2001-01-3042

New High Strength Steels Applied to the Body Structure of ULSAB-AVC

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ABSTRACT

In the ULSAB Project released in 1998, high strength steels (HSS) were applied to 90 percent of the body and structural components, and a mass saving of 25 percent compared to an average of benchmark vehicles was achieved. In the ULSAB-Advanced Vehicle Concepts (AVC) Project, high strength steels are used for most of the components, but many of these materials are identified as ultra high strength steel (UHSS) grades of advanced high strength steels. These grades include dual phase (DP) from 280 MPa yield (YS) to 1000 MPa tensile (UTS), complex phase (CP) 700/800 MPa (YS/UTS), and martensitic (Mart) 1200 MPa and 1520 MPa (UTS) grades. This paper reviews how these materials are applied to specific parts of the ULSAB-AVC Class-C and Class-PNGV vehicle concepts and the reasons for their selection. It also compares the materials used in the body structures of ULSAB and ULSAB-AVC

INTRODUCTION

Engineered steels provide automotive designers and manufacturers with the unique option of combining lightweighting with the traditional steel advantages of low cost and eco-efficiency. This was clearly demonstrated by the UltraLight Steel Auto Body (ULSAB) Program [1] and was achieved, in part, through the extensive use of both high strength steels (HSS) and ultra high strength steels (UHSS).

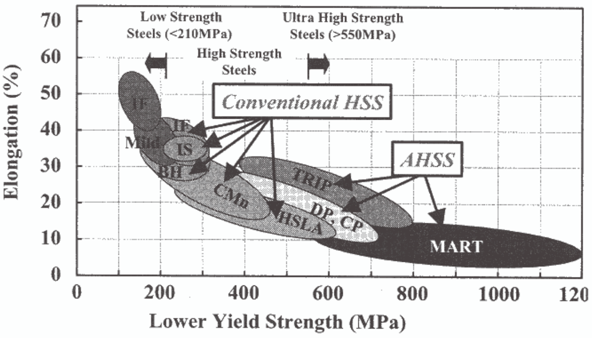

Figure 1. Strength-Formability relationships for mild, conventional HSS, and advanced HSS steels.

The HSS grades used in ULSAB utilized mostly conventional microalloy approaches. The goals for ULSAB-Advanced Vehicle Concepts (ULSAB-AVC) are more aggressive than for ULSAB because of the need to reduce the added mass required to satisfy future safety mandates. For ULSAB-AVC, it is therefore appropriate to also consider the application of newer types of high strength steels, the so-called advanced high strength steels (AHSS), to assist in achieving the overall aims of the program through the design of an efficient lightweight body structure.

In contrast to ULSAB, where a key focus was to demonstrate the manufacturing feasibility of the aggressive use of readily available HSS and modern manufacturing processes (e.g. tailored blanks, hydroforming, assembly laser welding), ULSAB-AVC is a concept program to develop designs for both US PNGV-class and European C-class vehicles. This provides an opportunity to expand the list of candidate steels by considering those steels that are currently available and those that will become available by 2004. This paper describes the rationale used to select AHSS for optimum performance in static structural and dynamic crash applications in the ULSAB-AVC body structure, highlights the steel grades selected for various body structure components, and compares body structure steels used in ULSAB and ULSAB-AVC.

DEFINITION OF AHSS

Consistent with the terminology adopted for ULSAB, high strength steels (HSS) are defined as those steels with yield strengths from 210–550 MPa; ultra high strength steels (UHSS) are defined as steels with yield strengths greater than 550 MPa. The yield strengths of advanced high strength steels (AHSS) overlap the range of strengths between HSS and UHSS, as shown in Figure 1. The principal differences between conventional HSS and AHSS are due to their microstructures. AHSS are multi-phase steels, which contain martensite, bainite, and/or retained austenite in quantities sufficient to produce unique mechanical properties. Compared to conventional micro-alloyed steels, AHSS exhibit a superior combination of high strength with good formability. This combination arises primarily from their high strain hardening capacity as a result of their lower yield strength (YS) to ultimate tensile strength (UTS) ratio.

For conventional steels, reduced formability is one of the consequences of selecting steels with higher strength levels. To overcome this, recent steel developments, which can facilitate further lightweighting of automotive structures, have targeted this phenomenon. The family of steels based on multi-phase microstructures typify the development of improved material concepts to enhance formability.

The multi-phase AHSS family includes dual phase (DP), transformation induced plasticity (TRIP) and complex phase (CP), products. The data of Figure 1 show the relative strengths and formability (measured by total elongation) of conventional low strength steels, such as mild steel (Mild) and interstitial free (IF) steels; conventional HSS such as carbon-manganese (CMn), bake hardenable (BH), isotropic (IS), high strength IF (IF), high strength, low alloy (HSLA); AHSS such as dual phase (DP), transformation induced plasticity (TRIP), complex phase (CP), and martensite (Mart) steels.

Although not displayed in Figure 1, another category of steels, known as press hardened or hot-formed steels are also of interest, especially for those components with a complicated shape but requiring ultra high strength levels. These grades are, essentially, martensitic grades.

The metallurgical aspects and physical properties of the AHSS described herein are discussed in greater detail elsewhere [2].

ULSAB-AVC STEEL NOMENCLATURE

Methods used to classify steels vary considerably. To provide a consistent nomenclature, the ULSAB-AVC Consortium adopted a standard practice that defines both yield strength (YS) and ultimate tensile strength (UTS). In this classification system, steels are identified as:

XX aaa/bbb

Where XX = Type of steel
aaa = Minimum YS in MPa, and
bbb = Minimum UTS in MPa.

The steel type designator uses the following classification:

Conventional Types:

Mild = Mild steel
IF = Interstitial-free
IS = Isotropic
BH = Bake hardenable
CMn = Carbon-manganese
HSLA = High strength, low alloy

Advanced High Strength (AHSS) Types:

DP = Dual phase
CP = Complex phase
TRIP = Transformation-induced plasticity
Mart = Martensitic

As an example, a classification of DP 500/800 refers to dual phase steel with 500 MPa minimum yield strength and 800 MPa minimum ultimate tensile strength.

CONSIDERATIONS IN THE SELECTION OF AHSS FOR THE ULSAB-AVC

GENERAL PRINCIPLES - The principal difference between advanced high strength steels, based on the multi-phase microstructure and conventional HSLA steels is the higher strain, or work, hardening capacity of AHSS. This behavior can provide significant benefits in both component manufacture and performance.

A high work hardening capacity positively influences formability by resisting local necking during component manufacture and is especially important in the stretch forming deformation modes typically encountered in the manufacture of many automotive body components. High work hardening capacities also result in higher yield strengths in the manufactured component, which enhances dent resistance and crash energy absorption. In multiphase steels, the as-manufactured YS is enhanced by bake-hardening effects, which increase with increasing forming strain [3]. Conventional BH steels attain a somewhat constant value of bake hardening after work hardening of 1~2%.

When deformed at ambient temperature, the flow stresses of conventional steels show positive strain rate dependence. That is, higher rates of deformation result in increased strength levels. This behavior persists with multiphase steels. The static (10^{-3} s^{-1}) and dynamic (10^{2} s^{-1}) tensile strengths of the steels for ULSAB-AVC were estimated from their true stress-true strain curves. The increment in UTS when strain rate increased from $10^{-3}s^{-1}$ to 10^{2} s^{-1} was generally constant, in the range of 80 to 110 MPa, independent of both strength and microstructure. The ratio of dynamic to static UTS is shown as a of function static UTS in Figure 2. At elevated strain rates, the strength of both conventional and multi-phase steels is dramatically enhanced.

In Figure 3, the static (10^{-3} s^{-1}) and dynamic (10^{2} s^{-1}) tensile strengths of three steels used in the USLAB-AVC are compared. In this example, the dual phase steels provide substantial tensile strength advantage over the

HSLA product under both static and dynamic deformation conditions.

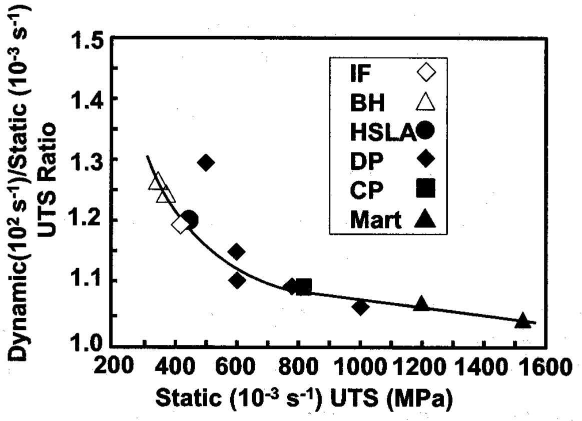

Figure 2. Ratios of static and dynamic UTS of steels in ULSAB-AVC body structure.

ULSAB crashworthiness simulations used static mechanical properties and relied on model tuning factors to match predictions to physical crash results. The ULSAB-AVC steel producers provided dynamic mechanical properties for use in computer crash simulations. These dynamic mechanical properties provide better prediction of load path, better prediction of plastic instability during collapse, and eliminate the need for some artificial tuning constants [4-6]. These aspects are, of course, to be examined in the ULSAB-AVC Program.

During a crash event, energy is absorbed by plastic deformation of the key structural components. The absorbed energy is related to collapse load (flow stress) and total strain imparted by the crash and can be estimated by the area under the stress-strain curve at

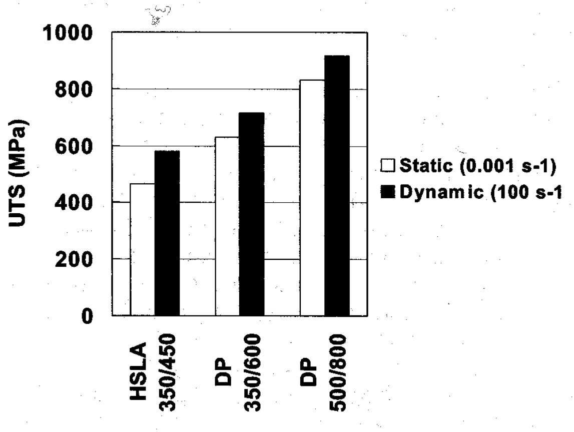

Figure 3. Comparison of static and dynamic UTS of three steels from ULSAB-AVC Steel Grades Portfolio.

specific levels of strain. Studies to determine these specific strain levels, and the strain rate, during typical vehicle crashes have shown that the majority of the energy is absorbed at plastic strains of up to 10% and strain rates between 100 ~300 s^{-1} [7]. In Figure 4 [8], energy absorbed at 10% strain during dynamic deformation of conventional and AHSS multi-phase products of three yield strength levels are compared. Under the conditions of strain and strain rate typically encountered in a crash, the AHSS products absorb more energy. Initial steel selection for crash-sensitive applications was therefore made on the basis of area under the stress strain curve at 10% plastic strain, measured at strain rates of 100-300 s^{-1}.

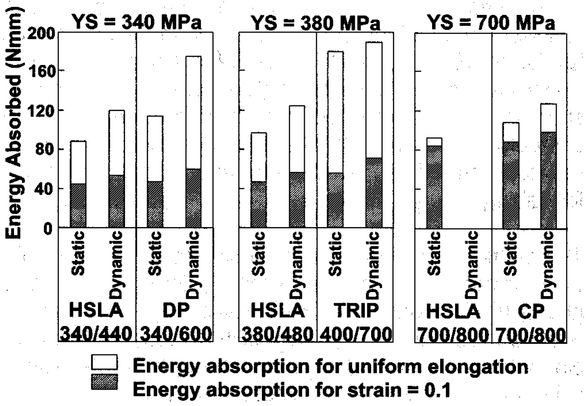

Figure 4. Energy absorbed in static and dynamic deformation at strains of 10% and uniform elongation (8).

CRASH ENERGY ABSORPTION - As already shown in ULSAB, the primary factors controlling the static bending and torsion performance of the automobile body structure are section design, gauge, and elastic modulus. These factors are independent of the material strength level and microstructure. However, designers must also ensure that working stresses do not exceed the yield strength of the material. Therefore, advanced high strength steels potentially provide a significant lightweighting opportunity by avoiding the need to use heavier-gauge materials for applications where gauge is limited by maximum working stress rather than by elastic deformation. This is particularly important for those components that take part in crash energy management.

In ULSAB-AVC, the design of structural components using bake hardenable or AHSS steels considered post-strain and bake properties. In this case, mechanical properties at the appropriate strain in the final part or the standard 2% strain plus bake property were used. When using this practice, FEA forming simulations assured that the minimum strain condition is achieved. This factor is especially significant with multi-phase steels due to the higher hardening (work hardening plus bake hardening) that can be achieved, compared with conventional steels.

The ULSAB-AVC body structure is designed to absorb crash energy so that the magnitude of both peak decelerations and intrusion into the passenger compartment are minimized. In these considerations, material mechanical properties and work hardening characteristics become extremely important and advanced high strength steels offer key advantages.

In longitudinally loaded components, such as front and rear rails (in front or rear impact) and cross members (in side impact), maximum energy is absorbed when stable progressive axial collapse (also called compact behavior or compact folding) is maintained. Increasing either the volume of material deformed or the energy under the material's stress-strain curve will increase the absorbed energy. The higher work hardening capacity of AHSS provides for improvements compared with conventional high strength steels of equivalent yield strength, in both respects. The higher work-hardening distributes strain more uniformly, involving a greater volume of material in the deformation event, and the greater area under the stress-strain curve (for equivalent starting yield strength) absorbs greater total energy for a given degree of deformation. While similar performance could be provided by conventional high strength steel with similar UTS levels, the greater formability of AHSS permits their use in applications that would preclude using the less formable conventional HSS.

To provide high crash energy absorption, front and rear end components must resist deformation by less efficient plastic buckling (also called non-compact behavior or non-compact folding). This requirement is illustrated in Figure 5, which compares the geometry of sections that deform by stable axial collapse and unstable plastic buckling. The section that deformed by stable axial collapse contains a greater number of regular folds, involves a greater volume of material in the deformation event, and absorbs greater energy for a fixed collapse length. Stable axial collapse is promoted by increasing yield strength, decreasing column width to thickness ratio (a geometry factor), increasing strain hardening rate, and decreasing the angle between direction of loading and axis of component [9].

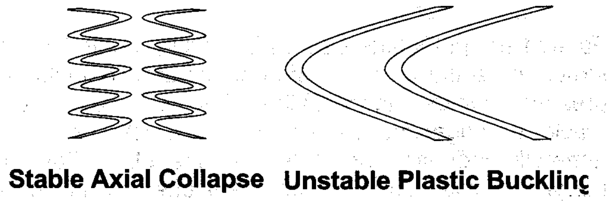

Figure 5. Comparison of deformed geometry resulting from stable axial collapse and unstable plastic buckling.

For components properly designed to deform by stable axial collapse, dynamic behavior during collapse of thin wall rectangular columns is frequently described by equations of the form:

$$Pm = K\sigma t^{a} \qquad \text{(Equation 1)}$$

where Pm = average load (or absorbed energy),
K = constant related to geometry,
σ = flow stress term,
t = thickness, and
a = thickness exponent.

Studies of impact deformation of square columns [10] found Equation 1 described experimental absorbed energy at 150 mm deformation when $\sigma = (\sigma_{uts})^{0.506}$ and a = 1.498. More recent studies of axial collapse of closed top hat structures made of conventional and dual phase steels of varying thicknesses have been performed [11]. These studies concluded that Equation 1 described experimental mean collapse load at 48 km/h when $\sigma = (\sigma_{uts})^{0.4}$, in good agreement with reference [10], but the thickness exponent, a, ranged from 1.6 to 2.0 depending on steel grade, geometry, and deformation conditions. In both studies, it was pointed out that the equations are valid only for stable axial collapse for the specific geometry and deformation conditions investigated.

While further study is required to fully explain the combined effects of steel grade, strength, gauge, geometry, and deformation conditions on crash performance, Equation 1 begins to demonstrate the profound effect of gauge on crash energy absorption. Figure 6 was generated by substituting $(\sigma_{uts})^{0.4}$ for σ and setting a=1.8 in Equation 1 and plotting UTS and thickness for several constant values of Pm/K. It illustrates the UTS required to maintain constant crash load as thickness changes. This plot is similar to plots of yield strength and gauge required to maintain constant crash energy absorption of other investigations [7]. Using this same form of Equation 1 (substituting $(\sigma_{uts})^{0.4}$ for σ and setting a=1.8), the data of Figure 7 show the relative increases in UTS required to decrease gauge (mass) while maintaining constant average crash load or energy absorption if the overall design (geometry) is not adjusted to fully benefit from AHSS. Figures 6 and 7 demonstrate that in the absence of geometry changes, exponentially greater increases in UTS are required to maintain constant energy absorption as gauge is reduced. This sets a practical upper limit for the degree to which mass can be reduced by substituting lighter gauge, higher strength materials. Substantial mass reductions in critical crash energy management components can only be achieved when geometry is optimized to take full advantage of the unique

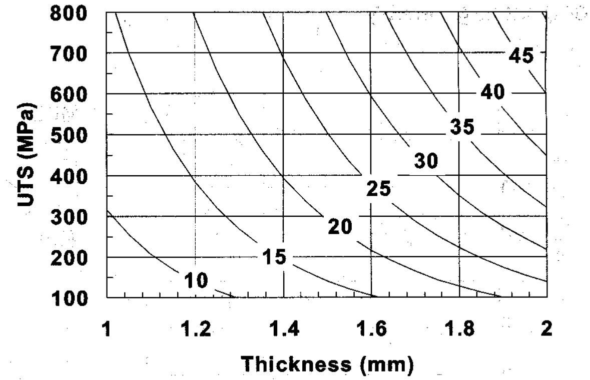

Figure 6. Thickness and UTS for constant values of Pm/K.

mechanical properties of AHSS. Efficient design must therefore be a primary emphasis for reducing mass while maintaining or improving crash performance.

For ULSAB-AVC transversely loaded components, such as rockers, pillars, and roof rails in side impact, resistance to plastic bending is a significant consideration. In these applications, high yield strength and high work hardening rate are of great importance.

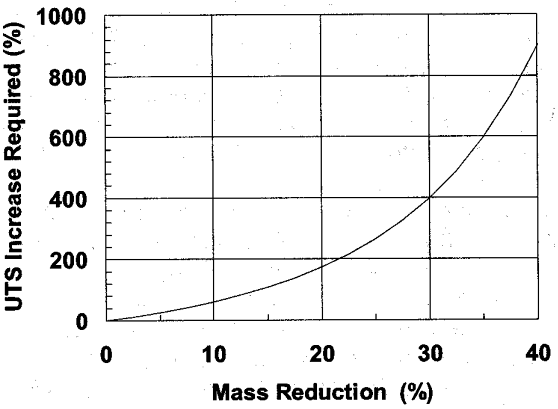

Figure 7. Tensile strength increase required to reduce mass by downgauging without changing component geometry.

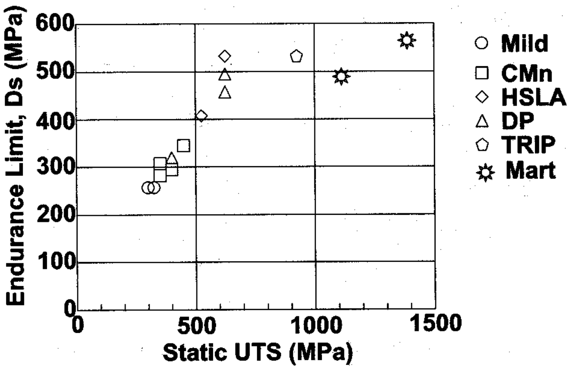

Figure 8. Fatigue Endurance Limit for several advanced high strength steels in uniaxial tension-tension (12, 13).

The higher strength multi-phase steels should excel in these applications as their excellent formability permits the use of higher yield strength products for components that could not be formed with conventional HSS.

FATIGUE - Excellent durability is, of course, a prerequisite consideration for vehicle design. Advanced High Strength Steels enable optimal fatigue performance to be achieved because they allow higher working stresses to be accommodated. To achieve this optimum requires that the design and manufacturing methods for the auto body structure be adjusted to match the higher working stresses allowable.

The fatigue strength of unnotched or mildly notched base material increases with increasing steel tensile properties. This is illustrated by the data of Figure 8 [uniaxial tension-tension, 12, 13] which shows the excellent fatigue performance. Fatigue endurance limit continues to increase with increasing tensile strength in these steels. Strain hardening and bake hardening improve fatigue endurance limit, Figure 9 [14].

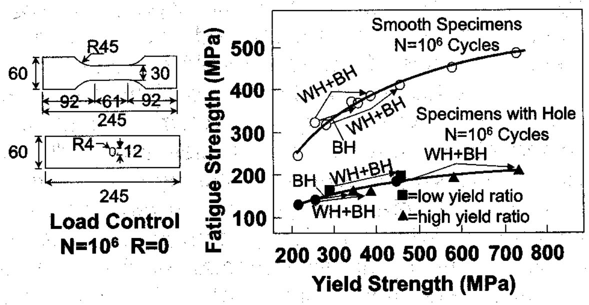

Figure 9. Effect of strain hardening (WH) and bake hardening (BH) on base metal fatigue properties (14).

For mechanically notched material such as punched holes, reversed plastic strains appear in the notch even if the nominal stress away from the notch is elastic. Investigations [14] have shown that due to cyclic softening there is little, or no effect, of strain hardening if the yield to tensile ratio exceeds 0.7-0.75.

Fatigue of spot welds can be a limiting factor for body structure endurance. Inherent natural defects are present in welds and the fatigue process is governed by crack propagation; resistance to crack growth is generally independent of tensile strength. For load carrying welds there is little or no effect of increased base metal tensile strength and consequently no effect of strain- or bake hardening. Decreasing spot pitch (increasing the number of welds) or increasing spot weld diameter can compensate for this. The most rational compensation, however, to use weld bonding or continuous welds in fatigue-critical areas.

ULSAB-AVC DESIGN EVOLUTION METHODOLOGY

Multi-phase advanced high strength steels used in the ULSAB-AVC vehicle offer superior strength, formability, and crash energy absorption capacity and provide very good dent resistance and fatigue performance. These steels provide exceptional potential for increased structural strength and mass reduction by using lighter thickness than could be used with less formable conventional steel. When selecting AHSS for ULSAB-AVC, the following guidelines were applied:

- The steel selection for crash-sensitive applications was made utilizing the area under the stress-strain curve at 10% strain, measured at strain rates from 100 ~300s $^{-1}$.

- Strength comparisons were made at strain rates that reflect those experienced.
- For constant component geometry (i.e. if overall design was not adjusted to fully benefit from AHSS) exponentially greater increases in strength are required to maintain crash energy absorption capacity as thickness decreases, limiting the extent to which mass can be reduced by substituting higher strength, lighter gauge materials. Component design (geometry or shape) was the primary initial focus for reducing mass while maintaining or enhancing crash performance in ULSAB-AVC.

There is a high degree of complexity and a strong interaction between component design and materials selection inherent in the development of advanced lightweight vehicles like ULSAB-AVC. Therefore, the design and materials teams worked closely throughout the design process to assure that design was optimized and that the steels selected, either conventional or AHSS, were used to their full potential. To assure the ULSAB-AVC takes full advantage of conventional and advanced steels, the following design methodology was applied:

For each component that is not limited by elastic modulus, the ULSAB-AVC static bending and torsion requirements were addressed using the lightest gauge, highest strength AHSS that simultaneously met stiffness, working stress, and formability requirements. Here, FEA forming simulations were used not only to verify forming feasibility but also to document in-part strength and gauge to determine if additional gauge reductions were possible. This process was carried out within the holistic, iterative design process so that changes in one component did not adversely affect stresses and deflections in other components.

When designing for crash performance, ULSAB-AVC crash model simulations used dynamic as-produced mechanical properties at minimum specified strength and gauge in the first design step unless forming simulation results were available to provide as-formed properties and gauge. If crash targets were not met in initial iterations, higher strength advanced steels were substituted first to determine if crash energy management can be improved without adding gauge. Candidates for substitution were selected by comparing energy under the stress-strain curve at 10% strain for minimum strength level products tested at a strain rate of 100-300 s^{-1}. As in the case of static design, components designed with AHSS for crash considerations were subjected to forming simulations to verify forming feasibility. Gauge increases were not considered until it was established that there was no higher strength product available to form the part successfully after redesign and meet both static and dynamic performance requirements.

MATERIALS SELECTED FOR THE ULSAB-AVC BODY STRUCTURE

The materials selected for the ULSAB-AVC Body Structure are illustrated as Figure 10 (C-Class) and Figure 11 (PNGV-Class), with the steel grades selected collated as Table 1. The pie charts of Figure 12 enable a comparison to be made of the materials used in ULSAB and in ULSAB-AVC and indicate that the complete body structure of ULSAB-AVC is comprised of high strength steel. Stamping, roll forming and hydroforming are the only processes used for the manufacture of all components. Initially, it was considered that hot-formed steels would be required. However, component geometry (shape) modifications enabled all press hardened components to be replaced with components made by less expensive stamping or roll forming processes. A complete list of the materials selected for each part can be found in Technical Transfer Dispatch #6, ULSAB-AVC Body Structure Materials, published by the ULSAB-AVC Consortium [15].

The data of Figure 12 illustrate that the body structures of both the PNGV-Class and C-Class ULSAB-AVC designs utilize approximately 85% Advanced High Strength Steels, with the clear majority of components designed using dual phase steels. The relatively simple shapes of the components in this concept design had a significant influence on the types of steels selected. In particular, for a number of components, both DP and TRIP steels were viable candidates for selection. The choice of a less-costly DP grade was enabled since part geometry rendered the superior formability of TRIP steels redundant, based on the first-approximation one-step forming simulations. In the case of the floor pan, TRIP 450/800 was selected rather than a DP grade. This particular component undergoes significant deformation during manufacture, so that manufacturing feasibility will benefit from the additional forming capacity of the TRIP grade. In addition, practical experience on similar components has indicated that one-step forming simulations may not be completely reliable in predicting the manufacturing feasibility for such components. The selection of TRIP 450/800, in this case, provides a greater margin of manufacturing feasibility than would be the case with DP grades.

It must, of course, be emphasized that ULSAB-AVC is only one possible solution to achieve lightweight steel body structures. Consequently, the particular AHSS selected for each component was based on the specific designs used in ULSAB-AVC. The steels selected should be considered as useful guidelines for similar components in other automotive designs. The material selected by other automotive manufacturers will be based on a balanced consideration of their specific factors — manufacturability, performance and cost. Based on ULSAB-AVC experience, the adjustment of component design (geometry) to take full advantage of the benefits of AHSS is of paramount importance.

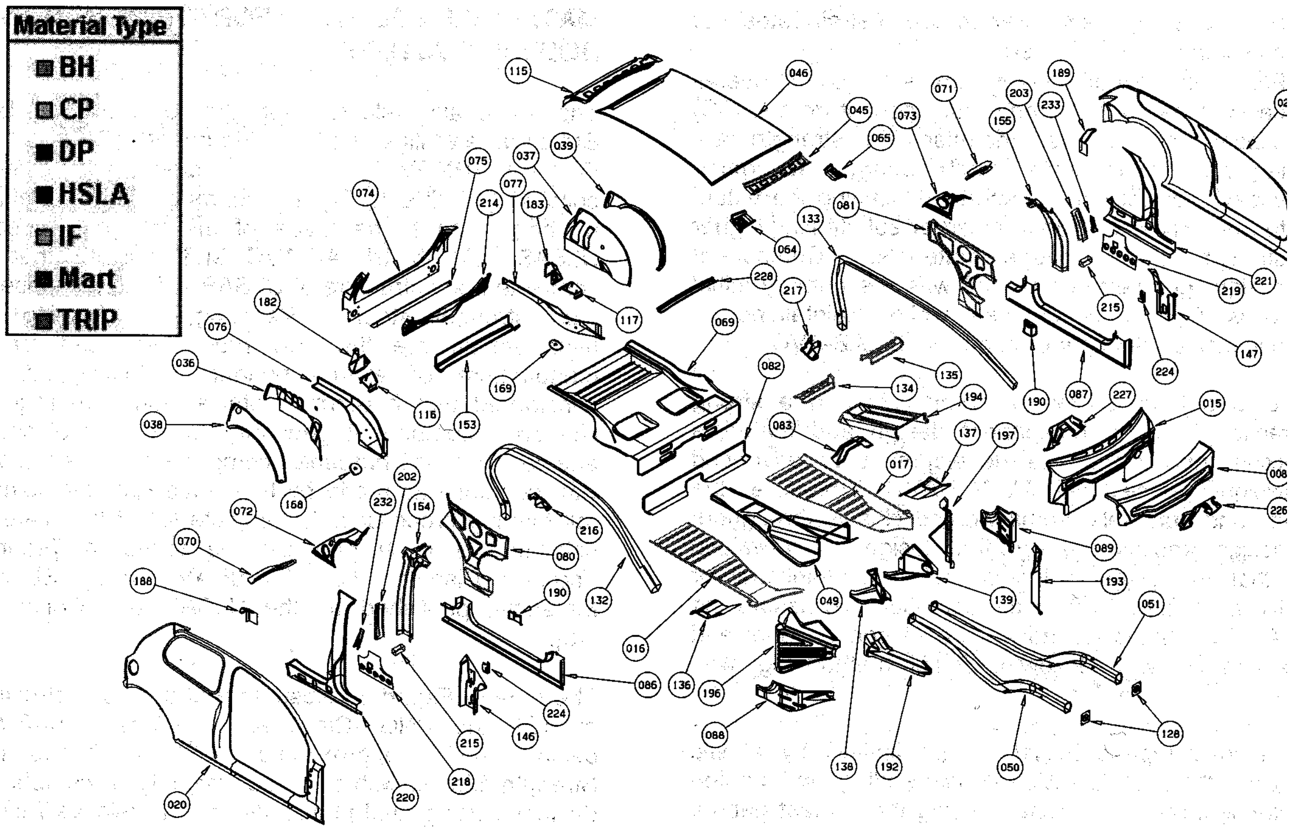

Figure 10. Exploded parts view of final ULSAB-AVC C-Class vehicle concept design, showing yield strength levels selected for individual parts.

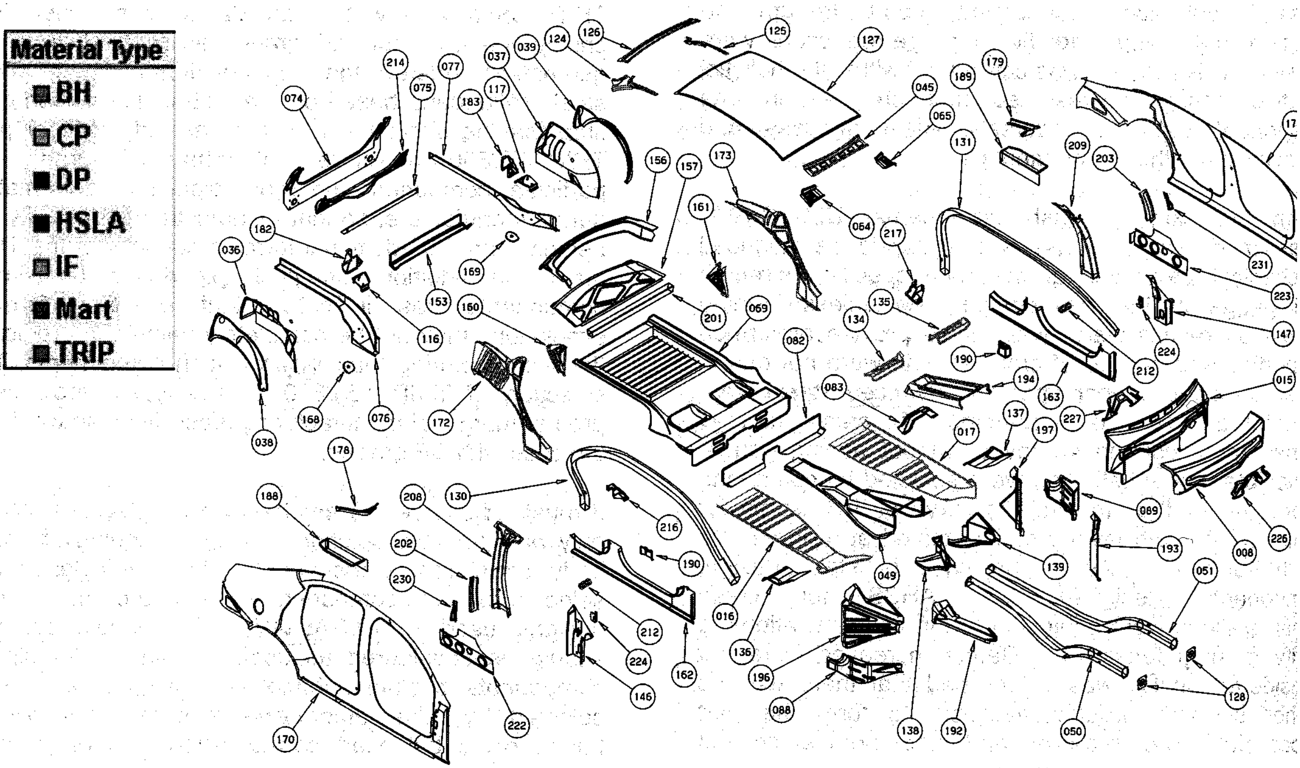

Figure 11. Exploded parts view of final ULSAB-AVC PNGV-Class vehicle concept design, showing yield strength levels selected for individual parts.

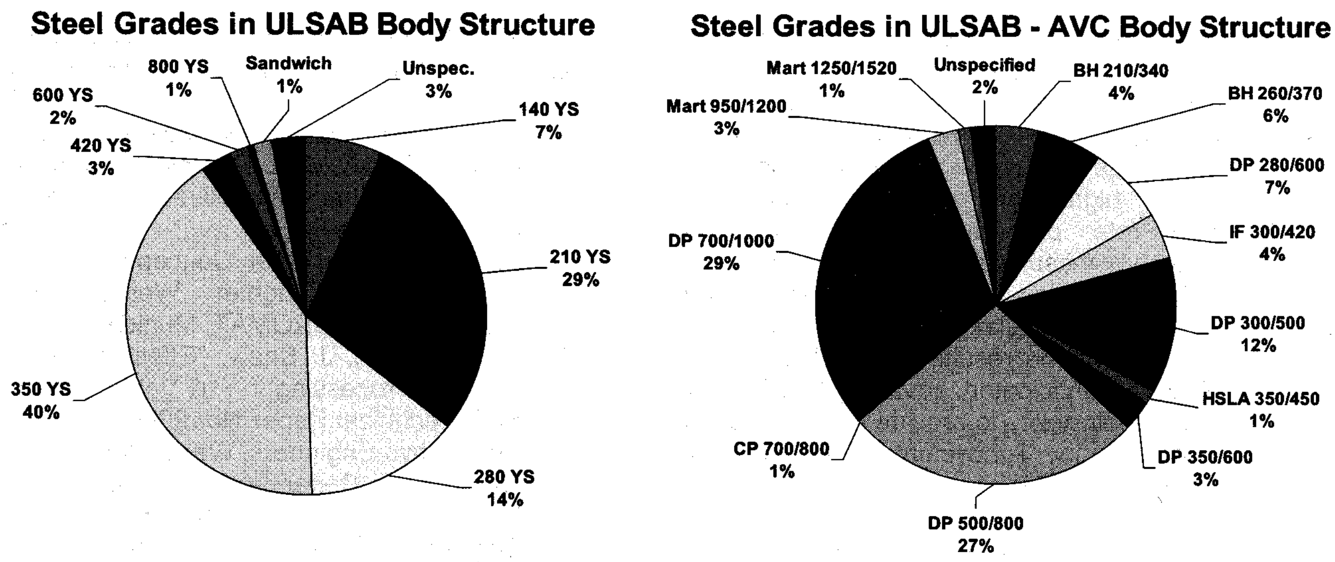

Figure 12: A Comparison of materials used in the body structures of ULSAB and ULSAB-AVC.

Table 1. Grades and quasi-static mechanical properties of steels used in ULSAB-AVC Body Structure.

Product	YS (MPa)	UTS (MPa)	Total EL (%)	n-value[1] (5-15%)	r-bar	K-value[2] (MPa)
	(flat sheet, as shipped properties)					
BH 210/340	210	340	34-39	0.18	1.8	582
BH 260/370	260	370	29-34	0.13	1.6	550
DP 280/600	280	600	30-34	0.21	1.0	1082
IF 300/420	300	420	29-36	0.20	1.6	759
DP 300/500	300	500	30-34	0.16	1.0	762
HSLA 350/450	350	450	23-27	0.14	1.1	807
DP 350/600	350	600	24-30	0.14	1.0	976
DP 400/700	400	700	19-25	0.14	1.0	1028
TRIP 450/800	450	800	26-32	0.24	0.9	1690
DP 500/800	500	800	14-20	0.14	1.0	1303
CP 700/800	700	800	10-15	0.13	1.0	1380
DP 700/1000	700	1000	12-17	0.09	0.9	1521
Mart 950/1200	950	1200	5-7	0.07	0.9	1678
Mart 1250/1520	1250	1520	4-6	0.065	0.9	2021
	(straight tubes, as shipped properties)					
DP 280/600	450	600	27-30	0.15	1.0	1100
DP 500/800	600	800	16-22	0.10	1.0	1250
Mart 950/1200	1150	1200	5-7	0.02	0.9	1550

YS and UTS are minimum values, others are typical values
Total EL % - Flat Sheet (A50 or A80), Tubes (A5)

[1] n-value is calculated in the range of 5 to 15% true strain, if applicable.

[2] K-value is the magnitude of true stress extrapolated to a true strain of 1.0. It is a material property parameter frequently used by one-step forming simulation codes.

CONCLUSION

The selection of steels for ULSAB-AVC was made to facilitate an optimum balance between structural strength, crash resistance, formability, joinability and total economy to meet ULSAB-AVC technical goals with good credibility. This process, which took into full consideration the high work hardening rates and elevated strain rate properties offered by both conventional and advanced high strength steels, drove the ULSAB-AVC design to incorporate large percentages of AHSS, particularly in components crucial to crash performance. The results of the ULSAB-AVC program verified the anticipated advantages of AHSS and demonstrated their ability to provide improved crash safety performance in lightweight, fuel efficient, environmentally-friendly vehicles.

Experiences gained during the evolution of the ULSAB-AVC program developed the following guidelines for designing vehicle body structures with AHSS:

1. AHSS for critical crashworthiness components should be selected on the basis of their ability to absorb energy at high strain rates. Area under the stress-strain curve at 10% strain, tested at a strain rate of 100 s^{-1}, is recommended as basis for comparison.

2. AHSS, because of their greater rates of work hardening, generally absorb greater amounts of crash energy than conventional steels of similar yield strength. They offer vehicle designers the opportunity to maintain or enhance vehicle crashworthiness while reducing vehicle mass by downgauging with higher strength material.

3. Absorbed crash energy decreases exponentially with decreasing gauge if the overall design is not adjusted to take advantage of AHSS, requiring exponentially increasing strength to maintain crash performance as gauge decreases. Proper vehicle architecture design must therefore be the primary initial focus for reducing mass while maintaining or improving vehicle crashworthiness.

4. AHSS present greater design and manufacturing challenges than conventional steels, but these challenges can be met by the expertise gained by the steel makers developing and manufacturing these products. Vehicle design programs anticipating use of AHSS should involve the steel supplier early in the concept design phase to assure that solutions to manufacturing problems are facilitated by design and materials selection modifications at a stage where these are still feasible.

ACKNOWLEDGMENTS

The authors wish to thank the ULSAB-AVC consortium for permission to publish this paper.

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