

Simulation and Optimization of an Aluminum-Intensive Body-on-Frame Vehicle for Improved Fuel Economy and Enhanced Crashworthiness - Front Impacts

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ABSTRACT

Motivated by a combination of increasing consumer demand for fuel efficient vehicles, more stringent greenhouse gas, and anticipated future Corporate Average Fuel Economy (CAFE) standards, automotive manufacturers are working to innovate in all areas of vehicle design to improve fuel efficiency. In addition to improving aerodynamics, enhancing internal combustion engines and transmission technologies, and developing alternative fuel vehicles, reducing vehicle weight by using lighter materials and/or higher strength materials has been identified as one of the strategies in future vehicle development. Weight reduction in vehicle components, subsystems and systems not only reduces the energy needed to overcome inertia forces but also triggers additional mass reduction elsewhere and enables mass reduction in full vehicle levels. Mass reduction can be achieved by removing materials that are not needed, substituting materials for those with lower density and/or higher strength, changing vehicle components and/or architectures to those require less material, or combinations of the above. New manufacturing and joining technologies and vehicle assembly processes as well as the associated simulation methodologies and tools also need to be developed in order to shift from current steel-intensive vehicles to lighter-weight vehicles with dissimilar materials, such as new generation advanced high strength steels, aluminum, magnesium, and composites.

In this paper, computer simulations and design optimizations conducted to develop an aluminum-intensive body-on-frame vehicle with improved fuel economy and enhanced crashworthiness are presented. The modeling of a body-on-frame vehicle is more difficult than that of a traditional unitized vehicle due to the challenges associated with components such as body mounts and ladder frame structures that are not part of unitized vehicle construction. In addition, material database and constitutive laws representing the mechanical properties of new high strength aluminum alloys and different joining methods utilized in the aluminum-intensive vehicle needed to be established. The models of the vehicle's aluminum-intensive bodies and cargo beds, high strength steel ladder frames, body mounts, and joining methods were developed based on material coupon and component tests. To minimize vehicle weight for improved fuel economy and to optimize the vehicle crash pulse and intrusion simultaneously for enhanced crashworthiness, design optimizations of geometry, shape, material, thickness, and joining method were conducted for major components in crash zones. Extensive full vehicle computer simulations with different frontal impact conditions and various vehicle configurations were performed during the design phase not only to enhance crash performance for federal safety regulations and internal requirements but also to meet manufacturing constraints.

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INTRODUCTION

With the first standards passed by Congress in 1975, the purpose of CAFE standards is to reduce energy consumption by increasing the fuel economy of cars and light-duty trucks [1]. In 2012, the

Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA), with the support of thirteen automakers, the United Auto Workers and the State of California, introduced new standards to reduce greenhouse gas emissions and

increase the fuel efficiency of model years (MYs) 2017 - 2025 light-duty vehicles sold in the United States [2]. The new standards are an extension of the 2012 - 2016 CAFE standards [3].

These latest fuel efficiency standards [2, 3, 4, 5], which have been mandated by the NHTSA on behalf of the Department of Transportation (DOT) and the EPA, require each automaker's sales-weighted fleet, including cars and light-duty trucks, to achieve an average fuel economy of 35.5 mpg (6.6L/100 km) by 2016 and 54.5 mpg (4.3L/100 km) by 2025. The 54.5 mpg (4.3L/100 km) is equivalent to a fleet average of 163 grams/mile of carbon dioxide for cars and light-duty trucks if automakers were to meet these standards solely through tailpipe CO₂ and fuel efficiency improvements. The actual MPG (Mile per Gallon) requirement for a given new vehicle is a function of its "footprint" determined by multiplying a vehicle's length by its wheelbase. Vehicles with smaller footprints are subject to higher MPG standards than vehicles with larger footprints. The new standards will require more aggressive development and implementation of new technologies in the industries.

There are many approaches to improve vehicle fuel economy and/or reduce CO₂ emission. General fuel-saving strategies can be developed by examining how the fuel energy is consumed during the vehicle's operation. It is known that the vast majority of energy from a fuel source is wasted as a result of heat, friction, pumping and mechanical losses. Less than 30% of the total energy is used to propel a vehicle, and even that is depleted by other factors such as aerodynamic inefficiencies, rolling resistance of tires, and so on. Advanced vehicle technologies developed in the industry recently to improve fuel efficiency can be characterized into one of following categories [6]:

1. *Advanced internal combustion engine (ICE-G or ICE-D)* to increase usable work output per unit of fuel energy input. Reducing engine friction, variable valve timing control, super/turbo chargers, direct injection, cylinder deactivation, or start-stop are examples of these;
2. *Transmission improvements* to increase the efficiency with which power from the engine is transmitted to the driveshaft and to the wheels such as continuously variable transmissions (CVT), dual dry clutch transmission (DDCT), and high-speed (e.g. 9-, 10-, or higher speed) transmissions;
3. *Use of alternative fuels* such as battery electric vehicle (BEV), hybrid electric vehicle (HEV), plug-in electric vehicle (PEV), plug-in hybrid electric vehicle (PHEV), hydrogen fuel cell vehicle (HFCV), or solar powered vehicle;
4. *Minimizing parasitic losses* in accessories like the cooling fan, alternator, and water pump. Technologies include regenerative battery charging, engine waste heat recovery, and HVAC (heating, ventilation, and air conditioning) control;
5. *Improving airflow or friction between a vehicle and its surrounding.* Technologies include aerodynamic body design to reduce drag (e.g. Figure 1), active-grill shutter (e.g. Figure 2), active-wheel shutter (e.g. Figure 3), low rolling resistance tire, and so on.
6. *Reducing vehicle weight* to reduce tractive forces and overall energy required to move the vehicle. It will require the developments of new lightweight materials, new component and system designs, new manufacturing and joining methods, or combination of the above to find optimal solutions.

Due to the number and complexity of the systems involved, vehicle weight reduction is one of the most challenging engineering tasks and is the main focus of this paper. Weight reduction of the Body-in-White (BIW) has an influence on overall vehicle weight reduction; a lighter body results in a lighter chassis, requiring a smaller engine and less battery and/or fuel tank capacity. Reducing vehicle weight introduces challenges and opportunities that affect all parts of the vehicle and engineering processes.

Vehicle lightweighting strategies will drive a shift to alternative materials and the associated manufacturing, joining, and assembly methods from those used in current steel-intensive BIW structures. There will be a fundamental change in vehicle development process and automotive engineers will rely more on engineering tools than on experience as they adopt these new weight efficient materials. To develop next-generation vehicle designs, it is also expected that new engineering simulation methods and material database will be required to help select the appropriate similar or dis-similar lightweight materials and to enable efficiencies in the vehicle development process.

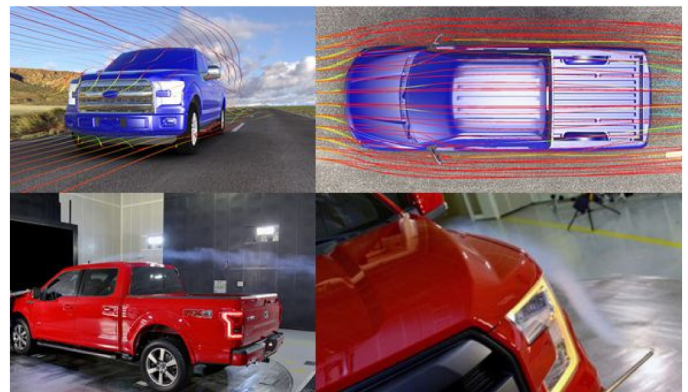


Figure 1. Wind tunnel aerodynamic drag testing.



Figure 2. Active grill shutters.



Figure 3. Active wheel shutters.

WEIGHT REDUCTION

Vehicle fuel consumption can be reduced through weight reduction. By reducing the mass of the vehicle, the inertial and rolling forces that the engine has to overcome as the vehicle is moving are

accelerated are reduced. As a result, the energy required to move the vehicle for a given distance is lessened. Reductions in vehicle weight can be achieved by a combination of (i) removing materials that are not needed; (ii) substituting materials for those with lower density and/or higher strength and (iii) changing vehicle component and/or architecture that requires less material. Removing materials that are not needed can be achieved by using topology optimization tool in component designs. Material substitution involves replacing heavier iron and steel used in vehicles with lighter-weight materials such as aluminum, magnesium, advanced high-strength steels, plastics and fiber reinforced polymer composites. Vehicle architectures can be redesigned by adopting new manufacturing technologies and simulation tools to consolidate different parts and/or to optimize the size and shape of components and/or systems. Vehicle weight reduction can be also enabled by redesigning the vehicle's packaging and reducing exterior vehicle dimensions while maintaining the same passenger and cargo space.

LIGHTWEIGHT MATERIALS

Advanced high-strength steels (AHSS) and aluminum are two alternative lighter-weight materials to conventional steel and iron. With continuous improvements, the AHSS are a family of steels that are stronger and have better formability than conventional high-strength steels (HSS) and are being used in some current mass production vehicles. Aluminum, with low density and good recyclability, is another lighter-weight material candidate and being adopted in some vehicle segments such as luxury and/or sport cars. Aluminum is now second only to steel as the most used material in vehicles.

Other lightweight material candidates include magnesium and polymer composites, such as glass- and carbon-fiber-reinforced thermosets (thermosetting resins such as epoxy, polyester, or vinyl ester) and thermoplastics (thermoplastic resins). Due to material pricing and process limitations, fiber-reinforced composites are used more often in super and/or race cars. Less common lightweight materials like titanium and metal matrix composites also have been used but material pricing limits their application in the mainstream vehicle fleet. In the continued weight reduction effort for improved fuel economy, CO₂ emission, and safety requirements, it is expected that AHSS, aluminum, magnesium, and carbon-fiber-reinforced composites will likely have wider application in the automotive industry.

Government and automotive industry have been in partnerships to increase lightweight materials usage in vehicles. In 2013, the Advance Research Products Agency-Energy (ARPA-E) awarded \$32 million in grants to develop cost-effective and energy-efficient manufacturing processes for vehicle lightweight materials. The U.S. Department of Energy (DOE), National Laboratories, Universities, and the United States Council for Automotive Research (USCAR) [7], a collaborative research organization of Fiat Chrysler Automobiles, Ford Motor Company, and General Motors Corporation, continue to work jointly on numerous research projects for automotive lightweight materials. To develop faster and fully-automated processes and to increase economic efficiencies, material suppliers are also working with major automakers in strategic partnerships. The strategic partnerships will also ensure sufficient production supply and continued technology advancements when

incorporating weight efficient materials into new vehicle designs to achieve improved fuel efficiency. The development history, types or grades, mechanical properties, application potentials in vehicles, as well as comparative advantages and disadvantages of these four major lightweight materials are reviewed in the following.

Advanced High Strength Steel

Conventional mild steels and high strength steels have been used in the automotive industry since early 1910s, especially in vehicle body and chassis. All-steel body vehicles were lighter, stronger, and easier to manufacture than those of the wooden vehicle bodies made with combination of wood and steels as illustrated in [Figures 4a](#) and [4b](#). CARS magazine predicted in October 1953 that "The day of the passenger car made primarily of iron and steel is on the wane and will give ground to aluminum, magnesium and plastics" [8, 9]. However, steel's percentage in a vehicle, in terms of vehicle weight, has remained steady at more than 50% for decades as published by SMDI (Steel Market Development Institute) and A/SP (Auto Steel Partnership) and summarized in [Figures 5](#) and [6](#) [8, 9]. Most existing vehicle manufacturing infrastructures today are built for steel-intensive vehicle designs and make it easier to extend to the application of different steel grades. According to 2012 AISI data, steel recycling rate is about 88%. Iron and steel are among the world's most recycled materials, and the easiest materials to reprocess, as they can be separated magnetically.



Figure 4a. 1932 wooden Talbot.



Figure 4b. 1932 wooden Talbot.

Materials Content - 1975

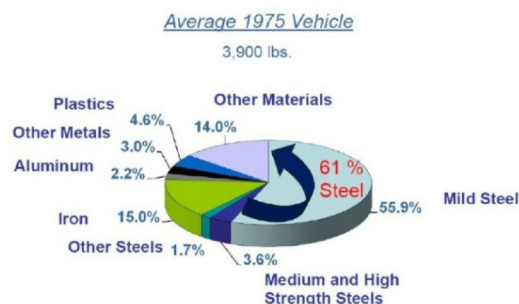


Figure 5. Material content in an average 1975 vehicle (GDIS).

Automotive steels can be classified in different ways. The most commonly used classification method is the strength of steel [8, 9]. The conventional mild steels and HSS are defined as steels with yield strength less than 210 MPa (or tensile strength 270 MPa) and from 210 MPa to 550 MPa (or tensile strength 780 MPa) respectively. The conventional mild steels and HSS grades include interstitial free (IF), bake hardenable (BH), carbon-manganese (C-Mn), and high strength low alloy (HSLA) steels. The conventional mild steels and HSS, as shown in Figure 7 (elongation-yield strength diagram), become less ductile when the strengths are increased and thus are less formable. The formability behavior of conventional high strength steels is self-explained by examining the engineering stress-strain curves of the HSLA family steels, as illustrated in Figure 8.

Materials Content - 2007

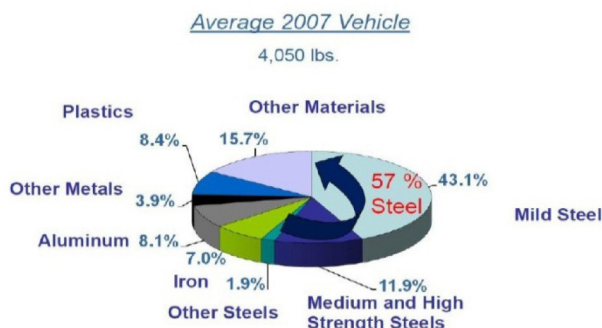


Figure 6. Material content in an average 2007 vehicle (GDIS).

To increase vehicle mass reduction opportunities, both the strength and ductility (elongation) of steels need to be increased. Steels with yield strengths above 550 MPa or tensile strengths exceeding 780 MPa are generally referred to as ultra-high strength steels (UHSS). UHSS grades are typical martensitic steels (MS or MART). Steels with tensile strength greater than 1000 MPa are also called "GigaPascal steel" (1GPa = 1,000 MPa = 1,000 N/mm² = 145,000 PSI). Even with different chemical compositions, the density, Young's Modulus, and Poisson's ratio of different steel grades remain rather constant and are around 7.85-7.87 g/cm³, 200 - 210 GPa, and 0.3 respectively. Steel is also easier to be welded together or formed to different shapes when compared to other lightweight materials.

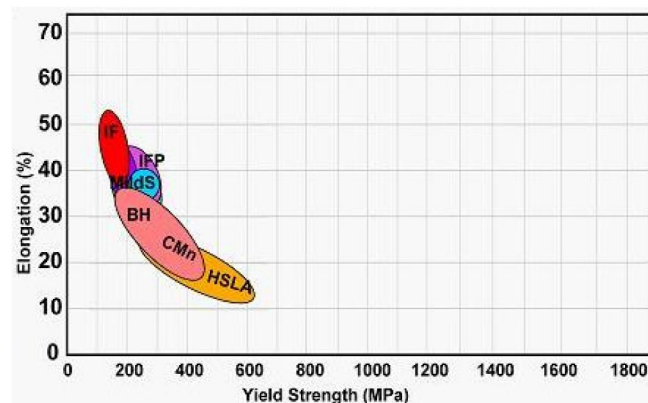


Figure 7. Conventional mild and high strength steels (GDIS).

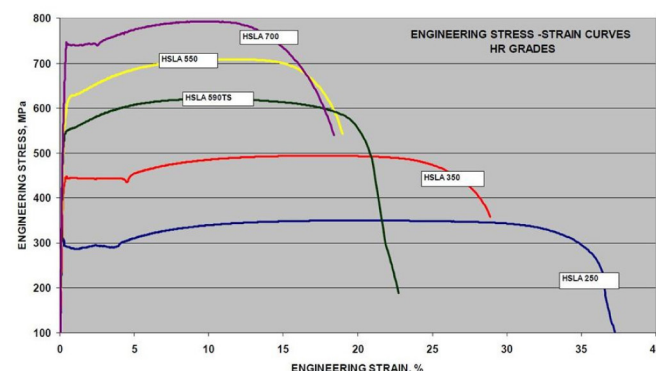


Figure 8. Engineering stress-strain relationship of HSLA steels (GDIS).

Due to the increasing challenges of fuel economy and safety requirements, the steel industry has been in partnership with the automotive industry [8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33] to enhance steel's properties for improved strength-ductility balance and to meet the needs for lightweighting and safety. As a result, AHSS illustrated in Figures 9 and 10 have been developed with unique chemical and physical properties. The AHSS family includes dual-phase (DP), complex-phase (CP), Ferritic-Bainitic (FB), hot-formed (HF), transformation-induced plasticity (TRIP), twinning induced plasticity (TWIP), light steels with induced plasticity (L-IP), austenitic stainless steel (AUST. SS), high strength and ductility (HSD), martensitic steel (MS or MART), boron-based press hardened steel (PHS), nano-structured steel (NS), and so on. These new AHSS are complex and sophisticated. They are manufactured with carefully designed chemical compositions and multiphase microstructures resulting from precisely controlled heating and cooling processes.

These new AHSS not only offer higher tensile strengths but also exhibit greater formability as compared to those of the conventional mild steels and HSS. The main difference between the conventional HSS and the AHSS is their microstructure. Some types of AHSS have higher strain-hardening capacity while other types have ultra-high yield and tensile strengths and show a bake hardening behavior. As a result, the AHSS have improved strength-ductility balance compared to conventional steels. Due to the improved strain-hardening capability, the DP, CP, and TRIP steels can absorb high impact energy and are material candidates to be used in the crash zones. MS, MART

and PHS with extremely high yield and tensile strengths are material candidates to be used in passenger compartment because of their abilities to resist plastic deformation at much higher impact loads.

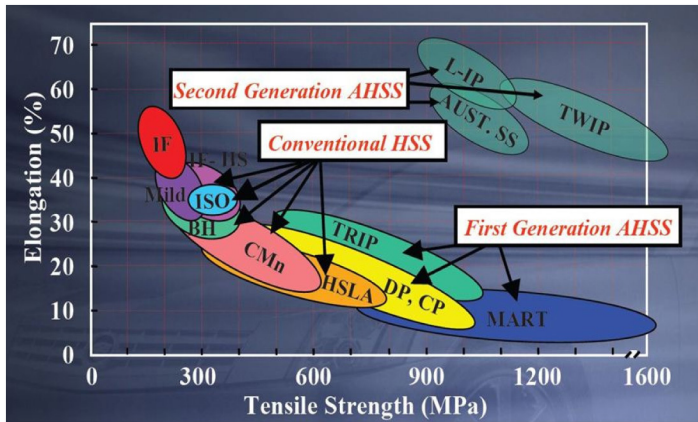


Figure 9. 1st and 2nd generation advanced high strength steels (GDIS).

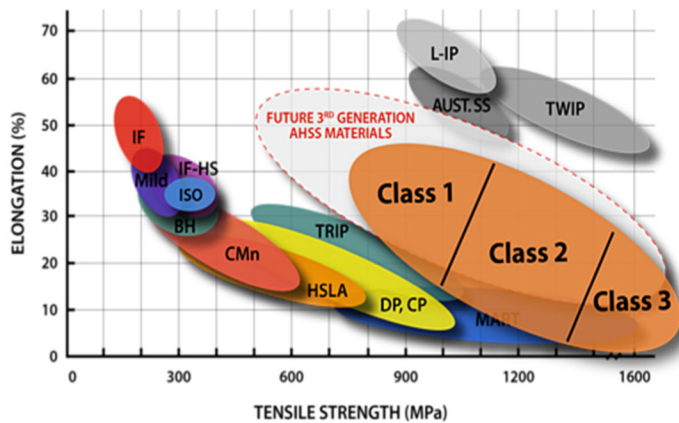


Figure 10. 3rd generation advanced high strength steels (GDIS).

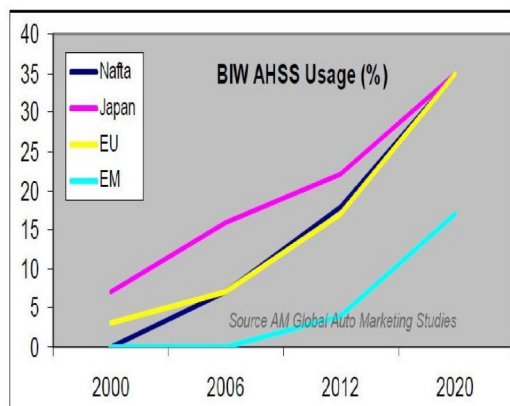


Figure 11. Global BIW AHSS usage (GDIS).

Now reaching the third generation, the availabilities of these AHSS offer effective steel solutions to reduce vehicle weight by allowing vehicle components to be designed with thinner gauges while keeping crash test performance at a high level. Based on the data from AM Global Auto Marketing Studies for different global regions (Figure 11), the AHSS usage in vehicle BIW (body-in-white) would continue to increase from less than 10 percent in 2000 to around 35 percent in

2020 in most global regions, including North America, Japan, and EU. Using the data in 2013 Ford Fusion as an example, the content of the AHSS in the medium size vehicle's BIW has grown to about 36.2% in 2013 as shown in Figure 12. The average yield strength of the medium size vehicle's BIW has reached almost 350 MPa, also illustrated in Figure 12.

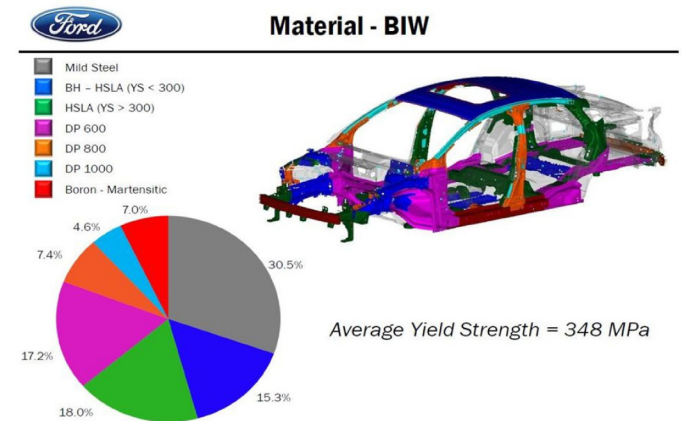


Figure 12. Material content in 2013 Ford Fusion BIW (GDIS).

Aluminum

With density ranging from 2.7 g/cm³ to 2.9 g/cm³ (Young's Modulus: 69 GPa, tensile strength: 91 MPa - 525 MPa, Poisson's ratio: 0.32 - 0.33) [34, 35], aluminum alloys are about one third of the density of steel. There are basically two methods for producing aluminum. Primary production involves mining bauxite deposits from the earth and performing electrometallurgical processing to ultimately form aluminum. The secondary production method makes new aluminum from recycled scrap products. Aluminum has good recycling capabilities and can be recycled multiple times without significant degradation of the material. Nearly 90 percent of the aluminum, on average, is recycled at the end of a vehicle's life. The re-melting of aluminum requires about 5 percent of the energy required to produce the primary metal initially. The low density and recyclability make aluminum a candidate for vehicle lightweighting.

Aluminum has material properties that differ from those of steels. Pure aluminum has poor mechanical properties such that it is not used in load bearing constructions. The metal is usually alloyed and heat treated or hardened to obtain the required properties. The main groups of aluminum alloys are: Al-Cu, Al-Mn, Al-Si, Al-Mg, Al-Si-Mg, Al-Zn. The most common type of classification for base materials is the AA (The Aluminum Association) classification [34,35,36,37].

- 1xxx Aluminum 99.0% minimum;
- 2xxx Copper (1.9%...6.8%);
- 3xxx Manganese (0.3%...1.5%);
- 4xxx Silicon (3.6%...13.5%);
- 5xxx Magnesium (0.5%...5.5%);
- 6xxx Magnesium and Silicon (Mg 0.4%...1.5%, Si 0.2%...1.7%);
- 7xxx Zinc (1%...8.2%);
- 8xxx Others.

The 1xxx, 3xxx, 4xxx and 5xxx alloys are strain hardened while the 2xxx, 6xxx and 7xxx alloys are heat treated. The second digit indicates modification of the alloy or impurity limits. The last two digits identify aluminum alloy or indicate the alloy purity. A so-called temper designation is put after the alloy to show how the hardening has been performed. The most common temper designations for wrought alloys are: “F” - as fabricated, “H” - strain hardened (cold worked) with or without thermal treatment, “O” - full soft (annealed), “T” - heat treated to produce stable tempers, and “W” - solution heat treated only. The “H” applies to products which are strain hardened through cold-working and is always followed by two or more digits. The first digit indicates basic operations and the second digit indicates degree of strain hardening. The “T” applies to products which have been heat-treated to produce a stable temper. The “T” is generally followed by one digit indicating the specific sequence of treatments. Common designations are the T4 (solution heat treated and naturally aged) and the T6 (solution treated and artificially aged).

Aluminum has greater “specific energy absorption” than conventional mild steels, meaning that equivalent energy management performance can be achieved with less weight than with the conventional steel. Aluminum is a more chemically reactive metal than iron and thus is less corrosion-resistant than steel generally. Aluminum naturally generates a protective oxide coating and is highly corrosion resistant. Due to good castability [38], aluminum has been used to produce casting automotive components, such as, engine, transmission, control arm, shock tower, wheel, and steering system. According to the Aluminum Association, aluminum parts made up only 2 percent of the weight of most cars in 1970. The number has increased to around 9 percent for cars manufactured in 2009. Use of automotive aluminum has grown continuously at an annual rate of 4% for the last four decades. Aluminum is now second only to steel as the most used material in vehicles.

Generally, aluminum has lower formability and weldability than steel. To form deep draw shapes and complex geometries, forming processes, such as superplastic forming, warm forming [39], hot forming [40,41,42], and hydro-forming processes [43,44,45,46,47], are needed to form automotive parts. Due to higher silicon content in the aluminum alloys, the abrasive nature of the material make dies wear out faster using aluminum sheets than with mild steel.

Aluminum has higher thermal properties (thermal conductivity, specific heat, and thermal diffusivity) than steel, which suggests that higher steady heat inputs are required to weld aluminum. Due to the large thermal conductivity of the material, aluminum can exhibit large deformations when subjected to heat. Aluminum also has lower melting temperature ($>570^{\circ}\text{C}$) than that of steel ($>1500^{\circ}\text{C}$). The heat from welding has great influence on the internal structure of the aluminum material. The strength in the HAZ (heat affected zone) is reduced, sometimes by as much as 50%, due to the thermal treatment the material receives during welding. Joining aluminum to steel directly also creates galvanic corrosion problems [48] when salt and water are present.

Aluminum alloys typically have an elastic modulus of about 70 GPa, which is about one-third of the elastic modulus of most types of steel and steel alloys. Therefore, aluminum is more suitable for closure

components such as doors, hoods, deck lids, lift gates, roof panels, and fenders. To use for structural components, the thickness of the aluminum component needs to be increased to achieve required strength. Therefore, aluminum space frame structures, e.g., Ford GT shown in Figures 13a and 13b, are usually designed and manufactured with extruded tubes (Figure 14) [49], casting components, and/or hydro-formed parts to ensure rigidity.

The dis-advantages of aluminum in mass production automobiles are material pricing and the investment for aluminum fabrication processes. As a result, aluminum space frame architecture was adopted mostly in luxury and/or high performance sport vehicle segments. With the on-going goal to reduce the weight of vehicles, aircrafts, and military weapon systems, advanced high strength aluminum alloys are now being developed [50] to increase the application of aluminum in various structures.

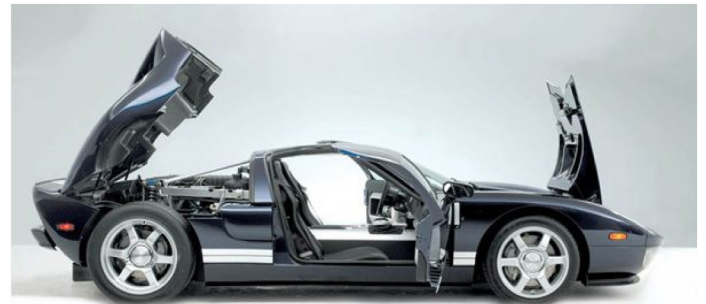


Figure 13a. Ford GT super car.



Figure 13b. Ford GT aluminum space frame.



Figure 14. Ford GT aluminum extruded cross sections.

Magnesium

Magnesium density is about 1.77 g/cm³ to 1.81 g/cm³ which is 75% lighter than steel and 33% lighter than aluminum. The Young's Modulus in tension and compression is around 42 to 45 GPa, The modulus of elasticity in shear, or modulus of rigidity, is about 16 GPa. Poisson's ratio is 0.35 [51, 52]. When alloyed, Mg has the highest strength-to-weight ratio of all structural metals. A combination of low density, high specific strength, and good castability makes magnesium alloys a promising material candidate for the automotive lightweighting. Magnesium is the eighth most common element. Seawater, the main source of supply, contains 0.13% Mg. Magnesium is also recyclable. High Pressure Die Casting (HPDC) [53, 54] and Super Vacuum Die Casting (SVDC) [55] are the primary production processes for automotive magnesium parts. Almost no wrought magnesium products are used currently in automotive construction. As one of the promising materials for achieving weight reduction, magnesium is relatively uncompetitive for most automotive applications due to its material pricing and energy consumption in the manufacturing process.

Currently, magnesium is sparingly used in vehicles because it is about seven times more expensive to make than steel and aluminum. Its price ranges from about \$14.0 to \$17.0 per kg. Magnesium is currently being used in relatively small quantities for automotive components, mostly limited to die casting components [43,44,45,46,47,48,49,50,51,52,53,54,55,56], such as steering column [57, 58], steering wheel armatures [57, 58, e.g. Figure 15], driver's air bag housings, seat frames (e.g. Figure 15), lift-gate inner panel (e.g. Figure 16), fuel tank covers, intake manifold (e.g. Figure 17), gearbox (e.g. Figure 17), cross-car beam (e.g. Figure 18), instrument panels (e.g. Figure 19), cylinder head covers, and transmission cases (e.g. Figure 20).

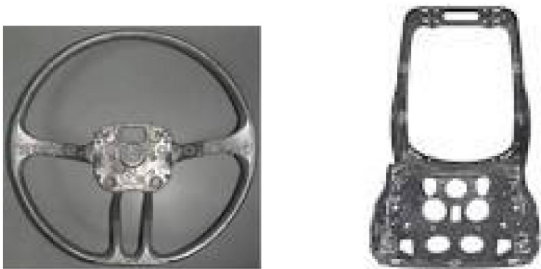


Figure 15. Magnesium wheel armature and seat frame.



Figure 16. Magnesium Liftgate.



Figure 17. Magnesium manifold and gearbox.



Figure 18. Magnesium cross car beam.



Figure 19. Magnesium instrument panel.



Figure 20. Magnesium transmission case.

Government and industry now are in partnerships to boost magnesium use in an effort to reduce vehicle weight. The Advance Research Products Agency-Energy (ARPA-E) recently awarded grants to develop processes for cost-effective and energy-efficient manufacturing of lightweight materials for vehicles. One of the research projects will focus on less-expensive and more energy-efficient ways of producing magnesium that can be used to make lightweight vehicle parts. According to the U.S. Automotive Materials Partnership (USAMP, an industrial coalition of the Ford Motor Company, the General Motors Co., and the Fiat Chrysler Automobiles), magnesium parts will contribute to a 15% weight reduction in cars and trucks, leading to fuel savings of 9% to 12% by 2020. The partnership says automakers used only 10 lbs. (4.5 kg) of magnesium per vehicle in 2005. The industry target is to use an

average of 350 lbs. (159 kg) magnesium components in vehicles by 2020. This would help lower the weight of the average car from the current 3,360 lbs. (1,524 kg).

The available magnesium alloys are divided into two groups [51, 52]: casting alloys and wrought alloys. Magnesium alloy types are often given by two letters following by two numbers. Letters tell main alloying elements (e.g. A = aluminum, Z = zinc, M = manganese, S = silicon, K = zirconium). Numbers indicate respective nominal compositions of main alloying elements. Magnesium casting alloys proof stress is typically 75 - 200 MPa, tensile strength 135 - 285 MPa and elongation 2 - 10%. Typical density is 1.8 g/cm³ and Young's Modulus is 42 GPa. Some of the most common magnesium casting alloys are: AM50 (Mg-5%Al-0.35%Mn), AM60 (Mg-6%Al-0.35%Mn), AZ63 (Mg-6%Al-3%Zn-0.4%Mn), AZ81 (Mg-7.5%Al-0.7%Zn), AZ91 (Mg-9%Al-0.7%Zn-0.3%Mn), ZK51 (Mg-4.6%Zn-0.75%Zr), ZK61 (Mg-6%Zn-0.7Zr), and so on. Table 1 summarizes the mechanical properties of three magnesium die-cast alloys that are commonly used in the automotive industry.

Table 1. Mechanical properties of magnesium die-cast alloys.

MECHANICAL PROPERTIES OF PRESSURE DIECAST PARTS				
properties	unit	alloys		
		AZ91	AM60	AM50
Ultimate Tensile Strength R _m	N/mm ²	200-260	190-250	180-230
Yield strength R _p 0.2	N/mm ²	140-170	120-150	110-130
Elongation A	%	1-6	4-14	5-15
Hardness HB		65-85	55-70	50-65

Magnesium wrought alloy proof stress is typically 160 - 240 MPa, tensile strength is 180 - 440 MPa and elongation is 7 - 40% [51, 52]. Some of the most common wrought alloys are: AZ31, AZ61, AZ80, ZE41, ZC71, and so on. Magnesium alloys harden rapidly with any type of cold work and therefore cannot be extensively cold formed without repeated annealing. Mg-Al-based alloys, especially the AZ and AM series, combine good room-temperature strength and ductility with satisfying salt-spray corrosion resistance and excellent castability.

Fiber Reinforced Polymers

Fiber reinforced polymers [59,60,61,62,63,64,65,66,67,68,69,70] are engineered composite materials that are fabricated by embedding webs of fibers (reinforcement) inside molded polymer resins (matrix). Similar to how steel rebar strengthens a poured-concrete structure, the fibers improve the physical properties of the plastic matrix components. Because fiber reinforced polymers consist of two distinct elements, fiber and polymer resin, the composite material properties depend on these two elements. Although other fibers, such as glass, nature fibers, and graphite fiber (99% carbon) are also being used as reinforcements in automotive applications, adoption of carbon fiber (about 95% carbon) reinforced polymer (CFRP) is increasing in a faster pace in the recent years as vehicle lightweighting becomes an enabler to meet the fuel economy and emissions regulations.

The CFRP has a higher strength-to-weight ratio over other lightweight materials. The CFRP is roughly five times stronger than steel and twice as stiff [63,64,65,66,67,68,69]. The density of some commercially available CFRP for high-performance applications is around 1.6 to 1.8 g/cm³. They offer a wide range of properties, with Young's Modulus ranging from 120 to 580 GPa and tensile strength varying from 1,720 to 7,000 MPa [63,64,65,66,67,68,69]. CFRP structures weigh about two-thirds less than steel counterparts and a third less than aluminum ones. Unlike materials such as steel and aluminum which are generally treated as isotropic, the CFRP has directional strength properties. The properties of the CFRP depend on the layouts of the carbon fiber and the proportion of the carbon fibers relative to the polymer. With the inherent corrosion, scratch, and dent resistance of composites and the flexibility to make purpose-designed and molded components, the CFRP has promise for automotive applications. But despite the many benefits, CFRP components take longer time to produce and material pricing is higher than those of other lightweight metals, such as AHSS, aluminum, and magnesium. To better understand the applications of such material, the operations for producing CFRP and the processes to make CFRP automotive components are summarized below [63,64,65,66,67,68,69].

The raw material used to make carbon fiber is called the precursor. The exact composition of each precursor varies from one company to another. About 90% of the carbon fibers produced are made from polyacrylonitrile (PAN). The remaining 10% are made from rayon or petroleum pitch. All of these materials are organic polymers, characterized by long strings of molecules bound together by carbon atoms.

The process for making carbon fibers is both chemical and mechanical. Typical sequences of operations to form carbon fibers from PAN include spinning, stabilizing, carbonizing, surface treatment, and sizing. The precursor is drawn into long strands or fibers and then heated to a very high temperature without allowing it to contact with oxygen or burn. The high temperature causes most of the non-carbon atoms to be expelled. The process is called carbonization and leaves a fiber composed of long, tightly inter-locked chains of carbon atoms with only a few non-carbon atoms remaining.

Carbon fibers are essentially very thin strands of carbon, thinner than human hairs, which are twisted together. These threads are then woven to form sheets of carbon, a process similar to the manufacture of cloth. The choice of the matrix, i.e., the resin, also plays an important role in the mechanical properties of the finished CFRP component. Many CFRP components are created with a single layer of carbon fabric that is backed with fiberglass. A tool called a chopper gun is used to quickly create these composite components. Once a thin shell is created out of carbon fiber, the chopper gun cuts rolls of fiberglass into short lengths and sprays resin at the same time, so that the fiberglass and resin are mixed on the spot. The types of carbon fibers can be characterized as follows:

- UHM (ultra high modulus). Modulus of elasticity > 65,400 ksi (450 GPa).
- HM (high modulus). Modulus of elasticity is in the range 51,000 - 65,400 ksi (350 - 450 GPa).

- IM (intermediate modulus). Modulus of elasticity is in the range 29,000 - 51,000 ksi (200 - 350 GPa).
- HT (high tensile, low modulus). Tensile strength > 436 ksi (3 GPa), modulus of elasticity < 14,500 ksi (100 GPa).
- SHT (super high tensile). Tensile strength > 650 ksi (4.5GPa).

The manufacture methods of automotive CFRP components may involve molding, vacuum bagging, compression molding, or filament winding. The process varies depending on the component being produced and how many are to be produced. CFRP components in the automotive industry were primarily made by hand, which resulted in the process being resources intensive.

The resource intensive production process has limited their applications to low-volume and high-speed vehicles such as high-performance race cars (e.g. Formula 1 and NASCAR monocoques as illustrated in Figures 21, 22, 23), super/luxury sport car components, bodies, and chassis (e.g. hoods, decklids, outside mirror casings, front spoilers, removable roof panels, fenders, doors, rear quarter panels, and underbody panels as shown in Figures 24a, 24b, and 25). Another challenge for the CFRP is the high energy consumption associated with the production of carbon fiber, leading to a negative carbon dioxide impact. Other obstacles for CFRP include volume ability, defect detection, repairability, recyclability, and joining.



Figure 23. Audi carbon fiber monocoque.



Figure 24a. Ford GT rear decklid and seat.



Figure 24b. Ford Mustang GT500KR hood.



Figure 25. Rezvani full-fledged carbon fiber body.



Figure 21. Audi CFRP race car.



Figure 22. Ford MSA Formula race car with carbon-fiber monocoque chassis.

Regarding price/mass, steel is approximately \$0.80/kg to \$1.0/kg, aluminum is between \$2.40/kg and \$2.60/kg, polyester and epoxy resins range from \$5/kg to \$15/kg and the reinforcing fiber costs an additional \$2/kg to \$60/kg, depending on type and quality [63,64,65,66,67,68,69]. As a result, adapting structural composites to large-scale production has always been a technical and manufacturing challenge. To enable the applications of the material in mass production vehicles, automakers are continuing to research ways to