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Eco-efficient lightweight carbon-fiber reinforced polymer for environmentally greener commercial aviation industry

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ABSTRACT

This research aims to perform comparative impact assessment for production of conventional aluminum alloy (AlMg3) used in aircraft fuselage and lighter weight carbon-fiber reinforced polymer (CFRP). The epoxy resin (EP), a thermosetting polymer typically impregnated with carbon fiber (CF) tows is assumed to be replaced by polypropylene (PP) which is a thermoplastic polymer. The assessment framework is demonstrated by postulating a scenario where AlMg3 in Boeing B737-800 fuselage is substituted with CFRP to reduce the fuselage weight by about 4.3 tons. OpenLCA 1.4.2 platform, including Ecoinvent v2.2 life cycle inventory (LCI) database and TRACE 2.1 methodology for life cycle impact assessment (LCIA), is used to quantify and compare mid-point impact categories of the AlMg3-based scenario and the postulated base case scenario using CFRP (53.8 wt% CF). The CF content in CFRP is used as a sensitivity parameter for impact categories calculations. The assessment results showed that AlMg3-based scenario leads to higher impact categories compared to the postulated CFRP (53.8 wt% CF) base case scenario. Additionally, results of the performed scenario analysis show ≈ 42% reduction in energy intensity associated with the high-volume CFRP production (base case scenario) compared to the low-volume production scenario. All calculated impact categories associated with the low-volume production scenario exceed the corresponding impact categories associated with the high-volume production (base case scenario). For example, ozone depletion potential (ODP) for the low-volume production scenario is ≈ 20.7% higher than that of the high-volume production scenario and global warming potential (GWP) for the low-volume production scenario is ≈10.2% higher than that of the high-volume production scenario. This research also compares impact categories associated with recycled CF (rCF) from end-of-life (EOL) CFRP (with PP resin matrix) to those corresponding to rCF from EOL-CFRP (with EP resin matrix). Overall, the results of this research support its alternative hypothesis (H_1) which claims that replacing PE with PP in CFRP reduces the energy intensity and LCIA impact categories associated with CFRP production as well as rCF from EOL-CFRP. Finally, replacing fuselage's AlMg3 with CFRP in Boeing's new aircraft fleet by 2035 (Boeing Market Outlook 2016–2035) will lead to an estimated global carbon footprint reduction of ≈ $1x10^6$ tons CO2 eq. Future global commercial aircraft could adopt the insights of this contribution to shrink their carbon footprint.

Keywords: Carbon-fiber reinforced polymer; Aluminum alloy; Fuselage; OpenLCA; Ecoinvent

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Abbreviations: AlMg3, aluminum 3 wt% magnesium alloy; CFRP, carbon-fiber reinforced polymer; CF, carbon fiber; EOL, end of life; EP, epoxy resin; FU, functional unit; LCA, life cycle assessment; LCIA, life cycle impact assessment; MCS, Monte Carlo sampling; PAN, polyacrylonotrile; PP, polypropylene; Prepreg, pre-impregnated product (a combination of a resin matrix and fiber reinforcement); vCF, virgin CF; VOC, volatile organic compounds; rCF, recycled CF; rPP, recyclate PP matrix.

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1. Introduction

Section 1.1 of this introductory section provides background information about air pollution from commercial aviation and highlights key contributions of other researchers in this area and Section 1.2 outlines importance and objectives of this research.

1.1. *Background*

Over the past three decades, the annual growth rate of world commercial air transport has averaged ≈ 5% and is projected to double over the next decade or two (Macintosh and Wallace, 2009). Moreover, Macintosh (2009) reported that by 2026, passenger and cargo traffic will rise by 2.2 fold compared to the 2000 levels. On a global scale, environmentalists as well as other governmental and private stakeholders are concerned about air pollution caused by the commercial aviation sector as demand for air transport ramps up year after year. In particular, emissions of CO_2, CO, NO_x, SO_x, H_2O, unburned hydrocarbons (UHC)/VOC, and particulate matter (PM)/soot, among many other toxic air pollutants, are generated not only during aircraft flight, take-off, and landing, but also during all the other phases of the aircraft life cycle including structural materials production, end-of-life (EOL) disposal, and recycling. One of the methods being pursued to achieve reduction of aircraft weight is to substitute the use of metal-based alloys, commonly found in aircraft structures and components, with lighter weight composite materials. Boeing 787 Dreamliner is a good case in point where composite materials represent ≈ 50 wt% of its weight (Song et al., 2009). It is this author's opinion that reducing aircraft weight to minimize aviation fuel consumption has become a central goal for the air transport sector. It should be noted that besides their use in aerospace applications, fiber-reinforced composites have broad applications as structural materials for buildings, power electronics circuit boards, ships, wind turbine blades, unmanned aerial vehicles (UAVs), and automotive.

Our review of the literature shows that several life cycle impact assessments (LCIA) of reinforced composites have been conducted using the SimaPro LCA platform. For example, Suzuki and Takahashi (2005a) performed impact assessment for carbon-fiber reinforced composites used in passenger vehicles and noted that high cost and high energy intensity of producing such composites are major obstacles for their use in broad ranges of industrial applications. Song et al. (2009) reported potential energy savings resulting from use of glass-fiber/unsaturated polyester in the automotive industry. They focused on energy consumption of the pultrusion process (which has an energy intensity of ≈ 3.1 MJ/kg) for material production and manufacturing phases of the life cycle. Also, they demonstrated feasibility of using composites as a substitute for steel. Song et al. (2009) also argued that the lightweight feature of CFRP can offset some of its associated production cost as less energy would be required to transport this lighter weight material compared to transporting heavier metal alloys of similar volumes. In the steel case, Mazumdar (2002) noted that a 60%–80% reduction in weight can be achieved by replacing steel components with CFRP components. Duflou et al. (2012) applied life cycle assessment (LCA) to quantify environmental impacts of fiber-reinforced composites over the life cycle. Also, they estimated potential energy savings that result from substituting metal-based structures with bio-based and traditional fiber-reinforced composites. They compared CFRP vs. aluminum and steel for the automotive application and reported ≈ 50–70 wt% reduction could be achieved by replacing metals like aluminum and steel with CFRP. Scelsi et al. (2011) performed LCA to compare environmental consequences of Al-2024, GLARE (glass fiber Al laminate), and CFRP. They used SimaPro 7.1 together with Ecoinvent LCI database and Eco-indicator 99 (E) to integrate estimated impact categories into a single score. Interestingly, however, the authors expressed their concerns about use of the aggregated single score as it is based on subjective weighting factors. They concluded that the environmental impacts associated with Al-2024 life cycle are more severe compared to that of CFRP. A similar conclusion was reported by Marcinko (2013) who performed LCA for CFRP as a substitute for a steel tube. He concluded that use of lightweight composites and hybrid composites such as GLARE in commercial aviation would result in reducing the associated environmental burdens. Asmatulu et al. (2013) discussed potential reuse and recycling of some aircraft components such as the engines, landing gears, and avionics but not the fuselage. They also noted that presence of elements such as magnesium (Mg), copper (Cu), zinc (Zn) and titanium (Ti) makes recyclability of aluminum alloys a complex process that involves specialized sorting and separation tasks. In this author's opinion, the assumption made by some researchers that aluminum alloys, like Al-2024, are 100% recyclable at end of life (EOL) does not apply to the aircraft industry which adopts stringent safety standards and reliability requirements.[1] Witik et al. (2013) compared the environmental benefits of CFRP (with epoxy resin) recycling via pyrolysis, incineration with energy recovery, and disposal via landfilling. The authors used 1 kg of used CFRP as the functional unit (FU). Their LCA tool was SimaPro with impact 2002 + for impact assessment methodology. The impact results of their work were provided in terms of four categories (climate change, human health, ecosystem, and resources). Using SimaPro 7.2 platform for LCA, Timmis et al. (2014) quantified environmental burdens associated with use of CFRP (with epoxy resin) in one section of the aircraft fuselage. The authors used Eco-indicator 99 (E) V2.05 Europe EI 99 E/E LCIA methodology and aggregated the impact categories into a single score. In this author's opinion, use of the single score methodology leads to subjective assessment and renders the published results of less value for benchmarking purposes compared to the more detailed mid-point impact categories that can be obtained from TRACE2.1 LCIA methodology, for example.

1.2. *Research importance and objectives*

The importance of this scientific contribution is manifested by its support of the overarching goal of the air transport sector in creating an environmentally greener commercial aircraft by replacing aircraft's conventional structural materials by lighter weight composites. The novelty of this research stems from the fact it addresses a critical knowledge gap in the open literature by performing impact assessment

[1] For safety reasons that are driven by changes in the intrinsic properties of used aluminum alloys, the aerospace industry does not allow recyclable metals to be reused in aircraft structure as substitutes for virgin metals alloys.

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