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Anticipating in-use stocks of carbon fiber reinforced polymers and related waste flows generated by the commercial aeronautical sector until 2050

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ABSTRACT

Carbon Fiber Reinforced Polymers (CFRP) are increasingly used in commercial aircraft. Thus, the amount of in-use stocks of CFRP and related waste flows generated by the aeronautical sector will grow quickly through waste generation of end-of-life aircraft. This publication will provide a prospective assessment of the amounts and their localization of the worldwide in-use stocks of CFRP and related water flows until 2050. It has been found that by 2050 nearly half a million tons of CFRP waste will be generated in total, most of the waste will be located in North America and in Europe with about 162,000 t and 145,000 t respectively. In fact, this will allow to anticipate the efforts needed to properly recycle those future CFRP waste flows. Thus, this study provides a useful guide on the establishment of a CFRP waste management program, including timeframes and specific recommendations for high priority locations, and finishes with a discussion on the most promising recycling techniques of CFRP waste.

1. Introduction

According to the Airbus Global Market Forecast based on the International Civil Aviation Organization (ICAO) study, annual world air traffic should double in the next 15 years with an average annual growth equal to 4.6% (Leahy, 2015). The development of the air traffic is favorable to aircraft manufacturing for the next few years. By 2034, Airbus and Boeing plan to deliver respectively, 32,585 and 38,050 new aircraft (Boeing, 2015; Leahy, 2015). The reduction of fuel consumption and CO_2 emissions are all of central concern to the aviation industry. Since the 1960s, aircraft manufacturers have succeeded in reducing CO_2 emissions by 70% (Wachenheim, 2015) and aim to continue its decrease through 2050, due to technological and operational progress (Harris, 2011). One way to decrease CO_2 emissions is to reduce the aircraft weight. Carbon fiber reinforced plastic (CFRP) provides a significant weight reduction, as a part made of CFRP is 25–30% lighter than the same part made of conventional metal. Moreover, compared to metal, CFRP enables an increase in strength, durability, corrosion resistance and improvements in fatigue behavior and damage tolerance characteristics (Soutis, 2005).

Additionally, assembly and maintenance costs are significantly reduced as composite manufacturing processes allow for the production of parts with complex shapes through molding, which would have required several metal sub-elements to be assembled, creating additional work. With all of these advantages, CFRP has been increasingly used in commercial aircraft since the 1970s. Fig. 1 shows the amount of composites per passenger used to manufacture aircraft from 1974 to 2015 calculated from data used for this study (Tables 1 and 6).

According to Fig. 1, the trend accelerated after 2000 with newer aircraft (A380, B787, A350) using CFRP in many structural parts (fuselage, wings, tail structure, etc.). For instance, the A350 model is globally composed of 7% of steel by mass, titanium 14%, aluminum 20% and principally CFPR 52%. Indeed the fuselage panels, the frames, window frames, clips and door are made from carbon CFRP (Mrazova, 2013). Nevertheless, CFRP has one major drawback: a lack of recyclability. Currently, CFRP is either incinerated or landfilled; both are poor environmental solutions (Witik et al., 2013). Moreover, virgin carbon fibers have a high monetary value ($33–$66/kg) as they require a lot of energy to be produced (Oliveux et al., 2015a). Thus, it would be relevant to recycle and/or reuse them. The price of recycled carbon fiber has been estimated to be between $13 and $19/kg (Oliveux et al., 2015a).

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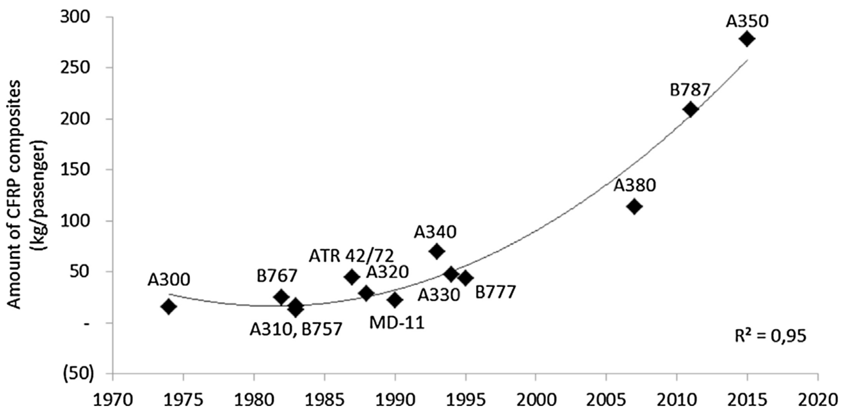

Fig. 1. Amount of composite used per passenger to manufacture aircraft from 1974 to 2015.

Table 1
Commercial aircraft with CFRP in their structure, with the composite proportion and the CFRP proportion relative to the composites, in percentage.

Aircraft model	Composite proportion (%)	CFRP/Composites (%)
A300	4,5	50
A310	5	50
A318	10	85
A319	10	85
A320	10	85
A321	10	85
A330	10	85
A340	13	85
A350	53	95
A380	23	85
ATR 42/72	22	85
B757	5	50
B767	6	50
B777	10	85
B787	50	95
MD-11	5	50
C-Serie	45	95
CRJ	20	85
ARJ21	20	85
ERJ 135/145	20	85
ERJ 170/175	20	85
ERJ 190/195	20	85
Fokker 50	10	50
Fokker 70/100	10	50
Il-96-300	10	85
Saab 2000	10	85
Saab 340	5	50
Sukhoi Superjet 100	20	85

All aircraft come to their end of life because of different factors such as the increasing costs of maintenance, legislation requiring expensive technology upgrades, difficulties in obtaining replacement parts, or damage too significant to repair. Consequently, in the next 20 years more than 6000 medium and long haul commercial aircraft will be retired from service at a rate of approximately 300 per year (PAMELA, 2009). In older models, the main material is aluminum, which is easy to recycle, but in 20 years the recyclability of new models carrying a higher amount of CFRP will be a greater challenge.

In aviation, there is neither legislation nor regulations that compel aircraft owners or manufacturers to recycle their end-of-life aircraft. The only existing regulation in the field of end-of-life aircraft was published in 2013 by the Aircraft Fleet Recycling Association, with the aim of securing the airworthiness of an aircraft using second-hand parts (Aircraft Fleet Recycling Association, 2013). An aircraft can be stocked indefinitely to be used for spare parts, but hangar storage can cost as much as $2000 per month for a large jet garaged in the state of Texas, USA (Kerrville Aviation 2012). As a result, they are most frequently stored outside, causing a slow deterioration of the aircraft due to an adverse climate and therefore a rapid loss in the value of the aircraft's parts.

The ever increasing consumption of the world's natural resources has made sustainability one of the main concerns of the 21th century. The situation calls for the establishment of a circular economy (Ellen MacArthur Foundation, 2017). In the automotive sector, the European directive (2000/53/EC) requires manufacturers to produce vehicles that are more than 95% reusable after the end-of-life. The aviation sector has been spared so far. However, Airbus and Boeing are working individually on the management of dismantling sites and aircraft recyclability through their projects named PAMELA (Process for Advanced Management of End-of-Life of Aircraft) and AFRA (Aircraft Fleet Recycling Association), respectively (Carberry et al., 2007). Because the current end-of-life aircraft were manufactured 25 years ago and do not contain CFRP, in 2016 only the management of the CFRP manufacturing waste is required. Nevertheless, the amount of CFRP to be recycled in the future will grow significantly when recent aircraft will be taken out of service. Currently, there is hardly any CFRP waste recycling system working on an industrial scale.

Assessing the in-use stocks of a specific material has become one line of research in the area of industrial ecology. In-use stocks correspond to amount of materials that are providing their function to the corresponding product during the use phase of its life cycle. This means that an assessment of the in-use stocks will provide the amount of resources stocks that are currently in use and that will become waste at the end of the life time of a product made out of this material. (Gerst and Graedel, 2008) define in-use stocks as he matter within any final commodity that is used by a human population during its entire time period. It has also been called "anthropogenic" stock by (UNEP, 2010) focusing on metal stocks in society, already extracted and processed, but currently put into use and providing service, that finally will be discarded or dissipated over time.

This concept has been developed with the idea in mind that instead of manufacturing a product from in-ground resources it can be done by recovering the in-use stocks resources inside a product at the end of its life. This work applies this concept as described in (Graedel et al., 2004; Pauliuk et al., 2013; Rauch, 2009; Wang and Graedel, 2010) for the first time to the specific case of CFRP. More precisely it focuses on the CFRP generated by the commercial aeronautical sector. Indeed, as indicated previously, the growing CFRP consumption by planes will lead to recycling opportunities in the future. However, assessing the potential of such a sustainable secondary resources "extraction" will require to quantify the amounts, to identify the geographic locations and to understand the respective timeframe. Moreover, in difference to metals, carbon fibers are not present as such in the earth crust since they are not made by geological process but man-made from non-renewable resources, based on a specific chemical process (Griffing and Overcash, 2010).

In summary, the objective of the present study is to assess the in-use stock of CFRP and related waste flows generated by the commercial aeronautical sector in the time period of 2016–2050. Numerous models