transformed into martensite to increase the strength level, and this transformation allows the steel to maintain a very high n-value throughout the entire deformation process (see Figure 2.D-7). This characteristic allows for more complex geometries and/or reduced thickness for mass reduction. After the part is formed, there is usually additional retained austenite remaining in the microstructure that will subsequently be transformed into martensite in a crash event, making TRIP ideal for parts in crush zones on a vehicle.

Figure 2.D-5 showed the relationship between springback and yield strength for as-received metal. However, forming the stamping also work hardens the metal, thereby increasing the flow stress (yield strength plus increase in stress due to work hardening). Figure 2.D-8 shows this new flow stress as location B for one location in the stamping. The increased stress also increases the elastic stress and the total springback for this point in the stamping. Other locations in the stamping will have different values of flow stress and springback. The stamping will take whatever shape is necessary to minimize total residual stresses.

Process changes, production modifications, uncontrolled lubricant quantities, and many other variables can cause the flow stress at this location to vary (often randomly) from B to C in Figure 2.D-8. The variation at this one location interacting with variations at all other stamping locations can generate a synergistic final output that produces a stamping completely out of print specifications.

2.D.4. Diffuse/Width Neck – Tensile Strength



The elongation of the tensile test sample activates two primary deformation modes. One is a geometrical softening created by the reduction in the sample crosssection. This reduction is necessary to maintain constancy of volume. The other is work hardening. Initially the work hardening is greater than geometric softening to create increasing forming load and stress. Because the work hardening rate (n-value) is a constant when true stress-strain is plotted on log paper, the work hardening is a parabolic curve when plotted as engineering stress-strain. At some level of strain, the geometrical softening of the cross-section becomes greater than work hardening. At this point a load maximum (ultimate tensile strength) is observed and the tensile sample develops a width or diffuse neck – usually in the middle of the sample. The amount of elongation in the gage length of the extensometer at the onset of the neck is called the uniform elongation. As the diffuse neck grows the load is dropping. The portions of the sample above and below the neck stop deforming.

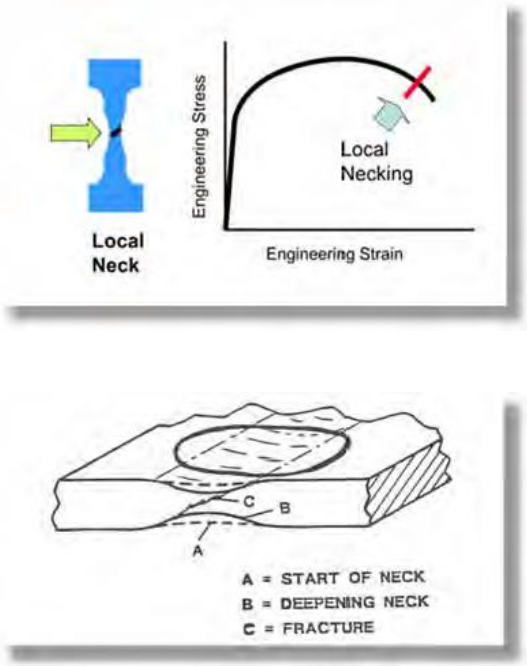
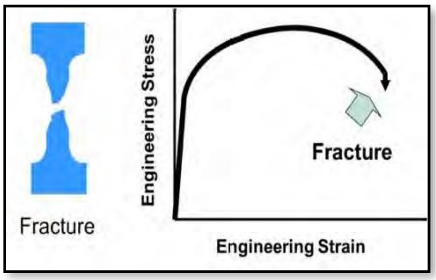


Figure 2.D-9: The maximum useful deformation of a stamping terminates when the local neck just begins to form.

2.D.5. Local/Thickness Neck – and the Forming Limit Curve

A very important parameter in stretch forming is the maximum allowable strain combinations within the plane of the sheet. This maximum stretch in the tensile test is the onset of a local or thickness neck – usually observed as a narrow band oriented about 54-degrees from the axis of the tensile sample. No deformation occurs along the width of the neck – only increased elongation and thinning (Figure 2.D- 9). This limit is not the uniform elongation or total elongation observed in the tensile test. This local or through-thickness neck occurs shortly before the traditional fracture of the specimen. When the local neck begins, deformation stops in the remainder of the stamping. Even though high strains can occur in the neck, the stamping has already gone over the edge of the "Deformation Cliff." The local neck also spoils a class A surface. This local neck is the source of the Forming Limit Diagram and Forming Limit Curve (see Section 3.B.3. Deformation Limits).

2.D.6. Fracture – Total Elongation



Deformation continues in the local neck until fracture occurs. The amount of additional strain in the neck depends on the microstructure. Inclusions, particles, and grain boundary cracking can accelerate early fracture. Total elongation is measured from start of deformation to start of fracture. Two extensometer gage lengths are commonly used: A50 (50mm or 2-inches) and A80 (80 mm or 3 inches). Past procedures attempted to position the two fractured strips back together and hand measure the distance between two gage marks on the sample. Today computer data acquisition identifies the data point at one-half maximum load and records the elongation of the previous data point.

2.D.7. Directionality of Properties (Anisotropy Ratio) – r-value

The normal anisotropy ratio (r_m) defines the ability of the metal to deform in the thickness direction relative to deformation in the plane of the sheet. For r_m values greater than one, the sheet metal resists thinning. Values greater than one improve cup drawing, hole expansion, and other forming modes where metal thinning is detrimental.

High-strength steels with UTS greater than 450 MPa and hot-rolled steels have r_m values approximating one. Therefore, conventional HSLA and AHSS at similar yield strengths perform equally in forming modes influenced by the r_m value. However, r-value for higher strength grades of AHSS (800 MPa or higher) can be lower than one and any performance influenced by r-value would be not as good as HSLA of similar strength. For example AHSS grades may struggle to form part geometries that require a deep draw, including corners where the steel is under circumferential compression on the binder. This is one of the reasons why higher strength level AHSS grades should have part designs and draw dies developed as “open ended” (to be discussed in detail in Section 3.B.10 – Springback Compensation).

2.D.8. Bake Hardening and Aging

Strain aging was measured using typical values for an automotive paint/bake cycle consisting of 2% uniaxial pre-strain followed by baking at 170˚C for 30 minutes. Figure 2.D-10 defines the measurement for work hardening (B minus A), unloading to C for baking, and reloading to yielding at D for measurement of bake hardening (D minus B).

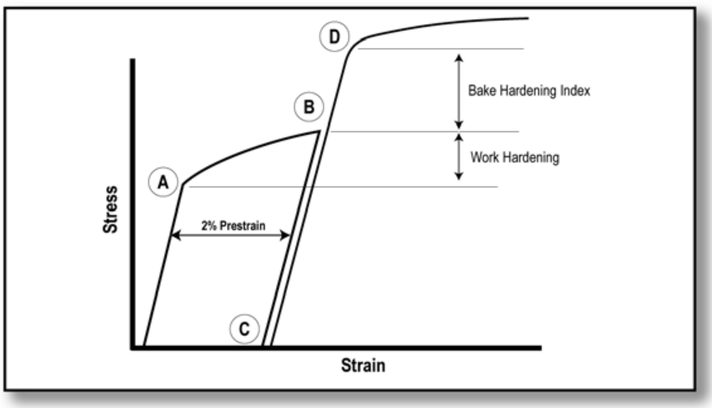


Figure 2.D-10: Measurement of work hardening index and bake hardening index

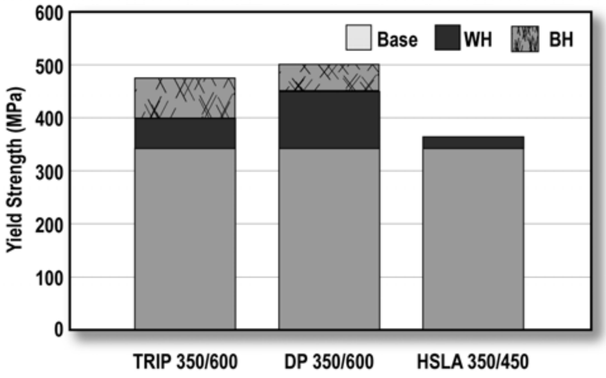


Figure 2.D-11: Comparison of work hardening (WH) and bake hardening (BH) for TRIP, DP, and HSLA steels given a 2% prestrain.[S-1, K-3]

Figure 2D-11 shows the work hardening and bake hardening increases for the 2% prestrained and baked tensile specimen. The HSLA shows little or no bake hardening, while AHSS such as DP and TRIP steels show a large positive bake hardening index. The DP steel also has significantly higher work hardening than HSLA or TRIP steel because of higher strain hardening at low strains. No aging behavior of AHSS has been observed due to storage of asreceived coils or blanks over a significant length of time at normal room temperatures. Hence, significant mechanical property changes of shipped AHSS products during normal storage conditions are unlikely.

2.D.9. Strain Rate Effects

To characterize the strain rate sensitivity, medium strain rate tests were conducted at strain rates ranging from 10^{-3}/sec (commonly found in tensile tests) to 10^{3}/sec. For reference, 10^{1}/sec approximates the strain rate observed in a typical stamping. As expected, the results showed that YS (Figure 2.D- 12A) and UTS (Figure 2D-12B) increase with increasing strain rate.

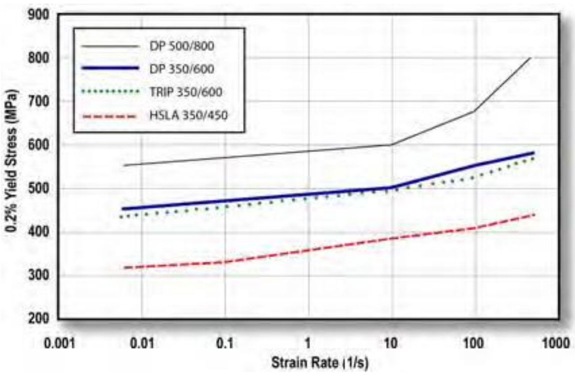


Figure 2D-12A: Increase in yield stress as a function of strain rate.[Y-1]

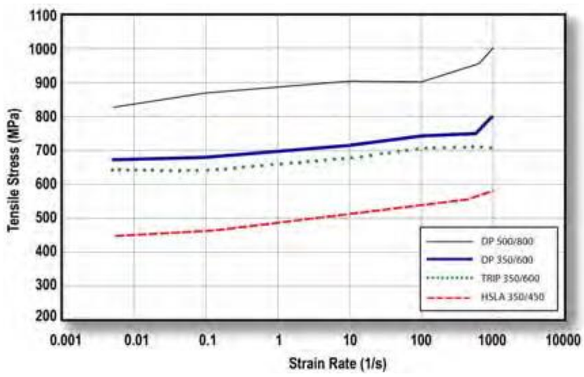


Figure 2D-12B: Increase in tensile stress as a function of strain rate.[Y-1]

Up to a strain rate of 10^{1}/sec, both the YS and UTS only increased about 16-20 MPa per order of magnitude increase in strain rate. These increases are less than those measured for low strength steels. This means the YS and UTS values active in the sheet metal are somewhat greater than the reported quasi-static values traditionally reported. However, the change in YS and UTS from small changes in press strokes per minute are very small and are less than the changes experienced from one coil to another. The change in n-value with increase in strain rate is shown in Figure 2.D-13. Steels with YS greater than 300 MPa have an almost constant n-value over the full strain rate range, although some variation from one strain rate to another is possible.

Figure 2.D-14 shows the true stress-true strain curves at several strain rates for HF steel after heat treatment and quenching to MS. The yield stress increases approximately five MPa for one order of magnitude increase in strain rate. It should also be noted that strain rate effects can be very different for different materials in very high strain rate modes (e.g. automotive crash). Refer to Section 3.G.1 – Crash Management for more information.

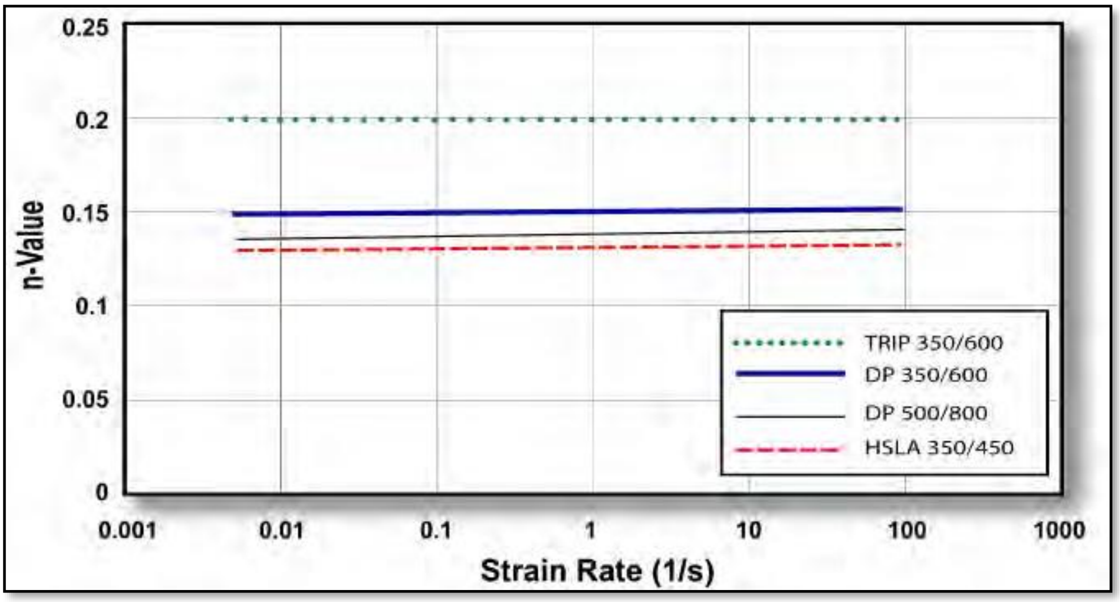


Figure 2.D-13: Relationship between n-value and strain rate showing relatively no overall increase.[Y-1]

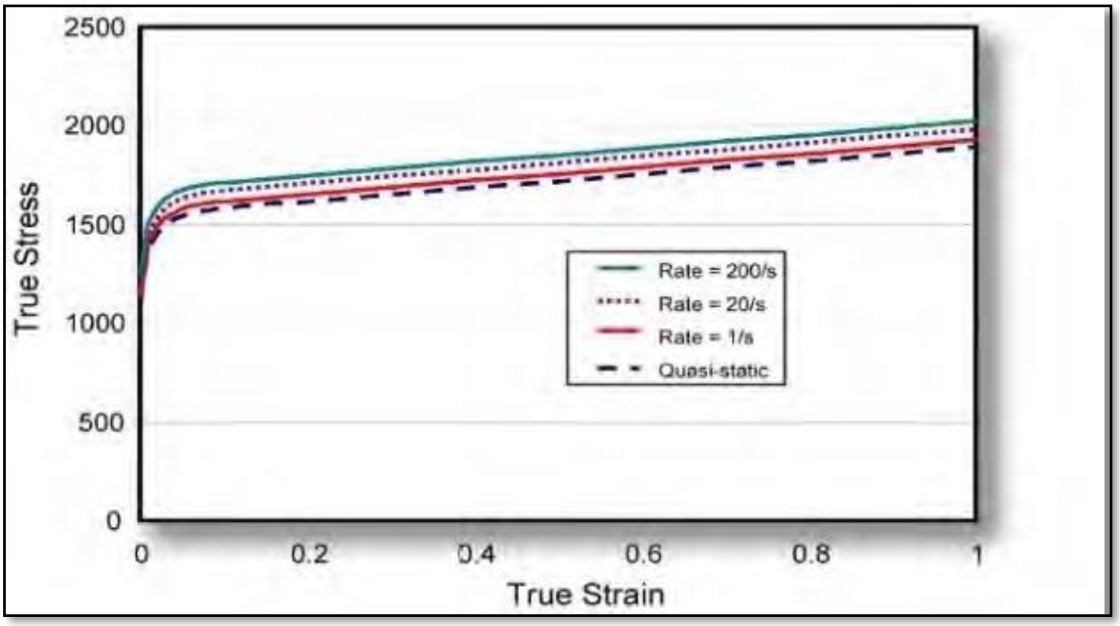


Figure 2.D-14: Extended true stress-strain curves for HF steel with different strain rates.[V-1] **Steel is 1.0 mm thick after heat treatment and quenching.**

2.D.10. Key Points

- **The multiphase microstructure in AHSS results in properties that change as the steel is deformed. An in-depth understanding of formability properties is necessary for proper application of these steels. Close supplier/user communication is required for proper material selection.**

- **Tensile test data is very useful for assessing a steel's ability to perform with respect to global (tensile) formability.**

- **DP steels have increased n-values in the initial stages of deformation compared to conventional HSLA. These higher n-values help distribute deformation more uniformly in the presence of a stress gradient and thereby reduce local thinning.**

- **Certain AHSS grades such as DP have an n-value that varies, with a very high n-value in the first 0-8% strain, then a drop as strain increases.**

- **TRIP steels have less initial increase in n-value than DP steels during forming but sustain the increase throughout the entire deformation process, allowing them to achieve more complex geometries or further reduce thickness for weight savings.**

- **TRIP steels have retained austenite after forming that will transform into martensite during a crash event, enabling improved crash performance.**

- **Most cold-rolled and coated AHSS and conventional HSLA steels with UTS greater than 450 MPa, and all hot-rolled steels have normal anisotropy values (r_m) around a value of one.**

- **AHSS work hardens with increasing strain rate, but the effect is less than observed with Mild steel. The n-value changes very little over a 10_5 increase in strain rate.**

- **As-received AHSS does not age-harden in storage.**

- **DP and TRIP steels have substantial increase in YS due to a bake hardening effect, while conventional HSLA steels have almost none.**

2.E. – Corrosion Resistant Coatings on AHSS

2.E.1. – Hot Dipped and Electrogalvanized Coatings

Many steel parts on a vehicle require corrosion protection, regardless of whether they are exposed or unexposed applications. Today's AHSS products are primarily used on unexposed structural parts. The most common way to accomplish corrosion protection is to coat the steel with zinc by means of a hot dipped galvanizing process.

The hot dipped galvanizing process requires the steel to pass through a molten bath of zinc (at ~460°C/ 860°F), and the steel is preheated to the same approximate temperature as the molten pot to facilitate adhesion. The steel is under tension during the process, and thus formability properties may be affected very slightly. Figure 2.E-1 shows a schematic of a typical hot dipped galvanized coating section.

Hot dipped galvanizing lines at different steel companies have similar processes that result in similar surfaces with respect to coefficient of friction. Surface finish and texture (and resultant frictional characteristics) are primarily due to roll textures, based on the customer specification. Converting from one coating line to another using the same specification is usually not of major significance with respect to coefficient of friction and formability.

There are several types of hot dipped coatings for automotive applications, with unique characteristics that affect their corrosion protection, lubricity for forming, weldability and paintability. One of the primary hot dipped galvanized coatings is a pure zinc coating (HDGI), sometime referred to as free zinc. This coating has small traces of aluminum in the molten zinc bath to improve adhesion among other things. The end-result is a very shiny surface with a very low coefficient of friction and Figure 2.E-2 shows a schematic of a cross section of typical hot dipped galvanized steel.

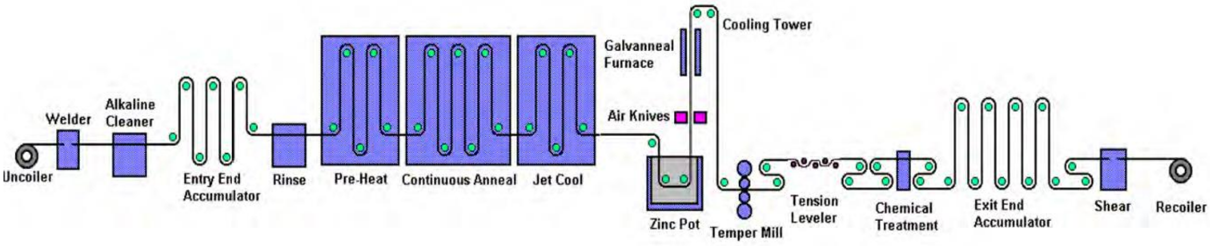


Figure 2.E-1: Schematic of a typical hot dipped galvanizing line.

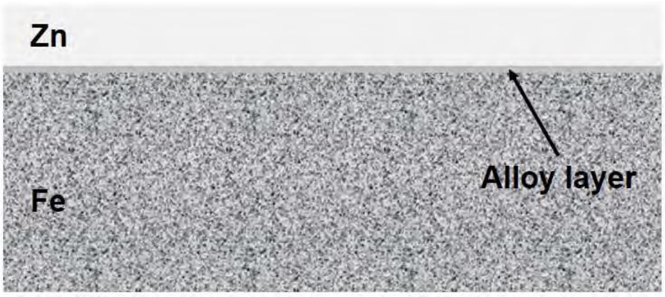


Figure 2.E-2: Cross section of free zinc hot dipped galvanized steel.

The other primary hot dipped coating used for corrosion protection is hot dipped galvanneal (HDGA). This steel goes through the same process as free zinc hot dipped steel, but after exiting the zinc pot, the steel strip passes through a galvannealing furnace where the zinc coating is reheated while still molten. Iron in the substrate diffuses into the zinc coating, creating an iron-zinc alloy with typical iron content in the 8-12% range. The iron content improves weldability, which is a key attribute of the galvanneal coatings. The iron content can be unevenly distributed throughout the coating (see Figure 2.E-3), ranging from 5% at the surface (where the coating contacts the die) to as much as 25% iron content at the steel/coating interface. The lower iron content at the surface creates a softer surface, resulting in an increased coefficient of friction and potential formability impacts. For difficult to form parts with HDGA, most automakers add press-applied lubricants; for example, phosphate is a dry film lubricant applied to the coil after the zinc coating process to improve formability.

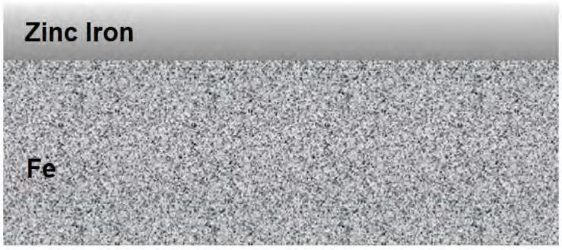


Figure 2.E-3: Cross section of galvanneal coating, showing higher iron content at the interface.

Hot dipped galvanizing is a desirable coating for structural steel applications requiring corrosion protection, as it is a relatively low cost solution because the steel can be annealed and coated in the same operation. However, the thermal cycle for this type of coating process inhibits the ability to produce some of the higher strength AHSS grades, where rapid cooling is required to achieve very high strengths (980 MPa and above). Most hot dip galvanizing lines are limited to coating steels up to 780 MPa in tensile strength.

The furnace section before the zinc pot in a hot dipped galvanizing or galvannealing line heats the steel to at least the temperature of the molten zinc (460°C/ 860°F), and is capable of continuously annealing cold rolled steel and recrystallizing the microstructure, dramatically improving forming characteristics. The temperature in this furnace can be adjusted to produce the desired microstructure in the final product; for example, temperatures can be set to prevent large changes in microstructure or properties. Thus, full-hard high strength steels can be recovery annealed, and hot rolled HSLA steels can be coated with only minor changes in mechanical properties. For Dual Phase steels the zinc bath serves as an aging section, maintaining the elevated temperature of the steel long enough to achieve the dual phase microstructure.

Martensitic steels and many advanced high strength steels with strengths above 980 MPa cannot attain their microstructure with the thermal profile of a hot dipped galvanizing line (with limited rapid quenching capabilities), and many AHSS grades have chemistries that produce surface oxides which prevent good adhesion of the zinc to the surface. These grades must be produced on a Continuous Annealing Line, or CAL. The CAL line features a furnace with variable and rapid quenching operations that enable the thermal processing required to achieve very high strength levels. If corrosion protection is required, these grades of steel are coated on an electrogalvanizing line (EG) in a separate operation, after being processed on a CAL line.

2.E.2 – Electrogalvanized Coatings

Electrogalvanizing is an alternative zinc deposition process, where the zinc is electrolytically bonded to steel in order to protect against corrosion (Figure 2.E-4) The process involves electroplating, running a current of electricity through a saline/zinc solution with a zinc anode and steel conductor. Since the electroplating process doesn’t elevate the temperature of the steel substrate significantly, the microstructure and physical properties of AHSS products achieved on a continuous anneal line (CAL) are largely unchanged after the EG process. As a result, there are three chief advantages of electrogalvanizing compared to hot dipped galvanizing: (1) lower processing temperatures, (2) thinner coatings with comparable corrosion performance, and (3) brighter, more aesthetically appealing coatings.

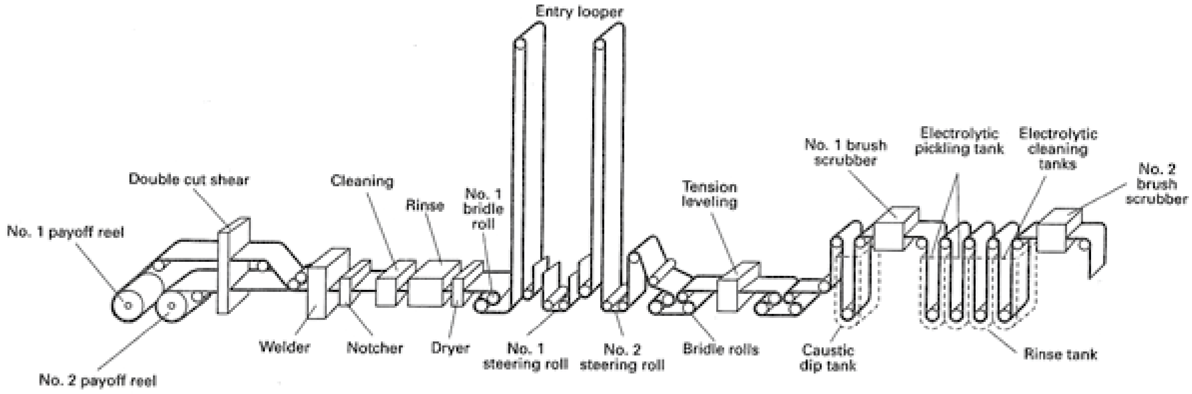
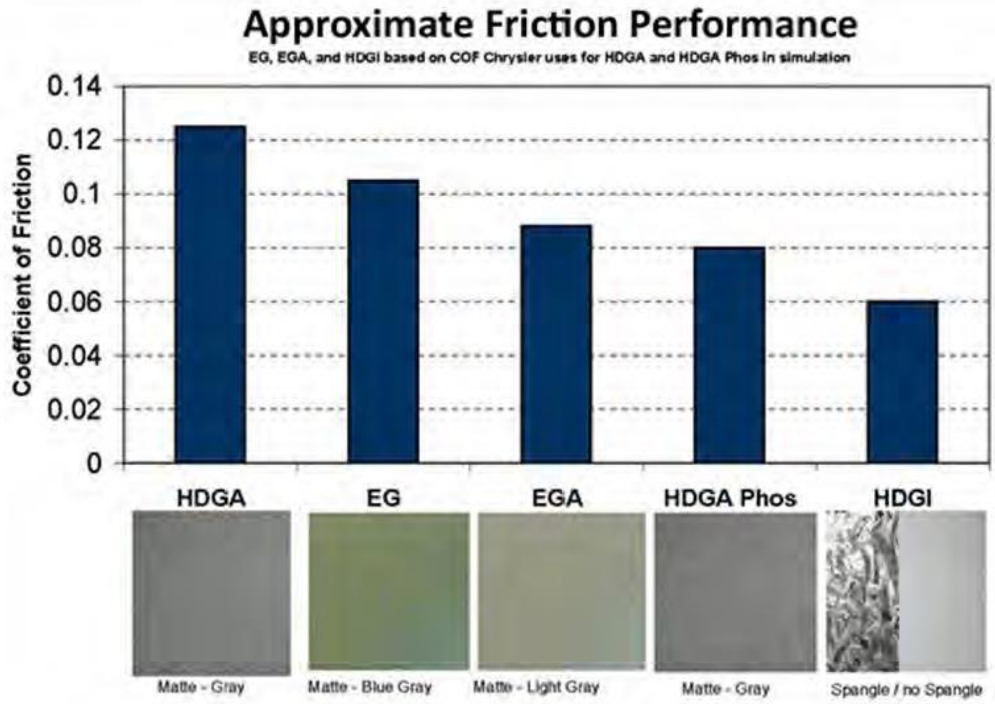


Figure 2.E-4: Schematic of a typical electrogalvanizing line with vertical plating cells.[A-19]

The overwhelming majority of electrogalvanizing lines can only apply pure (free) zinc coatings. There are no concerns about coating phases as with galvanneal coatings and there is no aluminum on the coating, which improves weldability. The biggest concern with electrogalvanizing lines is the coefficient of friction. Figure 2.E-4 is a chart that compares the approximate coefficient of friction for various coatings. As can be seen, electrogalvanized (EG) coatings have the second highest coefficient of friction, behind HDGA. With EG, some automakers will apply a more viscous oil, commonly called prelube, that also improves formability versus the typical mill oil that is normally applied and serves mainly as a rust inhibitor.

Different EG lines may use different technologies to apply the zinc crystals. These different processes lead to a potentially different surface morphology and, subsequently, a different coefficient of friction as the zinc crystals are deposited in a different fashion. Under dry conditions, the coefficient of friction can be quite high, yet the “stacked plate-like surface morphology” allows these coatings to trap and hold lubrication better than the smoother surfaces of hot dipped galvanizing coatings. Auto manufacturers should therefore consult the steel supplier for specific lubricant recommendations based on the forming needs.



Coating Hardness

	HDGA	EG	EGA	HDGA Phos	HDGI
Hardness	Hard	Soft	Hardest	Hard	Softest

Substrate

	HDGA	EG	EGA	HDGA Phos	HDGI
DQ or DS Type B	NA	**Low Carbon** (Appx. 0.04% C) Min n-val = 0.195	**Low Carbon** (Appx. 0.04% C) Min n-val = 0.190	NA	NA
DDQ	**Ultra Low Carbon** (Appx. 0.004% C) Min n-val = 0.210	**Low Carbon** (Appx. 0.04% C) Min n-val = 0.195	**Low Carbon** (Appx. 0.04% C) Min n-val = 0.190	**Ultra Low Carbon** (Appx. 0.004% C) Min n-val = 0.210	**Ultra Low Carbon** (Appx. 0.004% C) Min n-val = 0.215
EDDQ	**Ultra Low Carbon** (Appx. 0.004% C) Min n-val = 0.210	**Ultra Low Carbon** (Appx. 0.004% C) Min n-val = 0.210	**Ultra Low Carbon** (Appx. 0.004% C) Min n-val = 0.205	**Ultra Low Carbon** (Appx. 0.004% C) Min n-val = 0.210	**Ultra Low Carbon** (Appx. 0.004% C) Min n-val = 0.215

** Min n-val for EG & EGA is typically 0.005 lower (up to 0.010 lower) than same HDGI or HDGA grade

Figure 2.E-4: Chart comparing the approximate coefficient of friction for various coating types.[M-4]

2.E.3 – Key Points

- **Many AHSS parts require corrosion protection, achieved through the application of some type of zinc coating. The primary methods of applying zinc are through a hot dipped galvanizing line, or through an electro-galvanizing process.**

- **Most hot dipped galvanized lines result in very similar coefficients of friction for a given steel type. Electrogalvanized coating lines have varying surface morphologies, which can result in significantly different formability characteristics.**

- **Hot dipped galvannealed coatings have improved joining, but have different phases that can vary in their composition, and can cause adhesion or formability problems.**

- **Identifying the intended steel production source should be accomplished early in the die construction and die try-out process. Steel application engineers should be consulted regarding part design and intended processing parameters as early as possible, to ensure robust stamping and joining performance.**