Material Efficiencies and Recycling of Aluminum and Carbon Fiber Reinforced Plastics for Automotive Applications

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ACRONYMS

AA	Aluminum Association
BIW	body-in-white
CF	carbon fiber
CFRP	carbon fiber reinforced plastics
DOE	U.S. Department of Energy
EOL	end-of-life
GFRP	glass fiber reinforced plastics
GHG	greenhouse gas
LCA	life cycle assessment
PAN	polyacrylonitrile
rCF	recycled carbon fiber
RTM	resin transfer molding
USGS	U.S. Geological Survey
WPI	Worcester Polytechnic Institute

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1 INTRODUCTION

Car manufacturers are exploring vehicle lightweighting options to meet the increasingly stringent fuel economy and greenhouse gas (GHG) emission standards. Aluminum and carbon fiber reinforced plastic (CFRP) are two lightweight materials in use, due to their superior lightweighting potential. However, the production processes for aluminum and CFRP are considerably more energy-intensive compared with conventional materials on a per kg basis. This translates into higher GHG emissions if the energy consumed for material production comes from fossil sources. To better understand the environmental implications of vehicle lightweighting, it is important to evaluate the benefits offered by lightweighting through reduced fuel consumption during the vehicle use-phase, as well as the additional burdens incurred by using lightweight materials for vehicle production.

Aiming to evaluate the environmental impacts pertaining to vehicle manufacturing with lightweight materials, this study investigates aluminum and CFRP use for automotive applications, with two specific metrics that dictate the environmental burden of vehicle production from these two materials: 1). The material efficiencies (i.e. scrap rates) of automotive parts manufacturing; 2). Recycled contents of lightweight materials, and recycling practices during vehicle production and after vehicle end-of-life (EOL). State-of-the-art of lightweighting strategies with aluminum and CFRP within the automotive industry is examined. Assumptions regarding aluminum and CFRP in Argonne's Greenhous gases, Regulated Emissions, and Energy use in Transportation (GREET®) Model are reviewed. Knowledge gaps and areas of potential improvements are identified.

2 ALUMINUM

2.1 ALUMINUM OVERVIEW

The use of aluminum in vehicles has been growing steadily in the past 40 years. Ducker Worldwide estimates that the aluminum content in North American light vehicles has increased from 306 lbs per car in 2005 to 394 lbs in 2015, and is expected to reach 547 lbs in 2025 (Ducker Worldwide 2014). The projected growth of automotive aluminum content projected for the next ten years is contingent upon increasing penetration of aluminum body and closure parts in vehicles (Ducker 2014), while most of the aluminum currently used in vehicles exists in engine blocks, crankcase and gearboxes (Kelly 2015 and Kelly 2014). Since body parts are produced via stamping and extrusion of wrought aluminum, whereas engine blocks and other existing aluminum parts are produced via sand casting or die casting of cast aluminum, it is important that the modeling of aluminum use for automobiles in GREET represents the state-of-the-art of the industry, especially these associated with part manufacturing from wrought aluminum, to account for the industrial trend towards increasing aluminum content in the vehicle body.

2.2 ALUMINUM SCRAP RATES

The new Ford F150, which became available in the market in 2015, is the first mass-produced light-duty vehicle that features an aluminum body. According to Ford, building the body out of high strength aluminum alloy, together with increasing the high strength steel content in the vehicle frame from 22% to 77%, achieves a total weight reduction of 700 lbs. This weight reduction leads to a fuel economy improvement of ~12% (Ford 2015). The new F150 contains over 1000 lbs of aluminum, more than 60% of which is in the body and closure parts (Ducker Worldwide 2014). Compared with the previous model with a steel body, over 600 lbs of aluminum has been added to the new design. As of June 2016, Ford estimated that nearly a million of the new F150 has been built (Forbes, 2016). Given the popularity of the F150, and its significant aluminum content, the production of F150 aluminum parts could serve as the industrial state-of-the-art for aluminum use in vehicle body and closure parts.

As mentioned earlier, material efficiency and recycled content are two particularly important parameters in determining the environmental footprint of aluminum products. Ford has reported a scrap rate of 30~40% for the stamping process of the aluminum body parts (Ford 2016). This is consistent with the 72% material efficiency (i.e., 28% scrap rate) assumed for stamping in 2015 GREET (Burnham 2006). Therefore, no change is made in 2016 GREET regarding the stamping yield for light duty vehicles.

2.3 ALUMINUM RECYCLED CONTENT

During the production of the new F150 (MY 2015 and later), the scrap generated in the stamping process of aluminum parts has been recycled in a closed-loop fashion to make new parts for F150 (Ford 2016). However, no information is found regarding Ford’s plan to recycle aluminum from this new generation of F150s when they reach their EOL. Since wrought aluminum typically has a much lower tolerance for impurities than cast aluminum (AA 2015), and thermodynamic calculations showed that under practical remelting conditions, it is impossible to remove all the impurities from aluminum scraps (Reck 2012), wrought aluminum is predominately composed of primary metal. Secondary aluminum produced from old aluminum scraps, is primarily used for castings. In fact, cast automotive parts represent the single largest consumer for old aluminum scraps, excluding used aluminum cans, which are closed-loop recycled (Cullen 2013).

In the latest life cycle analysis (LCA) study conducted by the Aluminum Association (AA) of semi-finished aluminum products in North America, it was estimated that in 2010, 0.29kg of old scrap was incorporated back into 1 kg of extruded aluminum products in North America, and 0.39 kg into 1 kg of both hot-rolled and cold-rolled aluminum products (AA 2013). These two recycled content values were not adopted in 2015 GREET for two reasons. First, they represented aluminum products for all end sectors (not just for vehicles). The recycled content of aluminum extrusions for building and construction is higher compared to extruded parts for all other applications (IAI 2015), and building and construction is the third largest end user of aluminum (USGS 2015), thus the average recycled content reported by AA is not representative of the extruded parts for cars. Similarly, including the recycled content of aluminum cans and packages, which is generally over 60% (AA 2014), drove up the reported recycled content of average rolled products across all end-use sectors, and therefore would overestimate the recycled content of aluminum sheets in cars. Second, the estimates made by AA was based on survey data collected from North American aluminum semi-fabricators. Survey respondents represented 59% and 75%of North American aluminum extruded parts producers and rolled parts producers, respectively. AA cautioned that these two values should be deemed as the best estimates for the industry (AA 2013). Therefore, the existing recycled content of 11% for wrought aluminum in GREET, which was based on the 1998 Al report by AA (AA1998), is retained. For shape castings, AA could only collect very limited data from aluminum casting companies. Nevertheless, they estimated the recycled content of aluminum casting products to be 85% based on metal feedstock survey data collected from a few foundries (AA 2013). This estimate is identical to the existing assumption for the recycled content of cast aluminum in GREET.

Worcester Polytechnic Institute (WPI) conducted another study concerning aluminum recycling, focusing on a grave-to-gate analysis for automotive aluminum. The analysis concluded that the overall recycling rate for automotive aluminum is 91% in the U.S. (Kelly and Apelian 2016). This recycling rate suggests a higher recycled content for automotive aluminum than those assumed in GREET. However, it should be pointed out that the recycling rate reported by WPI does not represent the mass-balance of Al recycling from EOL cars in the U.S. Rather, it is determined by combining the material collection rate of aluminum from EOL vehicles with the material efficiencies of subsequent aluminum recovery processes. Moreover, the survey data collected by WPI only represented 5% of vehicles received by the car dismantling facilities, 32% of volumetric throughput of downstream separation facilities, and 60-70% market share of secondary aluminum production facilities. Given the limited data coverage and the methodology used to derive the recycling rate, the reported recycling rate does not represent the industrial average. Furthermore, since it is not clear if all of the recovered aluminum is used to make new automotive parts, this recycling rate does not represent the recycled content of aluminum for vehicle production. Aside from the recycling rate, the WPI study provides detailed information on the processes pertaining to aluminum recycling from EOL vehicles. These information should be revisited if data on mass flows of wrought and cast aluminum throughout the U.S. automotive recycling industry becomes available, to enhance the modeling of aluminum in GREET.

In should be noted that opportunities exist for the automotive industry to increase the recycled content of aluminum, especially with wrought aluminum. For example, another car manufacturer offering an Al-body vehicle, Jaguar Land Rover, began exploring the potential of incorporating more recycled aluminum into their new Range Rover by developing new wrought aluminum alloys that can tolerate a higher level of impurities. One success they already achieved is with RC5754, which has the same properties as AA5754, but targets a recycled content over 75% (Altair 2016). This new trend of design for recycling, and its prevalence in the automotive industry, should be tracked and reexamined in future aluminum updates for GREET.

3 CARBON FIBER REINFORCED PLASTICS

3.1 CFRP OVERVIEW

CFRP offers the greatest mass reduction potential among all lightweight materials for automotive applications, with a weight reduction up to 60% compared with steel (DOE 2013). Although current applications of CFRP in vehicles are limited to expensive and low-production-volume models, primarily due to high cost and long production cycle times, the demand of CFRP within the automotive industry is expected to grow from 3,219 tonnes in 2012 to 9,863 tonnes by 2018, representing a compound annual growth rate of 20.5% (Das, 2016).

The BMW i3, which contains 120-150 kilograms of CFRP per vehicle, accounts for over three quarters of the CFRP demand by the automotive industry since its production began in 2013, with an annual production volume of ~30,000 units (Das 2016). The use of CFRP in the i3 production, therefore, predominantly represents the state-of-the-art of CFRP use in the automotive industry.

3.2 CFRP SCRAP RATES

The i3 features an aluminum frame and a CFRP body-in-white (BIW). The frame and the BIW are bonded by adhesives, and bolted together at 4 points. In addition to the BIW, CFRP is also used in the powertrain, chassis, battery and interior of the i3 (American Chemistry Council 2015). Carbon fiber (CF) used in the i3 is produced from polyacrylonitrile (PAN) at a facility owned by SGL Automotive Carbon Fibers in Moses Lake, WA. The produced 50K tow (50,000 fibers contained in a bundle) CF is shipped to Germany, where it is processed into laminates and sent to the i3 plant in Leipzig. At the plant, CFRP parts are manufactured by a resin transfer molding (RTM) process, and then bonded by a glue to form the BIW (Automotive Design & Production 2013).

CFRP scraps from the composite production as well as parts manufacturing are recycled and incorporated into the roofs of i3. It was estimated that 10% of the CFRP used in the i3 comes from cut-offs (Composites World 2013). This translates into a scrap rate of 10%. Other sources reported a 10% scrap rate for composite products, which include those made of carbon fiber composites and glass fiber composites (Bains 2013), and an industry-wide 30% scrap rate for CFRP products, which encompass applications for aerospace, wind power, and automotive (Composite World 2016). Based on available data, the scrap rate of the i3 production is the most representative of CFRP use in automobiles. However, since it is comparable to the 14% scrap rate currently assumed for CFRP in GREET (Burnham 2006), and 10% appears to be a "ballpark" number rather than an accurate estimate, no change is made to the existing assumption for CRFP scrap rate in GREET for the 2016 release. The same also applies to the electricity mix for CF production and CFRP parts manufacturing. Although the CF production plant in Moses Lake and the i3 plant in Leipzig use electricity from hydro power and wind power, respectively (Automotive Design & Production 2013), the exact electricity mix for the entire process cannot be determined unless detailed mass and energy flows along the CFRP supply chain are disclosed. Therefore, the U.S. grid mix is retained in GREET for electricity consumption associated with CFRP.

3.3 CFRP RECYCLED CONTENT

CFRP recycling is not considered in GREET because the use of post-consumer CRFP scraps in automotive applications is nonexistent, at least not on a commercial scale. Nonetheless, available CFRP recycling technologies, along with efforts to improve CFRP recycling are examined to inform future GREET updates for CFRP.

Post-consumer aircrafts and wind turbines, manufacturing scraps from the production of all CFRP products, and expired prepregs are significant sources of waste CFRP (Pimenta 2011). Three types of technologies are available for composite recycling: mechanical recycling, pyrolysis, and solvolysis (Oliveux 2015). All of the three recycling technologies start with shredding or crushing the composite scraps into smaller pieces. Mechanical recycling typically grinds the shredded composites into finer particles, and uses the resultant recyclates as fillers or reinforcements for the production of composites and other materials such as asphalt and concrete. Since mechanical recycling does not reclaim fibers, and the recyclates are used for low value applications, its primary use is for glass fiber reinforced plastics (GFRP) (Pimenta 2011).

Pyrolysis and solvolysis, on the contrary, aim to recycle fibers in the composites, and are therefore preferred for CFRP recycling. Pyrolysis involves heating the CFRP pieces to 450-700°C, during which the matrix materials volatilize into lower-weight molecules, and the CFs stay inert and are recovered in the end (Pimenta 2011). Variants of conventional pyrolysis recycling include the fluidized-bed process, for which the pyrolysis occurs in a fluidized bed; and micro-wave assisted pyrolysis, which uses micro-wave for heating as opposed to a furnace. Currently, pyrolysis is the only commercialized recycling technology. Companies employing pyrolysis recycling for CFRPs include ELG Carbon Fibre in UK, CFK Valley Stade Recycling GmbH in Germany, and Materials Innovation Technologies in the U.S. Although pyrolysis recycling allows the recovery of CF embedded in CFRP scraps, the reclaimed CF suffers from mechanical degradation as a result of the heating process. Also, the matrix materials are generally combusted in the process for energy recovery rather than material recycling (Oliveux 2015).

Solvolysis involves treating the CFRP scraps with a solvent to degrade the matrix materials. The epoxy is decomposed into monomers, which are of high value and can be recycled into other organic chemicals. More importantly, solvolysis has the potential to produce recycled carbon fibers (rCF) with minimal mechanical degradation. However, the solvents used for this process, such as benzyl-alcohol, methanol, and acetone, may lead to harmful emissions and could be an environmental concern (Pimenta 2011).

In general, with recycling technologies that are currently available, rCFs are typically cut shorter, end up in a filamentised and low-density packing form, and are therefore not suitable for their original applications (Pimenta 2011). Nonetheless, downcycling of CFRP scraps for non-structural automotive applications is possible, as demonstrated by Johnson Controls, who use rCF and byproducts from CF production to make car seats (Composite World 2014). Meanwhile, new CFRP materials with full recyclability, such as the CFRP prepared from malleable polyimine networks and woven CF (Taynton 2016), are under development, and could substantially improve the recycled content of CFRP if commercialized. Recycling technologies, downcycling options, and recycled content of CFRP should therefore be a focus of future CFRP updates in GREET.

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