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Drawback of Ultra High Strength Steel -a 3rd Generation Steel in Automotive Industry

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Abstract: *Automotive industry relentlessly in a quest for higher performance of vehicles in several aspects such as increased fuel efficiency and hence reduced tailpipe emissions, improved aerodynamic and driving performance, elevated safety precautions such as crash energy absorption, etc. All these concerns should be addressed with minimal weight increase and without compromising from passenger safety. This manuscript, first gives an overview for world auto industry and projections, and then reviews benefits and problems encountered in development and implementation of high strength steels particularly in automotive industry.*

Keywords: *Auto steels, AHSS, formability, die wear, springback, weldability*

I. Introduction

1.1 Overview auto industry

Since the first mass-produced car Oldsmobile Curved Dash in the beginning of 20th century, auto industry has made a tremendous progress as one of driving power in technological innovation. These progresses included vehicle design, manufacturing technologies, new materials, improved performance, reduced tailpipe emission etc. Today, according to Plunkett Research, there are more than 1 billion registered vehicles worldwide and USA has the highest number of vehicles (around 250 million). China is the largest producer of motor vehicles by 19.3 million (including cars, light and heavy commercial vehicles and heavy buses) in 2012. Car production constitutes 63 million out of total 84 million motor vehicle production, and Toyota is biggest manufacturer with 10.1 million motor vehicles, and followed closely by General Motors, and Volkswagen [1].

1.2 Material trends in auto industry

Since 1920's, steel has been main material in automotive industry. According to Ducker Worldwide, a market research and consulting company, the steel content in lightweight vehicles will remain at 60% levels and a slight increase is expected for aluminum use as presented in Table 1. In the meantime, most of the mild steel applications in current vehicle designs will be replaced by ultra/advanced high strength steels as can be seen in Figure 1.

Table 1. Lightweight vehicle material trend according to Ducker Worldwide (After [2,3])

Material	**% Content (in 2009)**	**% Content (in 2015)**
Ferrous based (flat steel, iron, other steels)	66.5	60.2
Aluminum	7.8	9.6
Other metals (copper, lead, zinc, Mg, platinum, titanium	4.3	4.3
Non-metallic materials (polymers, glass, wood, rubber, coatings, textiles, and fluids)	21.4	25.9

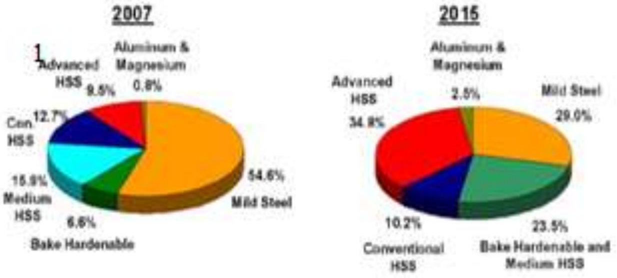

Figure 1. Metallic material types and their usage trend in vehicle body and closure, 2007 vs. 2015 comparison [3].

II. Ultra/Advanced High Strength Steels (U/Ahss)

As higher safety and fuel economy standards are enforced by regulatory commissions and/or governments, automakers are challenged to address those issues at reasonable cost levels. U/AHSS grades help engineers in realizing the requirements for safety, efficiency, manufacturability, emissions, durability etc. cost-effectively. AHSS grades are designed to achieve unique material and mechanical properties. Their chemical compositions are carefully selected and multiphase microstructures are controlled through precise heating and cooling processes so that desired strength, ductility, toughness, and fatigue properties are obtained. 1^{st} , 2^{nd} and third generation U/AHSS materials as well as conventional high strength steels are shown in Figure 2 which is also referred as “banana curve”.

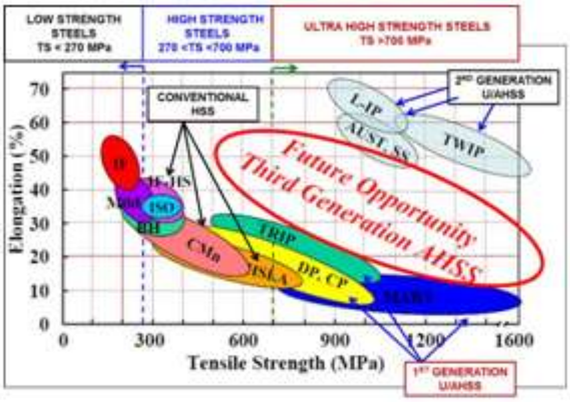

Figure 2. Conventional, current and prospective automotive steels and their corresponding elongations and strengths (After [4])

Conventional low-to high-strength steels include mild, interstitial-free (IF), bake-hardenable (BH), and high-strength low-alloy (HSLA) steel and those have simpler microstructures and have been commonly used in automotive industry for years. Another classification can be made in terms of tensile strengths. In general, steels with 270 MPa tensile strength or less are referred as “mild steels” while steels with tensile strength in between 270 and 700 MPa and with complex microstructures such as bainite, martensite, retained austenite etc. are called as AHSS; and steels with 700 MPa tensile strength and above are dubbed as UHSS. Nevertheless, in most cases, the term AHSS is preferred instead of AHSS and UHSS differentiation. AHSS materials include dual phase (DP), complex phase (CP), transformation-induced plasticity (TRIP), ferritic-bainitic, martensitic (MART), hot-formed, and twinning-induced plasticity (TWIP) steels. Each of these steels has unique microstructural properties, alloying elements, processing routes, advantages and challenges in its applications. Each type of steel has unique application, and specifically chosen to meet certain criteria. For example, DP and TRIP steels preferred in at engine compartment, and trunk zones as these steels have higher energy absorbing capability whereas martensite and boron steels with highest strength are utilized at passenger compartment zone as minimum deformation to prevent intrusion during the crash is required at this zone [4].

AHSS materials are increasingly used in structural parts in auto-body structures as it is illustrated in Figure 3. Moreover, various AHSS grades are used in non-structural parts including seat rack, recliner, seat frame, headrest tube, frame support, etc. [5].

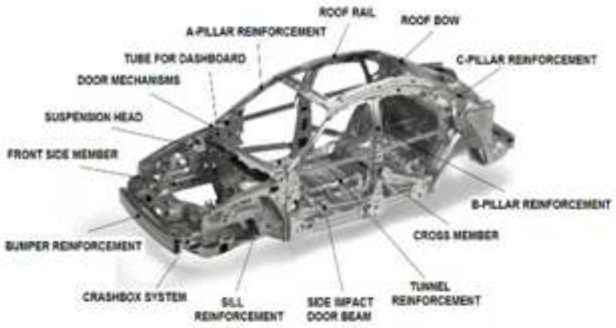

Figure 3. Some of the U/AHSS implementation locations on an auto body (After [5]).

Figure 4, on the other hand, shows a specific example to AHSS implementations in a passenger car. 2013 Ford Fusion exploits 29.2% DP steels, and 7% Boron-Martensitic steels in its body-in-white (BIW) [6]. As an ultimate example, UltraLight Steel Auto Body – Advanced Vehicle Concept (ULSAB-AVC) program realized 25% mass reduction in BIW at no additional cost by using 74% DP, 2% TRIP, and 4% MART steels in overall BIW weight [7].

As it can be inferred from the Figure 2 that in first generation AHSS, the higher yield strength the lower elongation is experienced. To overcome this problem second generation AHSS materials with high strength and superior elongation have been developed. Nonetheless, the application of 2nd generation AHSS may not be widespread due to high cost of alloying elements (e.g. Ni, Mn). A cost-effective alternative to weight reduction can be made possible through the development and use of 3rd generation AHSS materials which has ultra-high strength (above 1200 MPa in UTS) along with elevated ductility (at least 30%) [8].

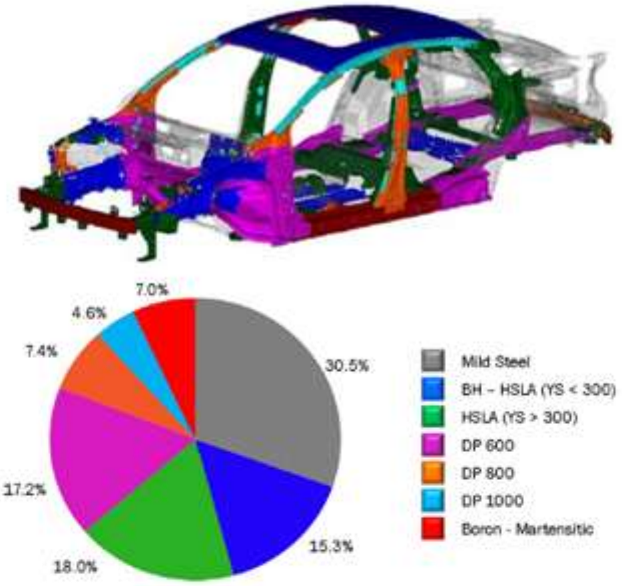

Figure 4. AHSS use by material type and its associated content on 2013 Ford Fusion's body-in-white [6].

III. Advantages Of U/AHSS Implementation

Increasing safety, fuel efficiency, and reducing tailpipe emission regulations should always be addressed by auto industry in a cost-effective manner. Although materials such aluminum, magnesium, carbon-reinforced composites have higher potential from mass reduction point of view, AHSS has superior features over its rivals such as higher formability, and crash energy absorption capacity, less greenhouse gas emissions during its production and recycling etc. Furthermore, the steel is the most used and known material in auto industry and its microstructure, formability problems are mostly solved. Contrary to steels, aluminum and magnesium have limited formability at room temperature and requires some new production and process technologies. On the other hand, same forming equipment and techniques can be implemented as in dealing with conventional steels when AHSS grades are exploited. Some of the benefits of AHSS use are summarized in following subsections.

3.1 Availability and Cost

Iron, main element in the steel alloy, is one of the most abundant elements on the earth's crust and it is most extracted element in the world. Although aluminum is reported to be more available, its extraction requires a series of cumbersome processes. Therefore, unit prices of both aluminum and magnesium have higher costs compared to steel. Table 2 shows comparison of alternative lightweight materials in terms of cost, mass reduction, and materials they replace.

Table 2. Weight savings and cost comparison for alternative lightweight materials (*: including both material and production) [9].

Lightweight Material	**Material Replaced**	**Mass Reduction (%)**	**Relative Cost (per part)***
High strength Steel	Mild Steel	10	1
Al	Steel, Cast Iron	40-60	1.3-2
Mg	Steel or Cast Iron	60-75	1.5-2.5
Mg	Aluminum	25-35	1-1.5
Ti	Alloy Steel	40-55	1.5-10 +

Titanium, magnesium, aluminum surpass the high strength steels from mass saving potential point of view, however; they have either limited formability, or insufficient mechanical property (e.g., crash energy absorption capability) matters for widespread implementation.

3.2 Environmental Effects: Greenhouse gas emissions, recyclability

Environmental factors such as greenhouse gas emission (GHG) of a motor vehicle during its production, use, and disposal is an important criterion in vehicle design. This concept is also known as carbon-footprint or life cycle assessment of a product. For a typical internal combustion engine vehicle, the material production, vehicle manufacturing, vehicle use, and vehicle phases are responsible from 10.3%, 4.3%, 85.3%, and 0.1% of total greenhouse gas emissions, respectively [10AHSS implementation has shown to be more favorable compared to aluminum and magnesium in terms of environmental impacts [10 -13]. Table 3 summarizes the equivalent GHG emission in terms of equivalent kg of CO_2 emission per kg of material during primary production phase [11].

Table 3. Greenhouse gas emissions from production (*: including all steel and aluminum grades) [11]

Material	**GHG Emission (in kg eq. CO_2/ kg of material)**
Steels (inc. AHSS) *	2.0-2.5
Aluminum *	11.2-12.6
Magnesium	18-45
Carbon RFP composite	21-23

As the vehicle use phase has the major impact on environment, several regulations are established for tailpipe emissions and fuel efficiency worldwide. For example, current standard for corporate average fuel economy (CAFE) in USA is 27.3 mpg (8.62l /100 km) while it will be raised to 35.5 mpg by 2016 (6.63l /100 km), 54.5 mpg (4.32l / 100 km) by 2025 [14]. CO_2 emission standards, on the other hand, are strictly enforced in Europe as the 2020 CO_2 emission targets for new passenger cars, and for light-commercial vehicles have been set as 95 g/km, and 147g/km, respectively.

Recyclability of the materials after their life cycle is another concern in material selection. Iron and steel are known as having the highest end-of-life recycling rates. Both recycling rate and GHG emission during secondary production values for AHSS are more favorable against aluminum as can be seen in Table 4. Mg, on the other hand, requires a very demanding recycling process, and its recycling rate is estimated in the range of 25-50% [15].

Table 4. Recycling rates and GHG emissions from secondary production [10].

Material	**Recycling rate (%)**	**GHG Emission (in kg eq. CO_2/ kg of material) in secondary production**
Steels, AHSS	90-96	0.7-1
Aluminum	83-90	1.4-2.0

3.3 Crash Energy Absorption

One of the key design considerations in vehicle structure design is to ensure that the structure is able to carry the required static and dynamic load, especially in a crash event. Proper material selection and geometric design play important roles in crash load management. Figure 5 shows major crash management zones in a vehicle. Energy management zones, (also referred as crushable zone, crumple zone), are located at the front and rear of the vehicle, and are to absorb as much as energy possible during the impact so that the influence to the safety cage should be minimized. Therefore, various AHSS grades with high work-hardening, strength, and ductility (e.g. DP, CP, TRIP steels) are chosen for these zones. Safety cage, or passenger compartment zone, is designed to maintain its integrity with minimal deformation to protect the occupants and the fuel system in the event of a low-to high -speed crash. To meet these requirements, the highest ultimate tensile strength materials (e.g. UHSS grades) such martensitic steels, hot-formed boron steels, and dual phase steels with tensile strength above 980 MPa are preferred [4,16,17]. Optimization efforts in material and geometry usually results in significant mass reductions with complex geometries as in case of FutureSteelVehicle (FSV) programme in which 35% mass reduction was achieved through use of nearly 50% gigapascal steels in 188 kg body structure. Mass savings was realized at no cost penalty and 5-start safety ratings were granted [18].

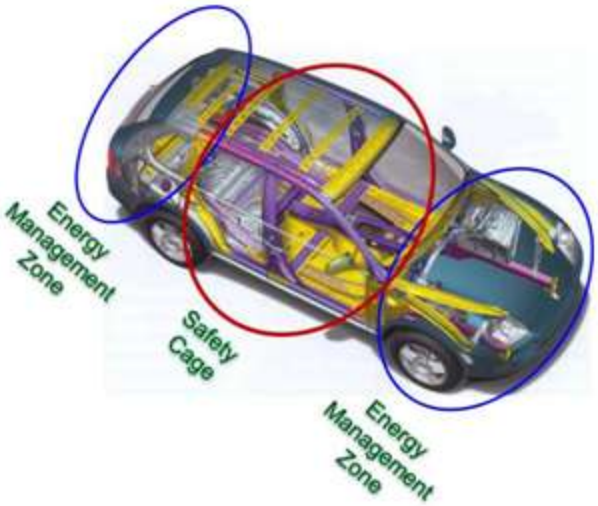

Figure 5. Crash management zones in a vehicle (After [4,16]).

IV. Problems In U/AHSS Implementation

Along with its noteworthy advantages, utilization of U/AHSS materials has certain challenges including elevated wear on forming dies, increased springback, weldability, flange stretching, edge cracking, fatigue etc. Concurrent efforts aim to address solutions to the problems encountered in AHSS implementations.

4.1 Die Wear

As the strength of advanced high strength steel sheet blanks is higher than those of mild steel ones, higher forming forces are needed. Consequently, significant die/tooling service life issues are experienced as elevated forming forces frequently lead to increased wear at contact interfaces and deteriorate the surface quality of the products. To overcome these problems, a multi-fold approach has been employed by the researchers.

These efforts include but not limited to development of better substrate material, surface modification/coating techniques. For this purpose several alternative uncoated and coated materials (stamping die of interest) were tested against AHSS sheet blanks with a test system developed by authors to provide always fresh contact surface interaction between die sample and AHSS sheet blanks. From substrate material point of view, it was shown by the authors that some recently developed cold-work tool steels and powder metallurgical tool steels outperformed the conventional tool steel material AISI D2. Finer grains and uniform distribution of hard-phase particles in the microstructure are considered to be key factors for improved performance [19]. Authors also tested the wear resistance performance of 4 different coatings on same substrate material in another study. It was noted that die samples coated with thermal diffusion (TD) and Chemical Vapor Deposition (CVD) techniques exhibited higher wear resistance than samples coated with two different PVD coatings [20]. Apart from substrate material and coating type, a strong correlation was obtained between substrate hardness and wear resistance [21-22].

4.2 Springback and its modelling

One of the primary concerns in use of AHSS grades is springback, and it is defined as material’s elastic recovery after forming. It is a significant problem as the final shape of the part critical for joining, and product quality [23]. Compared to mild steels, increased and inconsistent levels of springback issues are reported for U/AHSS [24,25]. Figure 6 illustrates comparison of springback levels for mild steel and U/AHSS on a stress-strain curve. A real example regarding with the springback behavior is shown in Figure 7 for the parts dual phase material and a high-strength low-alloy (HSLA) material.

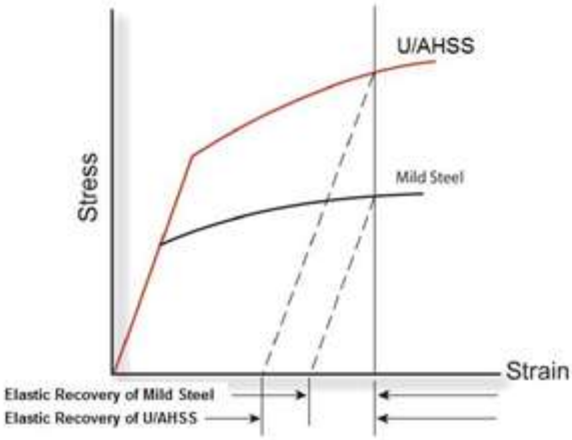

Figure 6. Comparison of springback levels for mild steel and U/AHSS on a stress-strain curve (After [16]).

Figure 7. Elevated springback issues for DP steels compared to HSLA steel [26].

Springback cannot be fully prevented yet it can be suppressed through process -based actions including forming the material at warm and hot temperatures [27], or thorugh mechanical actions such as working with small die profile radius to take advantage the strain-hardening capacity, optimization of clearance between die and punch; and increase blank holder force to increase tension in the part wall [24], or using draw-beads [28].

Prediction of springback is also challenging subject and has not been successfully simulated yet [24]. An Auto/Steel Partnership study reported that current software technology is capable of predicting formability performance (necking-related) but not accurate for springback and fracture related problems for AHSS [29].

4.3 Weldability

Welding is considered as one of the vital parameter for the integrity and crashworthiness of auto-body structures A typical auto body consists of large number of stamped sheet metals welded together by various kind of welding, an average automobile has 4,500-6,500 welds Welding is also vital in terms of formability and fatigue performance as failure location is often at welds. Therefore, weldability of U/AHSS parts should be assessed to determine the viability of the parts for assembly. Welding of AHSS parts differs from mild steel parts as higher carbon and alloying elements (such as C, Al, Si, Mn) make AHSS more sensitive to the welding In addition, rapid heating and cooling during the welding process and steel chemistry highly affect the microstructure, mechanical properties, and fatigue life Therefore tight control of welding parameters is required [16]. Nonetheless, welding practices developed certain type of AHSS may not work for other types [32]. UHSS parts, on the other hand, were reported to have very good weldability through MAG welding despite a higher alloying content is used for UHSS in comparison to AHSS and mild steels [24]. To increase the fatigue strength of a spot welded joint the spot weld diameter can be increased

Apart from spot and MAG welded parts in auto body, tailored welded blanks (TWBs), or sometimes referred as laser welded blanks (LWBs) are one of technically important products. They consist of two or more sheet metals of different material, (hence mechanical properties), thickness, and/or shapes, are laser welded together and then stamped into final three dimensional parts. They do not only provide reduction in weight but also offer decrease in manufacturing costs, and improved dimensional consistency. It is reported in the literature that welding has a significant influence on formability of DP steels as softened heat affected zone (HAZ) phenomenon is experienced with various welding processes. As a consequence, strain is concentrated in the weaker/thinner side of the blank and lead to fracture [33]. Studies on TWBs using limiting dome height (LDH) tests revealed that formability of dissimilar material laser welded blanks depend on weld location during stretch forming and increased formability of dissimilar laser welded blanks of AHSS can be obtained by manipulating the weld location and orientation in the tailor welded blank part design along with proper material combinations [34].

4.4 Edge Cracking, Fracture

Edge cracking is one of the roadblocks of U/AHSS implementation since formability is often limited by fractures of parts. As smaller gages can be used with AHSS blanks for lightweighting purposes, stresses increase in edges as well as weld region and potentially shorten the fatigue life and durability of auto-body structures [35]. Figure 8 shows examples to edge stretch cracking, and stretch bending fracture of AHSS parts.

Figure 8. Different failure modes for AHSS parts a) edge stretch cracking, b) stretch bending fracture of DP 780 [36]

Similar to problems encountered in estimation of springback, prediction of stretch-bending and edge-cracking based on forming limit diagrams, and localized necking based methods were not found to be satisfactory Several efforts are on effective to overcome fracture problems and its prediction. One alternative is to take advantage of local softening technology (through induction, and laser heating) [29]. In addition, new experimental methods to predict failure limits are needed in practice. To this goal, edge thinning limit is proposed to evaluate edge stretching failure for AHSS panel with interior cut [38].

V. Conclusion

AHSS grades can reduce the vehicle weight and are contributing the vehicle performance along with the improved safety without significant cost penalties. Those also lower the carbon footprint for vehicles at lower costs compared to aluminum and magnesium. Continuous efforts are needed to satisfy the ever increasing safety regulations, mass reduction and fuel economy targets. Specifically, realization of 3rd generation U/AHSS with excellent strength and, ductility at low cost will lead to increased implementation in auto industry. Therefore, fundamental relations between material processing techniques and formability as well as relation between microstructural features and deformation mechanisms should be revealed. In addition, increased knowledge on weldability and joining, prediction and controlling springback and fracture, increased fatigue performance will lead to exploitation of AHSS by other industries.

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