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NIOBIUM MICROALLOYED AUTOMOTIVE SHEET STEEL – A COST EFFECTIVE SOLUTION TO THE CHALLENGES OF MODERN BODY ENGINEERING

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Introduction

In the 1990s, the position of steel as the most established material in automotive body construction has been challenged by low-density materials such as aluminum, plastics and magnesium either for the entire body-in-white or in specific applications. This challenge motivated the steel industry to develop new steel grades that can compete with low-density materials in the race for lighter, safer, better performing and cost efficient body structures.

In recent passenger cars a broad variety of high strength steel grades has been introduced on the expense of mild steel grades. Often the share of mild steel is now below 50% of the total body weight and in more advanced vehicles even below 30%. Accordingly, the share of high strength steel has significantly increased. The focus has been much on multiphase steels (DP, CP, TRIP) during recent years, which typically account for around 10-20% of the body weight in current vehicles. The remaining part spectrum is mainly made from microalloyed (HSLA), high strength interstitial free (IF-HSS), bake hardening (BH) and rephosporized (P) steel grades. Hot rolled high strength steel grades are of importance for chassis parts and wheels. Hot forming steel has become popular more recently and is found in many of the current car models in areas where a combination of good formability and highest strength is required.

The automotive processing chain consists of forming, assembling and painting. Each process demands specific properties and characteristics from the material. However, the optimum material characteristic for one process may not be necessarily suitable for another. Therefore, compromises have to be found and these are for a considerable part based on the alloy design and the microstructure of the material.

The alloy design of automotive steel sheet is principally based on carbon and manganese. Depending on the particular grade, other alloying elements are added such as silicon, phosphorous, aluminum, chromium and molybdenum. The so-called "microalloying elements" niobium, titanium, vanadium and boron are of special interest. Microalloying means that the content of these elements is small, typically less than 0.1% by weight. Nevertheless, the influence of microalloying elements and of niobium in particular on the properties of the material can be very significant [1].

In combination with the alloy design, the processing route in the steel mill determines the microstructure of the material and, thus, the final material properties. In the early 1990s almost all steel grades used in automotive body construction mainly had a ferritic microstructure with.

Accordingly, microstructure at that time was not a variable that automotive engineers had to be concerned about. This situation has drastically changed with the introduction of advanced high strength steels. These steel grades involve ferrite, pearlite, bainite, martensite and austenite either as single, dual or multiple phases. The additional complexity by such microstructural variety has to be well understood with respect to the automotive production processes.

Modern Car Body Engineering

A number of principal decisions have to be made at the very beginning of the engineering cycle of a new body-in-white. This concerns the concept of the body, the manufacturing technologies to be employed as well as the materials to be used. Since these principal elements are strongly interrelated, deviations or major changes in a later phase of the engineering cycle will usually implicate huge cost penalties (Figure 1). Central in the engineering cycle is the strict control of feasibility and cost.

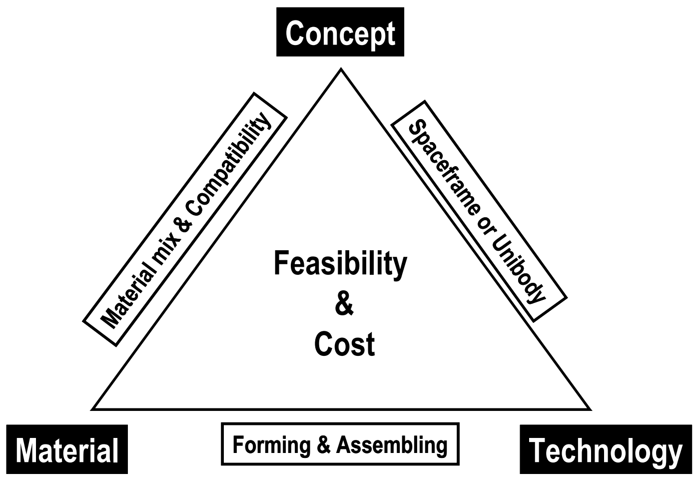

Figure 1. Principal aspects of modern car body engineering.

<u>Material concepts for future car bodies</u>

When Audi introduced its first A8 model, based on aluminum space frame technology, to the market in 1994, the dominant position of steel as material for vehicle body construction was put into question. The weight of its all-aluminum body-in-white was considerably lower as that of competing cars made from steel. However, the steel grades used at that time were mostly mild steels and the required stability and safety standards were achieved by using increased sheet gage and additional reinforcement parts driving up the total body weight.

The world steel industry reacted to the aluminum challenge by launching the Ultra-Light Steel Auto Body (ULSAB) project in 1995, which had the aim of creating an optimized body concept to significantly reduce the weight of the body-in-white without sacrificing on driving and crash performance. This was possible by using high strength steel on a large scale and also applying novel manufacturing technologies like tailor welded blanks and hydro forming (Table I). The range of high strength steels that were commercially available in the development phase of the ULSAB project was more or less limited to microalloyed HSLA, rephosphorized and bake hardening steels. Only selected steel mills were able to supply ultra high strength steels at that time. This situation has definitely changed as by now nearly all major automotive steel suppliers developed a full range of so-called advanced high strength steels (Figure 2). Typically these are coated multiphase steels having more than 350 MPa yield strength. The availability of these steel grades is reflected in the ULSAB-AVC project exposing a dominant share of advanced high strength steel and virtually containing virtually no mild steel anymore.

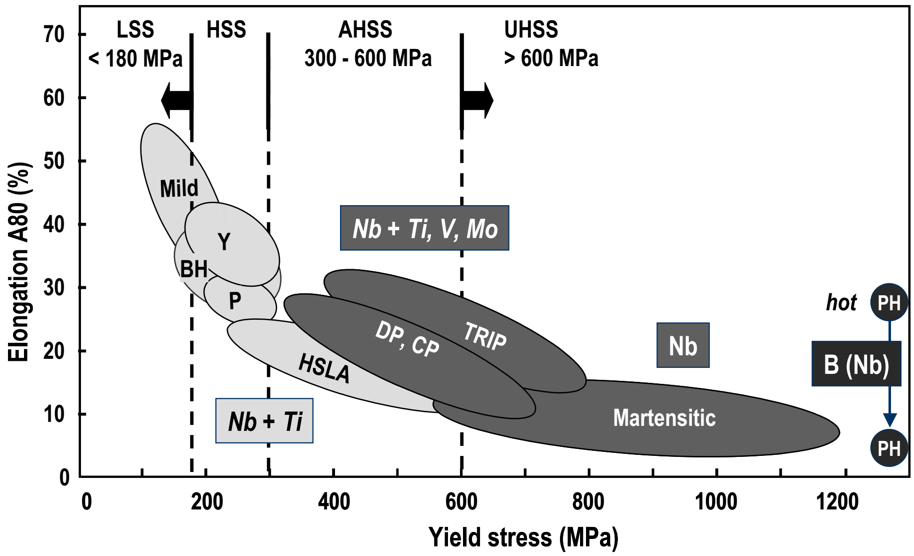

Figure 2. Stress-elongation diagram showing the different automotive steel families and typical microalloying elements contained.

The world automotive industry has accepted many of the ideas initiated by the ULSAB projects and introduced high strength and advanced high strength steels in the vehicle generations that followed these projects. In current mass production cars the share of traditional high strength steels is up to 60% and that of advanced high strength steels is up to 30% (Table I).

Table I. Technological achievements of the ULSAB projects and current implementation in serial production vehicles.

	ULSAB	USLAB-AVC	Serial 2004 +
Steel grades (YS)			
HSS < 350 MPa	83%	33%	30-60%
EHSS < 700 MPa	10%	61%	5-30%
UHSS > 700 MPa	—	4%	2-15%
Tailored Products			
Tailor welded blanks	✓	✓	✓
Tailored tubes	—	✓	occasional
Tailor rolled blanks	—	✓	✓
Roll Forming	—	—	✓
Hot Forming	—	—	✓
Tube Hydro Forming	✓	✓	occasional
Sheet Hydro Forming	✓	✓	occasional
Laser Welding / Brazing	<20 m	> 100 m	up to 60 m

A comparison of the weight reduction potential using different material concepts is shown in Figure 3. It is apparent that relative to a conventional steel body the all aluminum body has the highest weight reduction potential, however at a high cost surplus. On the contrary, an advanced steel body allows reducing the body weight by about 10-20% and simultaneously lowers the body cost by the same order of magnitude. Hybrid body concepts, where for instance the front car is made from aluminum and the remaining structure consists of an advanced steel concept is offering a compromise in the weight reduction to cost balance. Often carmakers are willing to pay a higher cost for weight reduction in the front and upper area of the car to optimize driving performance and handling. In other areas cost increases are less or not tolerated unless the total weight can be significantly reduced. Detailed discussions of engineering criteria and material options are given in this book by BMW [2] and Fiat [3].

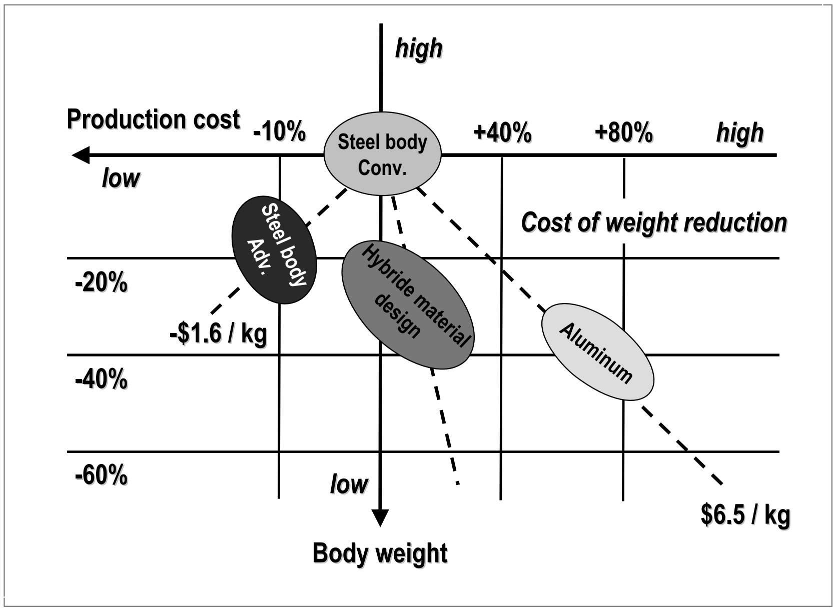

Figure 3. Impact of material concepts on the weight and cost balance of a car body.

In the premium segment several low volume cars are made from aluminum based on either space frame or unibody concept [4]. Higher margins in this segment justify higher production costs. Often such vehicles are candidates to test new materials and technologies as the low production volume makes productivity issues less critical. In the cost sensitive volume car segment, however, steel will remain the dominant body construction material also in the future. An attempt to establish an all aluminum car (Audi A2) in this segment has been abandoned after the first model generation. Another car model (Renault Espace) produced for two model generations with a plastic body shell was changed to steel in the third model generation to allow a significant increase of the production volume. Figure 4 indicates the evolution of the average material content in the body-in-white at present and in the future for the volume and premium segment, respectively [5].

Future scenarios indicate that in both segments steel is to contribute an average of at least 80% of the body-in-white weight (Figure 4). The use of aluminum is most evident for closure parts such as doors, bonnets and trunk lids. Figure 5 shows a forecast of the average aluminum consumption per vehicle. Plastic parts are typically used for outer skin parts such as fenders that can be screwed or bolted to the painted main body structure.

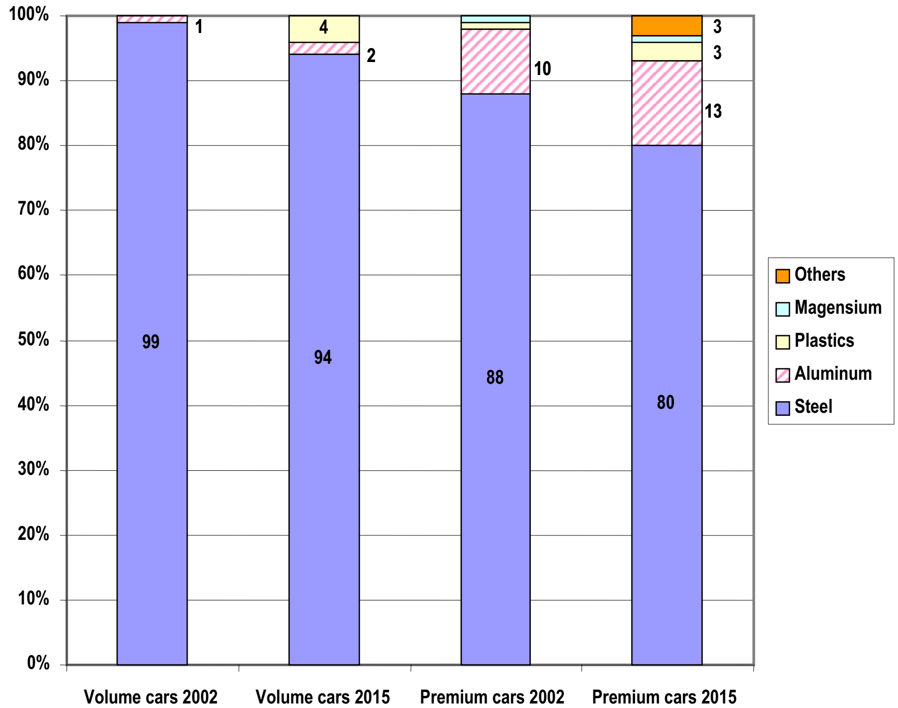

Figure 4. Evolution of material weight share in the body-in-white in volume and premium cars [5].

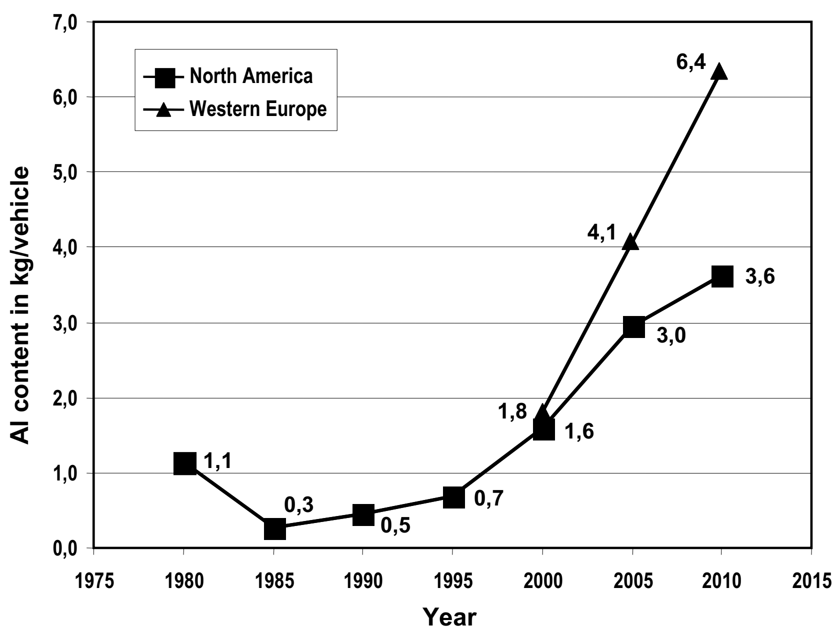

Figure 5. Evolution of the average aluminum consumption in volume cars.

Weight reduction using high strength steel

Body weight reduction with steel is a tedious exercise consisting of many small contributions. The key to weight optimized body components is based on systematic numerical simulation. In this way the body engineer determines the level a component is loaded either during service or in a crash situation. Based on such analysis the strength level of the steel to be used is specified. Once the strength level is determined, stamping and welding engineers have to assess if manufacturing of the component is feasible and also what particular steel grade should be most suitable. As mentioned before, many different steel types are available today and for a given yield or tensile strength often various metallurgical concepts can be applied offering options concerning formability and weldability. This requires a close cooperation of carmakers and steelmakers, and more precisely, a good mutual understanding of material properties and manufacturing processes.

Principally, the use of advanced high strength steel allows the further use of established manufacturing technology and equipment. However, specific know-how has to be built up concerning part layout as well as forming and welding methods.

Forming of High Strength Steels

General issues

Stamping engineers are used to specify the material to be applied by technological values such as yield and tensile strength, elongation as well as n- and r-value. Stamping simulation is typically performed using a tensile flow curve of the material as an input. Experience however has shown that this approach can result in inaccuracies or unexpected behavior especially when working with multiphase steel as discussed by Ford [4] and General Motors in this book [6]. Furthermore, the specific microstructural features of DP and TRIP steels steel can lead to failures during forming that are not predictable by numerical simulation.

Automotive forming methods usually consist of a sequence of individual forming operations. Figure 6 defines the basic forming operations such as deep drawing, stretching, stretch flanging, and bending. With regard to these specific forming modes the mere contemplation of the strength – elongation diagram (Figure 2) is not sufficient to select the optimum material. Each forming mode has additional demands with regard to specific mechanical parameters like the Lankford parameter (r-value), work hardening coefficient (n-value) and hole expansion ratio (λ-value). These parameters are strongly related to microstructural features of the material and, hence, they can be influenced by niobium microalloying in combination with a suitable processing strategy [1]. Accordingly, the effect of niobium in the different steel types is described briefly in the following.

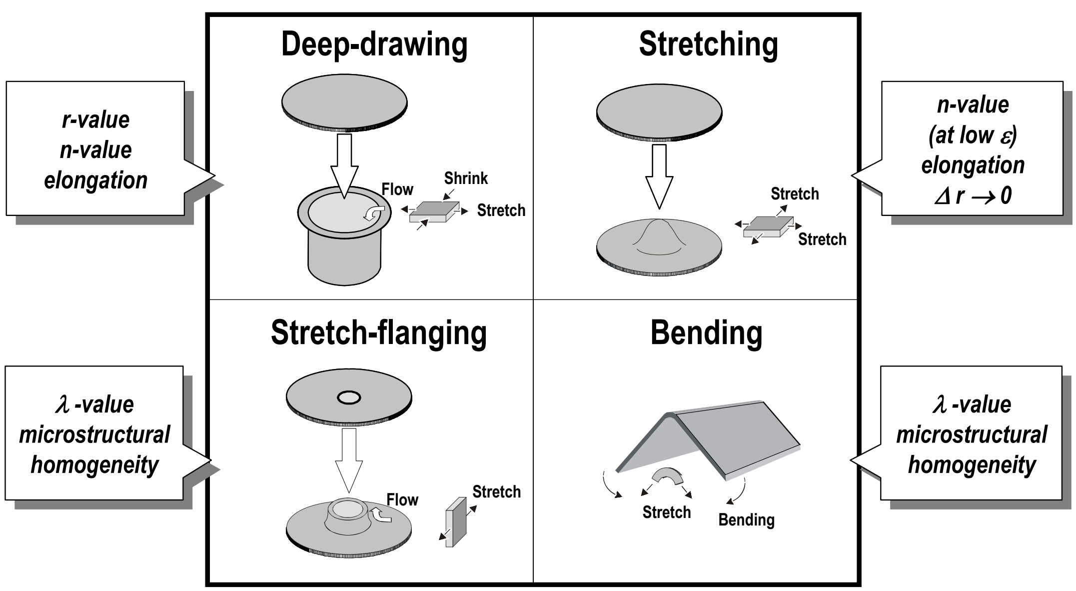

Figure 6. Different modes of sheet metal forming and characteristic material properties influencing the forming behavior.

IF high strength and IF Bake Hardening steel

The stabilization of residual solute carbon and nitrogen (less than 30 ppm each achieved by vacuum decarburization) in cold-rolled interstitial free (IF) steel is typically achieved via small additions of titanium and/or niobium. The good cold formability of IF steel is related to a high Lankford parameter (r-value) and appreciable strain hardening (n-value). High strength IF steels are typically based on niobium stabilization (~0.02%). Compared to a titanium grade, the niobium stabilized IF steel exhibits a finer grain size and thus higher yield strength. This derives from the already finer grain size in the hot strip material as niobium retards the austenite recrystallization during the final rolling passes due to a solute drag effect of the large niobium atom [13]. Furthermore, niobium in solid solution of the austenite also retards the transformation into ferrite, which has an additional grain refining effect. It should be noted however, that niobium stabilized IF steel requires a somewhat higher annealing temperature to achieve complete recrystallization after cold rolling as compared to titanium stabilization.

In contrast to the conventional ULC alloy design, two novel metallurgical approaches are reported in this book by Nisshin [7] and JFE [8]. Both concepts work with a significantly increased niobium content to either have niobium in solid solution or to form small NbC precipitates in combination with an elevated carbon content. Both concepts lead to a finer grain size, thus increased strength and better secondary cold work embrittlement behavior but still retain a very good r-value.

It is possible to also produce a bake hardening steel based on a partially stabilized ULC metallurgy. Such ULC based BH steels are advantageous compared to conventional low carbon BH steel as described by Voestalpine [9]. ThyssenKrupp outlines in this book that a partial stabilization based on niobium and at the most a substoichiometric addition of titanium with respect to nitrogen is the most favorable solution [10]. A solute carbon content of 5-10 ppm is necessary to obtain the desired BH-effect of at least 30 MPa and to avoid premature aging. The precise adjustment of the amount of solute carbon is easier to achieve in niobium-only stabilized steel. Thus, the scatter of mechanical properties of the BH steel is also reduced resulting in a better reproducibility of the final component properties. BH steel is very suitable for outer panels since it has a good formability and it is gaining extra strength after paint baking enhancing the dent resistance. Besides, Nb stabilized ULC BH steels expose a particularly low Δr-value, i.e. quasi-isotropy, which is beneficial with respect to stretch forming.

Microalloyed HSLA steel

Microalloyed HSLA steels were among the first high strength steel grades used in vehicle construction [1]. In some recent passenger cars they account for up to 40% of the body mass. A high yield ratio and thus a low work hardening potential is characteristic for these steel grades. This can be advantageous in achieving the specified minimum yield strength in the component, as the local yield strength is rather insensitive to the level of deformation induced during forming. Other characteristics of HSLA steel are the quasi-isotropy (Δr-value ~ 0) and the good fatigue resistance. HSLA steel is typically used for the manufacturing of parts with low and medium geometric complexity such as members, reinforcement and chassis components.

HSLA steel is available as hot-rolled and cold-rolled material. Cold rolled sheet can be produced by batch and continuous annealing in most of the existing cold rolling mills [11]. Accordingly, there is a broad worldwide availability of this material and also a large flexibility concerning the dimensions and surface treatments.

The production of HSLA steel is relying on niobium microalloying in combination with thermo-mechanical rolling in the hot rolling mill (see paper by SSAB in this book [12]). This treatment provides grain refinement and a homogeneous microstructure. Particularly the refinement of cementite particles is beneficial to improve the forming behavior. The desired strength level is adjusted by the Nb content (0.02 - 0.05%) and the content of solid solution strengtheners like Mn and Si. To achieve a yield stress of more than 400 MPa additional microalloying of Ti is applied (Figure 7). For a given chemical composition, hot-rolled material always exposes higher strength values as compared to cold-rolled material.

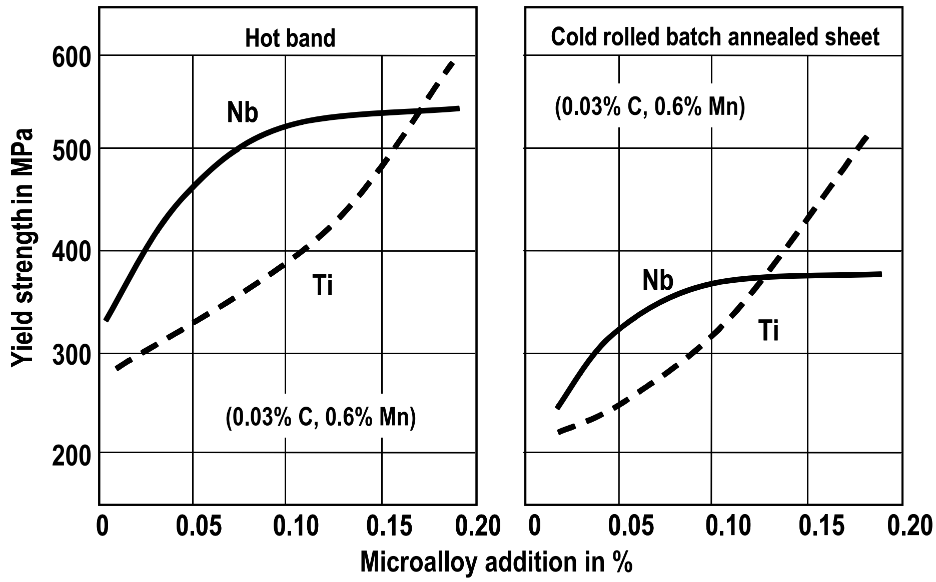

Figure 7. Strength increase of low carbon-manganese steel by Nb or Ti microalloying [1].

A recent approach to generate a microalloyed hot-rolled strip of 550 MPa yield strength was successful by reducing the carbon content to about 0.04 wt.% and increasing niobium content to at least 0.09 wt.% [13]. Besides of an extremely fine-grained microstructure, very low scattering in the mechanical properties within the coil and across batches was obtained. Particularly the narrow scattering of the yield strength is helpful to keep tight tolerances in the finished part. The sheet edges are particularly smooth after mechanical cutting operations due to the ferritic-bainitic structure. Furthermore, the rather low carbon content also results in a reduced edge hardening when laser cutting is employed. Accordingly, this steel is well suited for forming methods where high peripheral stress is induced to the sheet edge.

Dual Phase steel

Dual phase steels achieve their favorable combination of strength and ductility by developing hard martensitic particles embedded in a ductile ferritic matrix. The strength increase is mainly controlled by the volume fraction of the hard martensite phase ranging typically from 5 to 30 percent. A combination of low yield and high tensile strength, and consequently high work hardening is characteristic for this steel type. Currently commercialized cold-rolled DP steels with a strength level up to 600 MPa rarely use niobium alloying whereas in DP800 and DP1000 niobium helps to gain extra strength by grain refinement and precipitation hardening. This aspect is discussed in detail by SSAB [12] and Voestalpine [9] later in this book. It has been theoretically and experimentally shown that refinement of the microstructure in DP steel also leads to a better work hardening rate [14-16]. Accordingly, the optimum combination of strength and formability can be achieved by homogeneously dispersing fine martensite islands in a fine-grained ferrite matrix. Conglomerates of interconnected martensite can lead to premature failure of the material during bending operations and, thus, should be avoided as much as possible. The basis of obtaining a fine grained and homogeneous microstructure in cold rolled DP steel is the preparation of a suitable microstructure already in the hot band. This can be achieved by the combination of niobium microalloying and a low finishing temperature in the austenite region. A coiling temperature of 600 °C appeared to be most effective for precipitation of niobium carbide [17]. However, when exceeding 630 °C an increased degree of banded microstructure was found causing a deterioration of the n-value and the yield ratio [18].

In hot-rolled DP steel, niobium microalloying induces significant grain refinement causing a clear increase in strength [19]. Nb microalloying in combination with a high cooling rate and a coiling temperature below 200°C yielded a mean ferrite grain size below 2 µm. The tensile strength was found to be significantly higher than in a coarser grained material without Nb microalloying. Therefore, the Nb microalloyed material allows achieving a specified strength level with a lower martensite content, which is beneficial in maintaining a low yield ratio and high elongation.

In forming operations, the low yield strength facilitates the onset of plastic flow during stamping and the high strain hardening capacity of dual phase steel enhances the strain redistribution thus preventing local thinning. Depending on the forming method, the actual yield strength in the finished component varies locally according to the actual degree of forming and thus influencing the crash resistance of the component [20]. The large difference in hardness between ferrite and martensite impairs the performance of DP steel under forming methods with highly localized strain such as bending or stretch flanging. Microstructural refinement induced by niobium microalloying as well as the presence of a small amount of bainite help to improve the λ-value controlling this performance.

TRIP steel

The highest elongation at very high strength level is currently achieved with TRIP steel. The mechanism behind that favorable combination of properties is the conversion of metastable austenite to martensite upon straining. It is evident that the extent of the TRIP effect is depending on the amount and stability of retained austenite in the microstructure. Niobium microalloying to hot-rolled TRIP steel has been shown to stabilize retained austenite. This is described in more detail by Kobe Steel in this book [21]. Already the addition of a small quantity of niobium results in a significant increase of the retained austenite fraction. Moreover, grain refinement of the ferritic matrix is achieved contributing to a generally higher strength level [1, 19]. Both niobium induced effects work in a synergetic way towards a significantly increased energy absorption capability (Figure 8).

When producing cold-rolled TRIP steel the combination of a low coiling temperature (~500°C) and niobium microalloying was found to cause a remarkable decrease of the martensite start temperature [22]. Solute Nb precipitates as very small particles during intercritical annealing after cold rolling controlling the grain size and ensuring a homogeneous microstructure. It has also been speculated that the fine-grained microstructure might be responsible for a delayed bainite formation and could thus explain the reduced amount of bainite found experimentally.

Similar to DP steel, TRIP steel shows excellent performance under stretching conditions due to its significant work hardening behavior and its high homogeneous elongation. Additionally, it is noteworthy that TRIP steel exhibits also a good deep-drawability. This is due to the observation that less austenite is converted to martensite under shrink flanging conditions and more during plane strain deformation in the wall [23]. Accordingly, the stronger wall area is pulling the softer flange area into the die without breakage. The potential of this mechanism should be enhanced by Nb microalloying as it increases the retained austenite content in the steel.

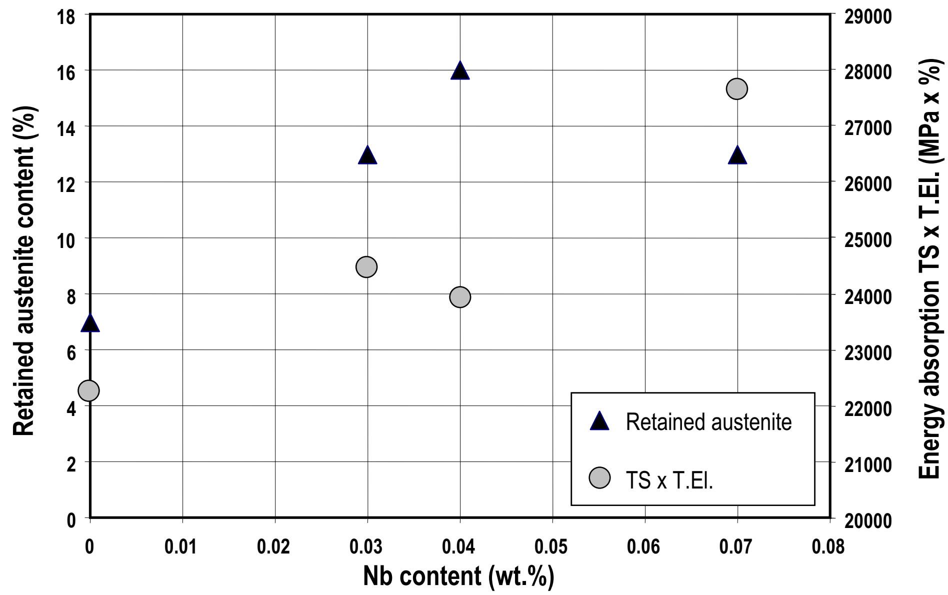

Figure 8. Effect of niobium on energy absorption capability and volume fraction of retained austenite in hot-rolled CSiMnAl TRIP steel [19].

A major concern when forming DP and TRIP steels is the dimensional accuracy of the parts. High residual stresses generated in these steels during stamping cause part distortions in form of springback, twist and curl. There are several countermeasures to compensate these effects by adapting the part layout and optimizing the stamping method. These approaches are described in more detail in this book by General Motors [6], Ford [4], Nissan [24] and Fiat [3].

Ferritic-bainitic and bainitic steels

For the application in chassis parts and wheels, stretch flanging, bending, hole expansion and flare forming are dominating forming modes. These forming modes require a material with high λ-value. The part application demands a high stiffness and fatigue strength. Part stiffness is governed by the Young's modulus and gage whereas fatigue strength is related to the tensile strength and sheet gage. Besides, a fine-grained microstructure and absence of inclusions is also important to obtain a good fatigue performance. Bringing all these demands together, high strength hot-rolled steel with ferritic-bainitic or bainitic microstructure is the material of choice. Figure 9 shows that this combination of properties can be clearly optimized by selecting an appropriate microstructure and chemical composition of the steel.

Low carbon-manganese-silicon steel with ferritic-bainitic microstructure shows the best property combination and the lowest scatter in the tensile strength class of up to 600 MPa. Niobium is the standard microalloying element in these steels.

The theoretical lightening potential of 600 MPa class steel grades as compared to conventional 340 MPa material is around 20%. Applying however a 800 MPa material would increase the lightening potential to more than 30%. In this respect, the paper of Sumitomo [25] demonstrates the development of hot-rolled steel for wheel application in the 700 and 800 MPa class. A single chemical composition based on low carbon and silicon, manganese, chromium as well as niobium and titanium microalloying allows reaching the targeted strength. By variation of the coiling temperature the steel's microstructure can be adjusted to give either a better hole expansion ratio or a better elongation.

An important issue in the steel development of several Japanese steel mills is the design of so-called balanced steel grades meaning that these steels combine a high hole expansion ratio and a high elongation. This is achieved by microstructural control and avoidance of large hardness gradients in the microstructure [26].

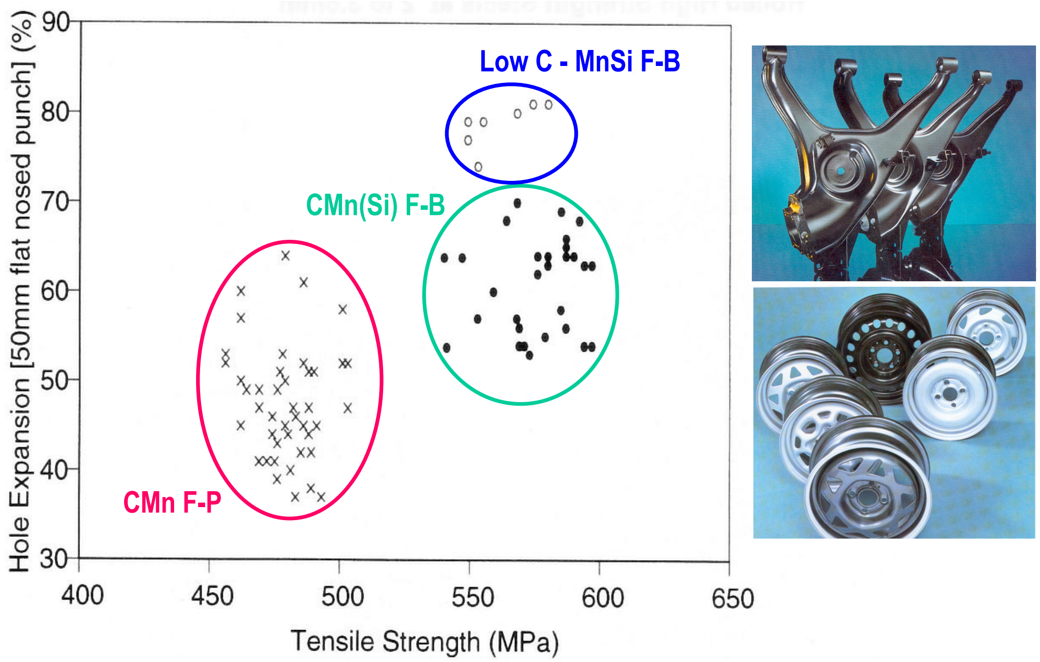

Figure 9. Relationship between hole expansion ratio and tensile strength for various steel types (F-P: ferritic-pearlitic, F-B: ferritic bainitic) and typical applications.

<u>Martensitic steel</u>

Partial or fully martensitic steels currently offer the highest strength for automotive body and chassis parts. These steels are available as hot rolled and cold rolled grades having a tensile strength of more than 1000 MPa. Naturally the formability is limited and only relatively simple part geometries can be manufactured. Refining the microstructure has a favorable impact on the formability and, thus, niobium is usually microalloyed to these steels as outlined by Voestalpine [9] and SSAB [12].

Since some years the use of hot-formed components has become increasingly significant. In a recent Volkswagen model the share of hot-formed components reaches about 15% of the structural body weight. The typical press-hardening (PH) steel is 22MnB5 with titanium and boron microalloying. The steel sheet is heated to around 950 °C just before stamping and is then pressed in a water-cooled die. Formability of the hot material is excellent and due to the die quenching the final strength of the part will be in the order of 1500 MPa as outlined by Volkswagen [27]. A process variant is described by Toyota [28] where the component is cold formed starting from a cold-rolled recovery annealed material and selective hardening is done by induction heating and quenching on the stamped component. The final strength of the martensite is determined by the carbon level in the steel (see Figure 10) and the cooling rate after stamping.

One of the concerns arising with PH steels is that of impact toughness. As the microstructure fully consists of very hard martensite, ductility is low. This is particularly critical as such parts a typically used in areas being prone to high impact load in the event of a crash. However, no reliable data are available on the ductile-to-brittle transition behavior. The use of niobium microalloying could help to improve the toughness of hot-forming steel as is inferred from a recent study by ThyssenKrupp on quench-tempered heavy plate [29]. In this case titanium, which serves to protect the boron from combining with solute nitrogen, would be replaced by a combination of niobium and aluminum. This has the effect that coarse TiN particles that could act as crack initiators are avoided and replaced by finer Nb(C,N) precipitates reducing the grain size during hot-rolling as well as limiting grain growth during the heating to 950°C before stamping. Grain refinement is always beneficial for toughness.

Welding of High Strength Steels

Welding is still the by far dominating joining technology in today's car body assembling. One advantage of steel as a construction material is its in general good weldability as compared to aluminum. Nevertheless the aspect of weldability must be discussed in view of the different steel grades mentioned before and also regarding the particular welding processes used in modern car assembly plants. Resistance spot welding is the standard method for joining but laser welding is gaining significant share since several years (see Table I). Besides, MAG and MIG welding is used for specific applications for instance in chassis construction, and flash-butt welding is applied for closing the wheel rim. In the sequence laser, resistance spot, MAG, MIG and flash-butt welding the heat input increases and the cooling speed decreases, respectively. Both characteristics have influence on the weld hardness as well as the size and microstructure of the heat affected zone. Depending on the metallurgy of the steel, the material response is quite different.

Weld hardness

When estimating the tendency of a steel grade to form hard structures in the HAZ, usually the carbon equivalent is considered. The two most common formulae of the carbon equivalent are:

$$CE\left[IIW\right] = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15} \qquad \text{for } C \geq 0.18\% \tag{1}$$

$$CE\left[Pcm\right] = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5 \times B \qquad \text{for } C \leq 0.16\%. \tag{2}$$

The higher the carbon equivalent, the lower is the critical cooling speed to form martensite. The final hardness of martensite, however, solely depends on the absolute carbon content [30]. Microalloyed high strength steel has a carbon content of less than 0.10%. Traditional C-Mn high strength steels as well as modern ultra high strength multiphase steels can considerably exceed this value. It is not possible to directly link the carbon equivalent to the cold cracking susceptibility as microstructure, hydrogen content and restraint conditions also play an important role but generally hardness values of less than 350 HV in the HAZ are considered to be safe. On the other hand, the HAZ should not be too soft as in this case it would form a weak link having the risk of premature and unpredictable failure.

Under automotive laser welding conditions in thin sheet, the cooling speed will be always high enough to produce martensite in the fusion zone, regardless of the carbon equivalent. Therefore, the hardness of the fusion zone depends on the absolute carbon content only as demonstrated in Figure 10 for a wide variety of modern automotive steels [31]. For typical chemistries of TRIP and PH steels the weld hardness exceeds 500 HV making such weld seams very sensitive to cold cracking.

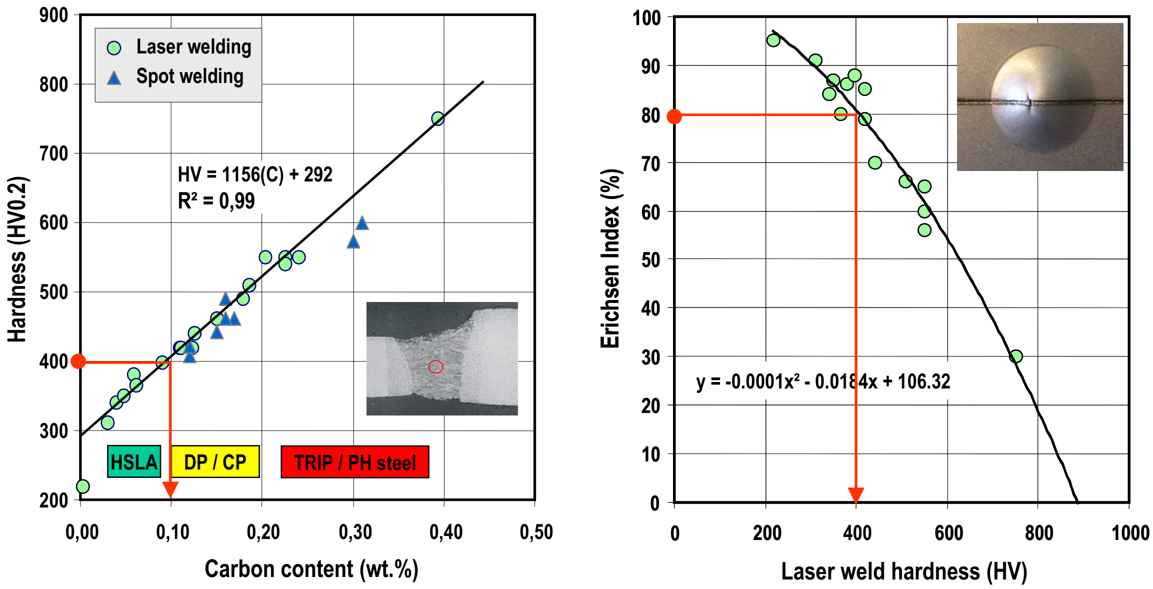

Figure 10. Relationship between carbon content and weld hardness in automotive steel after laser and resistance spot welding (left). Correlation between weld ductility and weld hardness after laser welding evaluated by Erichsen cup testing (right).

The weld ductility can be evaluated by Erichsen cup testing. The Erichsen index relates the ductility of a welded material to that of the base material. Good ductility of the weld may be required because a forming operation is taking place after welding in the case of a tailored blank or tube. On the other hand, an assembly weld in the body structure must remain sound in the case of crash deformation to avoid premature structural disintegration. To avoid cold cracking and to provide reasonable weld ductility, the weld hardness should not exceed 400 HV. Translating this in to the steel's chemistry, the carbon content should be preferably below 0.10%.

ULC based steel types having a carbon content below 50 ppm exhibit a very moderate weld hardness being below the expected maximum value (Figure 10). This is due to a self-tempering effect assisted by the high martensite start temperature in ultra low carbon steel [31]. In HSLA grades self-tempering can also be achieved, e.g., by artificially increasing the heat input. In DP, TRIP and PH steel grades self-tempering is not effective as the martensite start temperature is too low. Besides, a significantly increased heat input would weaken the material in the heat-affected zone below the strength of the base material. Therefore, the weld hardness can only be reduced by post-weld heat treatment. A feasible technology is to trail the welding head with an induction coil post-heating the weld seam to temperatures in the order of 600 °C. Alternatively BMW [32] has investigated the possibility of pre-heating before laser welding. Most feasible is such an additional heat treatment during spot welding by including pre- and post-weld current cycles. However, either treatment is not always practical in a mass production assembly line be it due to geometrical constraints or due to time limitation.

Nissan [24] shows a correlation of the tensile-shear strength and the cross-tensile strength of resistance spot welds with the carbon content in high strength steel. Based on the results the reduction of the carbon level in high strength steel is suggested to obtain higher tensile-shear and cross-tensile strength.

Heat-affected zone (HAZ)

In the fusion zone weld hardness and thus strength are usually higher than those in the base material. The critical area is the HAZ neighboring the fusion zone. The heat cycle can modify the material in many different ways depending on the local peak temperature and the cooling speed.

Ultra low carbon steel

According to the iron-carbon phase diagram, the α to γ transition temperature in ultra low carbon steels is considerably higher than in conventional carbon steels. As indicated in Figure 11, the transition temperature is between 723 and 911 °C depending on the free carbon content. Particularly the zone around the spot weld experiencing more than 800 °C shows significant grain growth. Figure 11 gives evidence of such grain growth in the HAZ of a resistance spot weld on titanium stabilized IF steel. The HAZ surrounding the fusion zone exposes huge grains of columnar morphology. According to the Hall-Petch relationship the coarse grained microstructure has a lower strength than the finer grained base material making the heat affected zone to a weak link. Upon mechanical loading the spot weld will button out in the heat affected zone under a reduced force. Similar grain coarsening has been observed in the HAZ of laser welds on such material. Impeding the grain boundary mobility either by precipitate pinning or by solute drag of niobium or boron atoms in the grain boundary can avoid grain coarsening. From that point of view the new ULC high strength steels presented by JFE [8] and Nisshin [7] in this book should have favorable welding properties.

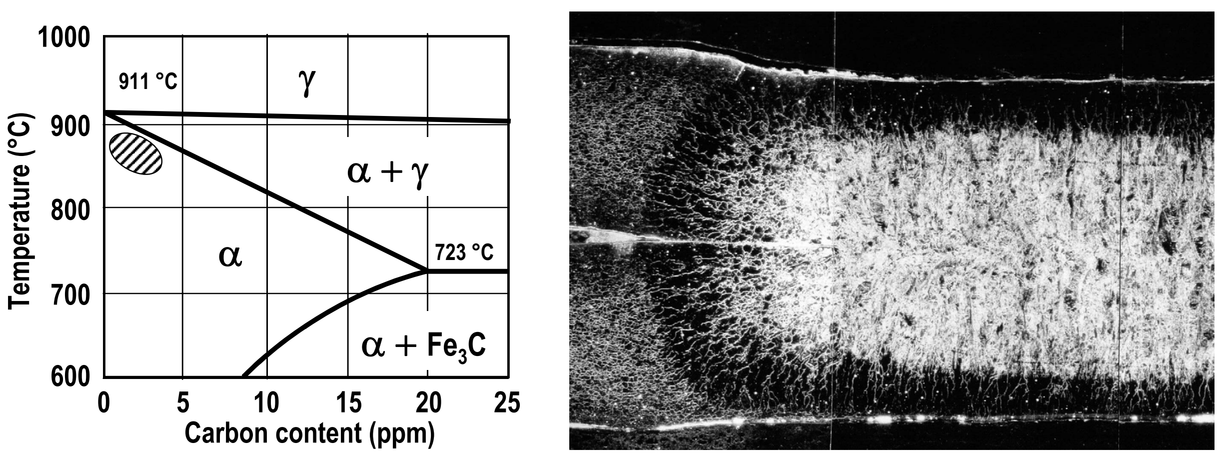

Figure 11. Ultra low carbon corner of the iron-carbon phase diagram indicating the region of effective α-grain growth. Grain coarsening in the heat-affected zone of titanium stabilized IF mild steel after resistance spot welding.

Advanced high strength steel

Multiphase steels contain hard martensite phases in the original state. Thus any significant heat input will lead to a tempering of the existing martensite. On the other hand, depending on the cooling speed and the alloying concept, new martensite can be formed in the HAZ. Consequently, the mechanical strength depends on the balance of modified existing phases and newly formed hard phases.

This is most obvious in dual phase steel where the original material consists of ferrite and martensite. The share of both phases determines the ultimate tensile strength. The very fast heating cycle of a laser welding process is ideally suited to generate additional martensite in the HAZ. This is demonstrated in Figure 12 (a) for DP800 and Figure 12 (b) for DP600. It can be recognized that the amount of martensite in the HAZ is larger than in the base material (BM). Therefore the material hardness continuously increases from the BM via the HAZ to the fusion zone (FZ). Other multiphase steels behave similarly as shown in Figure 12 (c-d) for laser welding on complex phase steel (CP800) and transformation induced plasticity steel (TRIP700).

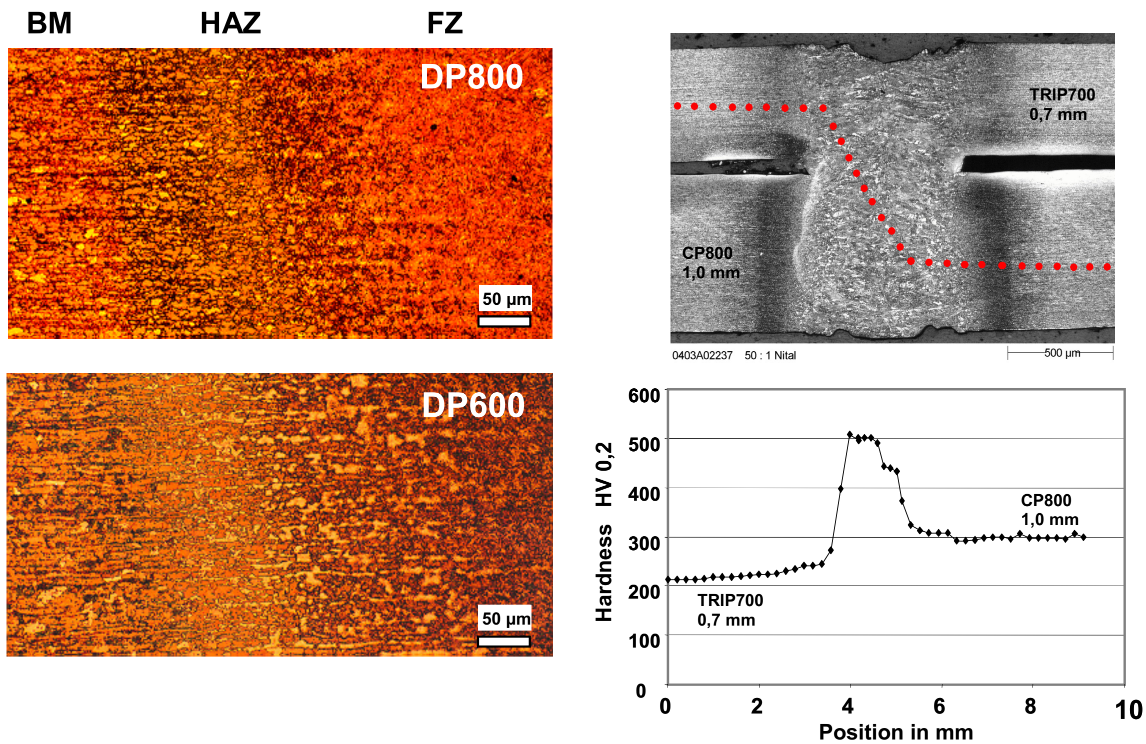

Figure 12. HAZ of laser welded dual phase steels (a) DP800 and (b) DP600; light phases are martensite, dark phases are tempered martensite. Laser overlap weld between TRIP700 and CP800 (c) and hardness scan across the overlap weld (d).

For steel grades above a strength level of around 1000 MPa even the fast thermal cycle by laser welding leads to softening in the HAZ. This is demonstrated by SSAB [12] for their DP1000 grade. The hardness drop in the HAZ is approximately 50 HV as compared to the base metal. A more severe softening effect is observed when laser welding a quench-hardened hot forming steel (22MnB5) as shown in Figure 13. Here the hardness drop is about 200 HV below the base metal hardness [38]. Such a loss in hardness and strength can severely deteriorate the performance of the welded structure under applied loads.

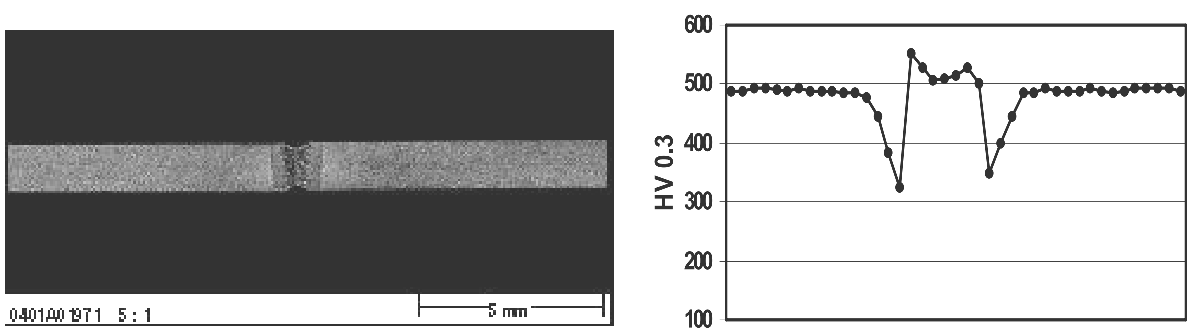

Figure 13. Hardness scan across a laser weld seam applied to hot forming steel (22MnB5) after quench hardening.

Hot-rolled steel grades

Hot rolled steel grades are typically used for chassis, suspension and wheel applications. In these areas welding processes such as MAG and MIG welding or flash butt welding are typically applied. These welding processes have a much higher heat input as compared to laser welding and consequently expose a lower cooling rate. Hence the microstructural modifications in the weld zone will be different to that in a laser weld. To estimate the tendency to form martensite at this lower cooling rates indeed the carbon equivalent as defined in equations (1) and (2) is applicable. Clearly, low carbon microalloyed steels perform better than traditional carbon-manganese steels.

SSAB indicates that MAG welded hot rolled microalloyed steels have the same tensile strength across the weld as the non-welded base material up to a strength of 800 MPa [12]. Softening only occurs in material above this strength level.

Softening unavoidably occurs when flash butt welding hot rolled DP600 for wheel rim closing. Since the welded rim is expanded later on local necking and premature failure is likely to occur in the softened zone. Therefore ferritic-bainitic steel appears to be the better choice for this application. Tata Steel [33] outlines that the formation of NbC precipitates limits the grain growth in the HAZ and restricts softening in a ferritic bainitic steel of 600 MPa tensile strength. However, some low temperature transformation products are found in the fusion zone leading to a moderately increased hardness.

The so-called HTP (high temperature processing) steel offers a very favorable welding behavior. This steel concept is based on low carbon (≤0.04%) and high niobium (~0.10%). The strength level can be adjusted by the specific alloy concept. Currently, a S550 hot rolled strip is being produced using this concept [34]. The CCT diagram of typical HTP steel shown in Figure 14 demonstrates that bainite is obtained in the HAZ over a wide range of cooling speeds rendering very moderate hardness variation. Only for highest cooling rates as prevalent in laser welding the formation of martensite can be expected. Due to the low carbon content, the hardness of the martensite remains definitely below 350 HV according to Figure 10, which is a major asset with regard to cold cracking susceptibility. Furthermore, the low temperature toughness of the HAZ in welded HTP steel was proven to be very good [35].

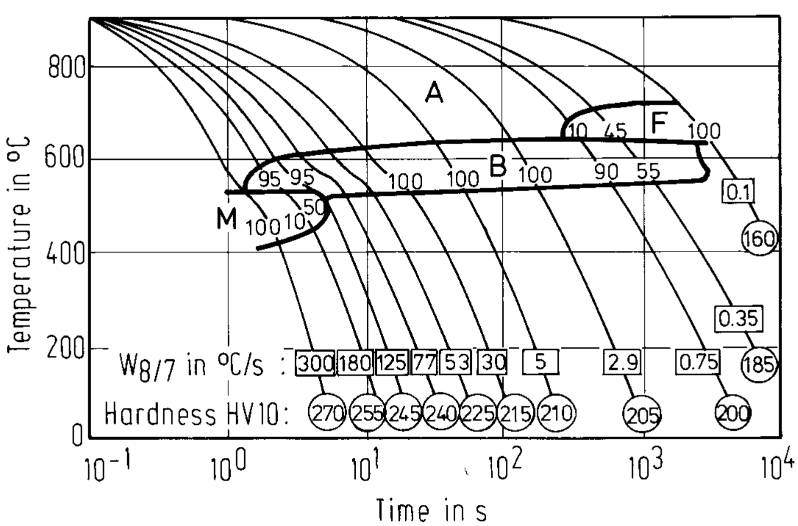

Figure 14. Transformation behavior for simulated HAZ (peak temperature 1350 °C) of HTP steel (0.03 %C, 0.10 %Nb, 1.75 %Mn).

Lightweight Enabling Technologies

In Table I it was indicated that several novel technologies are utilized to enable further weight savings and cost reduction in modern body construction. Some of these technologies require innovative semi-products such as tailor welded blanks or tubes. Others demand specific material properties.

Tailor welded blanks

Tailor welded blanks are produced by laser butt-welding two or more individual configured blanks to a preassembly that is subsequently stamped. As such the technology represents an inversion of the traditional process chain of forming before welding [36]. Necessarily the technology requires a highly formable weld seam. A criterion is the Erichsen index as defined in Figure 10. Accordingly, steel grades with a maximum carbon content of 0.10% can be considered to perform without any problem. Steel grades with higher carbon content require a specific qualification and may limit the design possibilities or need a post weld heat treatment to reduce the seam hardness [31].

The laser butt-welding process demands high dimensional tolerances of the configured sub-blanks. This is provided by low residual stress and high flatness of the coil before blanking. Furthermore the quality of the blanked edge that is to be welded must be superior exposing a high cut-to-break ratio and a smooth edge surface. This behavior is influenced by the cutting die clearance as well as by the strength and microstructure of the material [37].

Tailored tubes

Tube hydro forming relies on a thin walled tube, which is expanded under high internal pressure resulting in high stress transversely to the weld seam. Therefore HAZ softening must be absolutely avoided to prevent premature bursting of the tube. Often also pre-bending of the tube is necessary. Hence, the hardness of the weld seam should be moderate to reduce the risk of weld splitting. Since laser welding is typically used to manufacture such tubes, the weld hardness can be anticipated by the relationship given in Figure 10. The same conditions concerning material preparation before welding apply as for tailor welded blanks.

Tailor rolled blanks

This relatively new technology rolls a narrow strip to variable thickness by systematically varying the rolling gap in a special cold rolling stand. Blanks are cut off from the coil containing specific gage sections according to the engineering requirements in the vehicle application. In the current process the full hard coil is subjected to batch annealing and can be optionally hot dip or electro galvanized. Due to the batch annealing process the choice of steel grades is limited to soft steels and microalloyed high strength steels up to 420 MPa yield strength. The production of multiphase steels requiring a continuous annealing process is more difficult since the heating and cooling rate depends on the varying gage along the strip. In some cases full hard multiphase steel is formed to parts like bumper beams. Tailor rolled blanks are also being formed to tailored tubes, which are then subjected to hydro forming.

Press hardening

As mentioned before, hot forming with subsequent die quenching is frequently applied to produce ultra high strength parts of complex shape. One of the challenges is that of surface coating. Uncoated parts carry an oxide layer after stamping that must be removed by shot blasting. In current practice the AlSi coating is the most often applied surface protection. However, the AlSi coating is brittle and can flake off when a cold forming operation is necessary before hot stamping. Other technologies overcoming this problem are in development.

A further considerable problem is that of assembling press hardened parts in the body shop. As the current press hardening steel contain at least 0.22 %C, weld hardness after spot or laser welding easily reaches 500 HV but also softening occurs in the HAZ (see Figure 13). To avoid such welding related problems, tailor-welded blanks have been designed consisting of press hardening steel and low carbon microalloyed steel [38]. The hardness variation generated by laser butt-welding is homogenized during soaking at 950 °C rendering a hardness step after quenching from the softer to the harder steel without HAZ softening (Figure 15). By designing the blank so that the softer material covers the area to be joined in the assembly line, welding problems are completely avoided. From Figure 14 it appears that HTP steel should be particularly suitable for this type of application due to its low carbon content and its small hardness sensitivity with respect to the cooling rate.

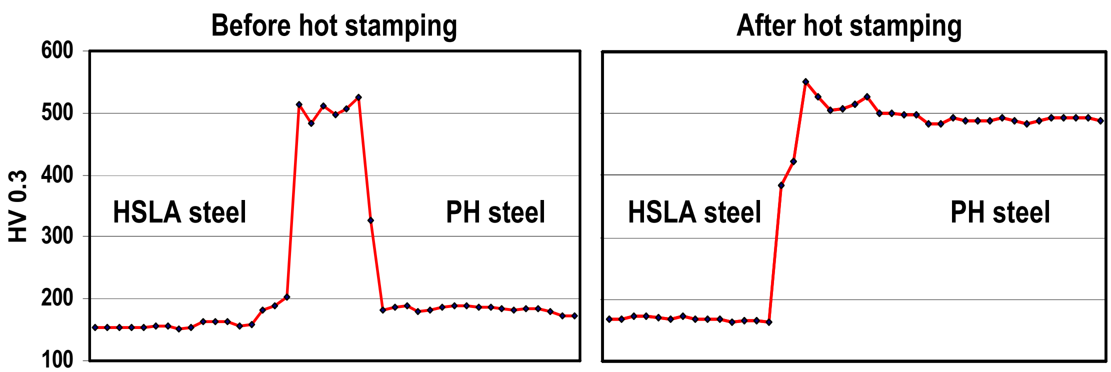

Figure 15. Hardness variation in a laser welded blank consisting of a low carbon HSLA and a press hardening steel before and after hot stamping.

Roll forming

Roll forming is a very flexible technique to produce open or closed profiles that can be used for rails, beams or members. The possibility to dynamically compensate springback is particularly advantageous with respect to multiphase steels. The major forming mode during roll forming is bending. Thus, microstructural homogeneity and a good λ-value in the material to be roll formed are desired characteristics. An important aspect with respect to the final performance is the part strength. As typically yield strength is the design criterion, steel with a low yield ratio such as dual phase or TRIP steel should be considered carefully. Since there is only localized bending occurring in the roll forming process, global strain hardening and thus a significant increase of the yield strength is not taking place in the material. Hence, ferritic-bainitic, complex phase and martensitic steel with initially high yield strength and a good λ-value seem to be the best suited materials for roll forming parts.

Modern press line technology

Stamping of high strength steel necessarily requires higher stamping force. The article of Ford Motor Company [4] clearly indicates that the increase in peak press force is proportional to the increase in tensile strength of the material to be stamped. Therefore many carmakers had to invest in new press lines with higher force but also with larger table size because other trends are the increase of the part size as well as the stamping of multiple parts in one hit [39]. The increased part size is a consequence of part integration, which became possible by using formable high strength steel or tailor-welded blanks. Figure 16 shows an example of such an integrated panel using a combination of tailor welded blank and high strength steel. Part integration avoids overlap zones that are required of overlap welding in the body shop, gives better packaging possibilities and reduces the amount of stamping and assembling work. It thus not only supports lightweight engineering but also reduces production cost. Stamping of multiple parts per hit is an efficient way of increasing press line productivity and reducing cost as indicated by Figure 17.

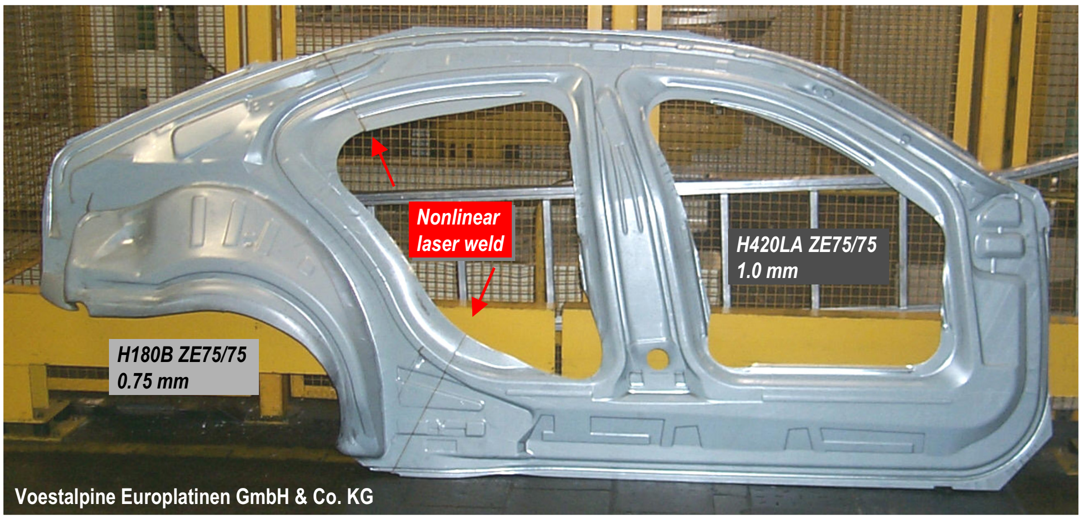

Figure 16. Example of an integrated body side inner panel of the BMW E65 (7-series) using a non-linear laser welded blank consisting of BH steel (YS: 180 MPa) and microalloyed high strength steel (YS: 420 MPa). Blanks are stamped as two per hit (LH & RH side) on a 9,500 t transfer press.

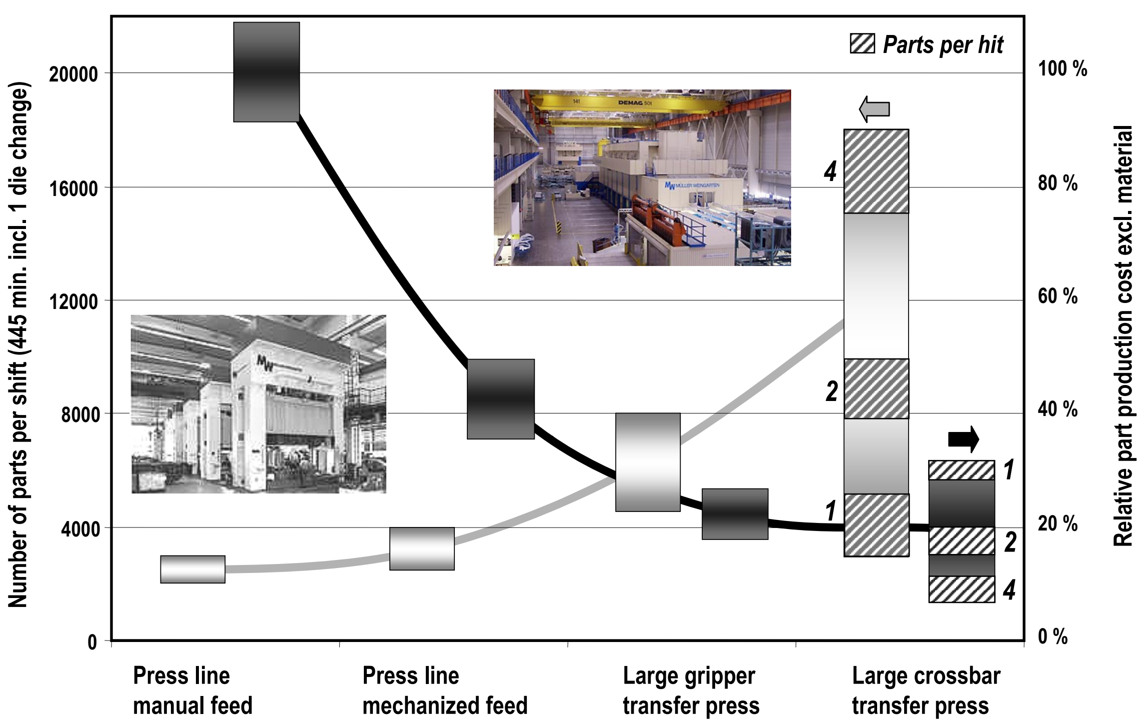

Figure 17. Performance and part production cost of different press line systems [39].

Using such modern press line technology adds further requirements to the material. Large area panels usually require a big coil width, sometimes as wide as 1900 mm. Obviously, the mechanical properties of the material have to be in a tight scatter band across the coil width. When multi part stamping is performed additionally a tight scatter band over coils originating from different heats is required. Such low property scattering can only be guaranteed by strict parameter control along the entire process chain in the steel mill as shown in Figure 18. In this respect the prediction of microstructures and mechanical properties is an important point for the control of steel properties and quality. Models have been developed to simulate the thermo mechanical history of a steel product, its metallurgical evolution and final properties as described in detail by Arcelor [40]. Such models assist the industrial process setup.

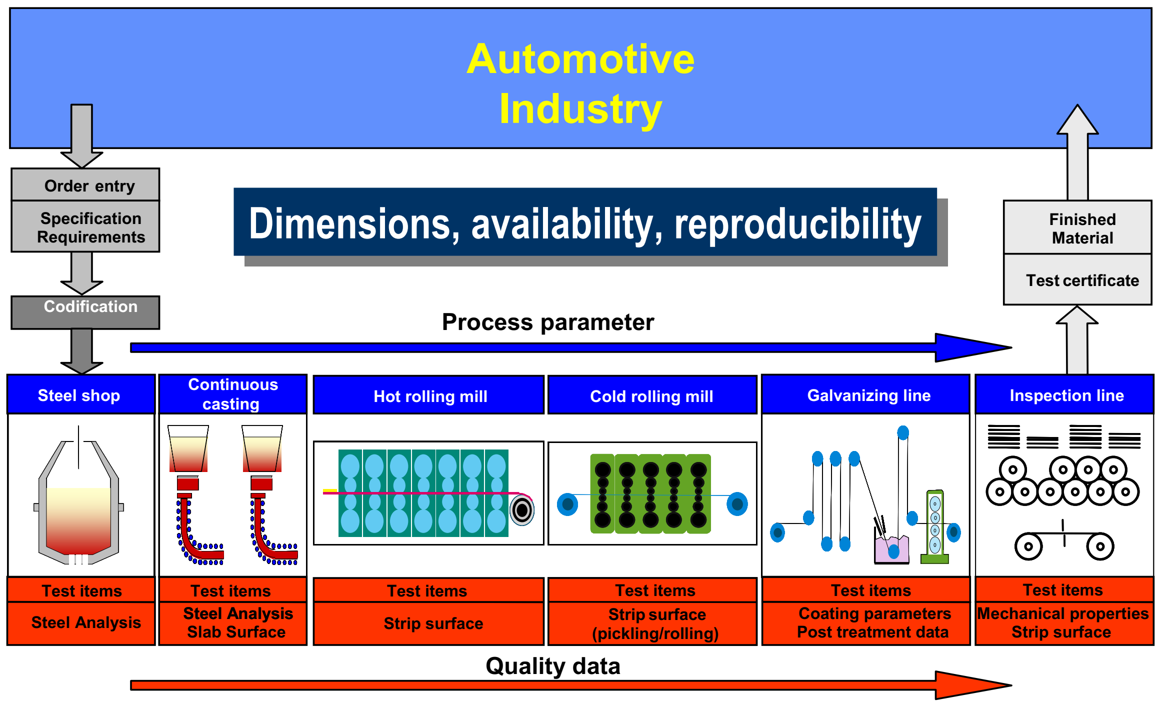

Figure 18. Process parameter and quality monitoring along the process chain for automotive flat steel products.

Summary

Recent lightweight body engineering makes massive use of modern high strength steel. This approach simultaneously enables moderate weight and cost reduction and nevertheless meeting the targets of emission control, safety, driving performance and lifetime. The full recyclablity of steel is an additional asset with regard to end-of-vehicle-life regulations.

The different classes of high strength steel for automotive applications are primarily defined by the constitution of phases being ferrite, pearlite, martensite, bainite and retained austenite. The deliberate mixture of two or more phases is used to achieve a particular property profile of the steel. Microstructural control by niobium microalloying was demonstrated to be a powerful tool for optimization of the property profile of such steels:

- The fundamental effect of niobium is that of grain refinement increasing the strength without deteriorating the ductility. This mechanism allows a leaner alloying concept to reach the specified strength level.

- A leaner alloy concept is beneficial with regard to welding operations. Especially welding processes with high cooling rate require a low absolute carbon content to keep the weld hardness on a tolerable level.
- Grain refinement also brings about a more homogeneous microstructure improving the forming behavior particularly when highly localized strains are being induced such as in bending and stretch flanging.
- Niobium can exert a significant influence on the transformation behavior allowing to promote or retard the formation of individual phases. This can be exploited to exert better process control and optimize properties when producing multiphase steels.
- The formation of NbC precipitates is used to partially or fully scavenge carbon from the ferrite matrix of ULC steel to obtain bake hardening or high strength IF steel.

Of all the considered high strength steels for automotive body applications, microalloyed HSLA steel has the best worldwide availability as it can be produced via batch annealing and continuous annealing processes. Tolerances of the mechanical properties are small. Microalloyed HSLA steels are readily suited for all different coating processes such as galvanizing and galvannealing. Furthermore, these steel grades offer the widest spectrum of gage and coil width. Some of the most recent body structures consist already of up to 45% microalloyed HSLA steel.

Multiphase steels have gained a significant share in vehicle bodies reaching about 20% in the currently most advanced body structures. The best-established multiphase material is dual phase steel. The majority of the material is produced using the hot dip continuous galvanizing process. Compared to microalloyed HSLA steel the availability of multiphase steel is limited to fewer steelmakers operating specialized equipment and having considerable experience in automotive strip production.

Ultra low carbon steels with increased strength are an established and indispensable material especially for parts that require highest formability and best surface appearance. Niobium microalloying offers an additional potential to further improve these characteristics but also allows to tightly control the scatter of mechanical properties.

The cost of niobium as a ferroalloy has been kept nearly stable by CBMM on a moderate level since many years as compared to other microalloying elements such as titanium, vanadium or molybdenum. Since the amount of niobium needed to achieve the desired effect in terms of strength enhancement and property improvement is also comparably low, niobium microalloying is a very cost attractive way of producing automotive high strength steel.

The total niobium consumption in Europe’s 2005 vehicle generation is in the range of 60 to 100 grams including trim scrap losses. This represents a cost contribution of less than $2 to the entire body-in-white. Thus, it can be truly stated that niobium microalloying to steel is one of the most cost efficient approaches to lightweight body engineering.

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