Research on Scrap Recycling of Retired Civil Aircraft

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Abstract. With the acceleration of the decommissioning of civil aircraft and the huge economic and environmental benefits, how to dispose and recycle the waste materials of decommissioned aircraft has become an important issue to be solved urgently. This article first introduces the current status of the international aircraft dismantling and recycling industry, and then elaborates the scrap recycling technology of the retired aircraft from the second-hand aviation material market, metals and composite materials, respectively. Finally, the positioning and advantages of the main aircraft manufacturer are clarified, and the future prospects for the field of dismantling and recycling are put forward.

1. Introduction
Currently, the development of the global civil aviation fleet is accelerating, and at the same time a large number of obsolete aircraft are facing retirement. Figure 1 shows the predicted data of the global passenger aircraft fleet in 2030. In order to obtain higher economic and environmental benefits, the dismantling and recycling of retired aircrafts are becoming the focus of global attention. For example, in the latest report, the Airc Fleet Recycling Association (AFRA) predicts that in the next 20 years, about 12,000 aircraft will be scrapped worldwide. Avolon’s "World Fleet Forecast" predicts that the data is 13,000, while Flightglobal calculates it as high as 17,000 [1]. In view of the huge market, though a reasonable dismantling process developed according to different types of scrapped aircraft, and by using of mature and standardized industry operating procedure, various parts and materials that can be recycled is 80% - 85% over the aircraft's total weight, and the annual recycling value is as high as 80 million US dollars.

![Figure 1: The predicted scale of the global passenger aircraft fleet in 2030](image)
The aircraft dismantling industry emerged at the beginning of this century, mainly involving civil aviation official agencies, companies and associations specializing in aircraft dismantling, aircraft major manufacturers, aircraft maintenance and waste recycling companies. Official agencies such as the International Civil Aviation Organization (ICAO), civil aviation administrations and environmental protection agencies of various countries, formulate regulations and guidelines for the dismantling industry to ensure that the dismantling and recycling process is carried out under safe and environmentally friendly conditions. Industry associations and organizations, such as the International Air Transport Association (IATA) and AFRA, are engaged in the compilation of instruction manuals, i.e., aircraft dismantling procedures, and are committed to promoting the industry standardization process. In addition, professional aircraft dismantling companies, such as Netherlands’ AELS (Aircraft End-of-Life Solutions), are not only engaged in aircraft dismantling business, but also involved in the reuse of waste aviation materials.

The full lifecycle of a civil aircraft includes seven stages, as shown in Figure 2. The major aircraft manufacturer has always been well-known as for the upstream role of the aircraft's lifecycle. However, with the in-depth development of the aircraft dismantling industry, how to accurately and efficiently formulate the optimal dismantling plan based on the historical state of the aircraft, has become the key to determining the benefits of aircraft dismantling and recycling. There is no doubt that a master manufacturer who knows the design and manufacturing process of the aircraft is an excellent candidate for the study of aircraft dismantling strategies. This has also become one of the main reasons why more and more major aircraft manufacturers are deploying and participating in the aircraft dismantling industry. In 2005, Airbus conducted a project research on the Process for Advanced Management of End-of-Life Aircraft (PAMELA), which became the first Classic case of complete aircraft dismantling and recycling process in the world [3].

![Figure 2 the lifecycle of a civil aircraft](image)

2. Recycling of scrap parts and materials
After excluding the possibility of passenger aircraft being converted to cargo aircraft or continuing to be used in other industries, civil aircraft usually enter the dismantling and recovery process after 20-25 years of service. Relevant recycling data of several types of typical materials for civil aircraft in Table 1 shows that there is still a great potential for recycling of aviation materials, and energy consumption and CO₂ emissions can be greatly reduced through recycling and reuse. In the intelligent disassembly process of modern aircraft, different disassembly technical solutions should be formulated according to the recycling channel, such as system disassembly, rough and fine cutting, electromagnetic eddy current and sink-floating separation and crushing, and even a specific disassembly sequence, to achieve the optimal dismantling. To disassemble parts and cut other component materials, the tools used for the aircraft disassembly mainly include plasma torches, different types of angle grinders, high-pressure water guns, chain saws and hydraulic clamps [4-5].
Table 1 several types of typical recyclable materials

| Recyclable materials | Potential recovery (kg/year) | Actual recovery (kg/year) | Scrap recycling process/kg | New raw material production process/kg |
|----------------------|-----------------------------|---------------------------|----------------------------|----------------------------------------|
|                      |                             |                           | Energy consumption (MJ)    | CO2 emission (kg)                      | Energy consumption (MJ)    | CO2 emission (kg)                      |
| Al alloy             | $1.1 \times 10^7$          | $2.2 \times 10^6$         | 2.4                       | 0.29                                   | 47                        | 3.83                                   |
| Steel                | $1.5 \times 10^6$          | $3.1 \times 10^5$         | /                         | /                                      | /                         | /                                      |
| Non-ferrous metals   | $7.4 \times 10^5$          | $1.5 \times 10^5$         | /                         | 0.44                                   | /                         | 1.25                                   |
| (except Al)          |                             |                           |                           |                                        |                           |                                        |
| Composite material   | $2.2 \times 10^5$          | $4.3 \times 10^4$         | 33                       | 2                                      | 234                       | 12                                     |
| Other                | $1.9 \times 10^7$          | $3.8 \times 10^6$         | /                         | /                                      | /                         | /                                      |

2.1. Second-hand aviation materials market

Retired aircraft can be disassembled to obtain approximately 50,000 large components, of which approximately 20,000 components can be returned to the aviation material market for circulation after being repaired and strict quality testing and standard appraisal. Usually these parts can take 40%-50% wt. % of the whole aircraft \(^7\). The used parts with the same type and being certified after disassembling are generally collectively referred to as the second-hand aviation materials. Compared with the new parts, they are cheaper and have become a strong competitor in the aviation spare parts market.

The international second-hand aviation materials market mainly involves the trading, leasing, dismantling, replacement, and repair of second-hand aviation materials. The engine is the most recyclable component of the aircraft, accounting for more than 60% of the aircraft value. There also have other components after aircraft dismantling, such as the manipulator, oil pump, battery pack, shock absorber, cockpit windshield, and cabin row seats \(^8\). P3 Aviation of the United Kingdom has been committed to providing second-hand aviation parts for various aircraft, such as engines, auxiliary power units (APU), ram air turbines, and alternators \(^9\). Table 2 shows the average disassembling cost of the retired aircraft or engines, and the economic value of recycling parts after being sorted. It can be seen that even if the cost of disassembly is included, the profits brought by the recycling industry are extremely generous. International Consulting Firm (ICF) believes that the annual growth rate of the second-hand aviation material market is expected to reach 5.2% in 2026, which will exceed the growth rate of the total market value in the aviation maintenance industry. This also causes the fierce competition between the second-hand aviation material suppliers, aircraft major manufacturers and maintenance companies \(^8\).

Table 2 economic benefits of disassembly and recycling of retired aircraft

| Type                               | Narrow-body (10 thousand dollar) | Wide-body (10 thousand dollar) | Regional (10 thousand dollar) |
|------------------------------------|----------------------------------|---------------------------------|-------------------------------|
|                                    | Disassembly cost | Recycle cost | Disassembly cost | Recycle cost | Disassembly cost | Recycle cost |
| Fuselage (Except system)           | 7.4               | 150           | 10               | 250           | 4.9              | 200          |
| aircraft engine                    | 2.4               | 270           | 3.3              | 370           | 2.3              | 150          |

At present, with the benefit of its main business in the aviation component manufacturing, especially in the field of aviation engine manufacturing, the international aircraft dismantling and recycling business is mainly concentrated in Europe and the United States. In June 2018, a new aircraft recycling and remanufacturing base in China was put into operation in Harbin. After the completion of the third phase of the project, it is expected to become the world’s largest one and also the unique aircraft dismantling and recycling base in Asia. Its production capacity is expected to be 100 narrow-body aircrafts per year, and a public bonded warehouse as the disposal volume of about 30,000 square meters will set up to store, manage and sell foreign distributors’ aviation materials and second-hand aviation materials obtained through dismantling channels \(^10\).
2.2. Recycling of metal materials
Metal materials have always occupied a considerable proportion of materials used in aircraft. After the retired aircraft is disassembled, most of the high-performance aviation-grade metal and alloys can be directly sold to the raw material factories, and then enter the manufacturing process after remelting, which can bring considerable economic value and good environmental protection. In 2017, the members of the AFRA organization recycled about 30,000 tons of aluminum alloys, 1,800 tons of special alloys, and 600 tons of other parts. Among them, aluminum metal accounts for 93% of the total recycling volume [7]. In response to the question about the quality of recycled materials, a complete set of material property evaluation methods can be established to redefine the recyclable value of scrap materials after processing [12].

2.2.1. Recycling of aluminum alloy.
Among all kinds of aluminum alloy products, the aluminum alloy used in the aviation industry is the one with the highest degree of alloying and manufacturing cost. The aluminum alloy materials used in the aircraft are mainly 2000 series, 5000 series, 6000 series and 7000 series, which are mainly used as aircraft skins and other structural parts [13]. The 2000 series aluminum alloy contains high content of elements such as copper, magnesium, manganese, and silicon, while the 7000 aluminum alloy contains high content of elements such as zinc, copper and magnesium. 2024 and 7075 aluminum alloys are the most widely used aluminum alloys in the 2000 series and 7000 series, respectively. AFRA's statistics show that the weight of aluminum alloy parts and components of civil aircraft accounts for 80 wt. % of the entire aircraft [7].

Aluminum smelting is a very energy-consuming production technology [14]. Compared with the traditional method which prepares aluminum alloy by using bauxite as the main raw material through electrolysis method, the cost savings of scrap remelting and recycling aluminum alloy can reach 90% [15]. Figure 3 compares in detail the differences between the two smelting technologies of scrap remelting and electrolysis [16]. Non-metallic slags that contain many alkali metal ions like Na, Ca, Li, such as alumina, carbon slag and other non-metallic particles, are generated in the electrolytic raw aluminum liquid. These slags are easy to become defects of aluminum alloys and affect the quality of materials. However, the molten aluminum obtained by remelting the scrap is of relatively pure quality, which is convenient for recycling. In the subsequent process, a spectrometer is used to accurately analyze the chemical composition, and then the molten aluminum is poured into the smelting furnace of the aluminum product production line. Through the adjustment of the alloy composition ratio, it is finally cast into aluminum alloy products of different specifications. This method of organically integrating scrap aluminum recycling technology and aluminum alloy manufacturing technology not only saves resources but also reduces costs, which is regarded as a fast and efficient recycling production mode for aluminum alloy materials.
According to the principle of similar size and the same alloy series, the recycling of aluminum alloy first starts with the grouping of components, and then the parts are shredded and melted, and finally made into cast parts through the refining processes. Especially for aluminum alloys of the same series with high purity, which produce fewer pollutants after remelting, they are easier to mix and be compatible with each other. The Laser-Induced Breakdown Spectroscopy (LIBS) technology developed by Huron Valley Steel Company has been widely used in the recycling and processing of large aircraft parts and components. No matter what kind of alloys, it can be effectively classified and then shredded [17]. This technology is committed to the direction of how to finely distinguish the element content in alloys. For example, aluminum alloys with high toughness (grades 7175, 7475) have an iron content of 0.05-0.20% while 0.35-0.50 wt. % for grades of 2024 and 7075. If the difference in the Fe content in the alloys can be automatically distinguished, the flexibility and cost-effectiveness of metal recycling and reuse will be greatly improved. During the "Thirteenth Five-Year Plan" period, China has already planned the research on the reuse of aluminum alloys from scrap aircraft in advance, focusing on key technologies such as impurity distribution and removal, gas content and mechanical performance control, harmless disposal of aluminum slag, and resource utilization [18].

The recycled and remelted alloys can be used in many non-critical aircraft components, such as stiffeners, flaps and other low-stress and medium-stress components made of thin plates, plates or extrusions. For aluminum alloys with high iron content, they can also be used as aluminum deoxidizers in the steel metallurgy process, which not only expands the recovery path of aluminum materials, but also reduces the production cost of the metallurgical process [19].

2.2.2. Recycling of aluminum-lithium alloy.

The third-generation aluminum-lithium alloy has gradually begun to be used in the aviation industry. Table 3 shows the chemical composition of some third-generation aluminum-lithium alloys. The lithium element contained in the aluminum-lithium alloy is a rare metal, and the economic and environmental value of recycling is great. Although aluminum-lithium alloys are also aluminum alloy materials in a broad sense, the smelting of aluminum-lithium scrap and the purification process of pure...
lithium are different from conventional recycling methods of scrap aluminum materials because of the impurity such as potassium and sodium are not easy to control [20].

| Alloy type | Cu   | Li   | Mg   | Mn   | Zn   | Ag   | Zr   | Al   |
|------------|------|------|------|------|------|------|------|------|
| 1460       | 2.5–3.5 | 1.9–2.5 | /    | /    | /    | /    | 0.12 | Matrix |
| Wel-49     | 2.3–5.2 | 0.7–1.8 | 0.25–0.8 | /    | /    | 0.4   | 0.14 | Matrix |
| 2060       | 3.4–4.2 | 0.6–0.9 | 0.6–1.1 | 0.1–0.5 | 0.3–0.45 | 0.1–0.5 | 0.04–0.18 | Matrix |
| 2094       | 4.5   | 1.3   | 0.4   | /    | /    | 0.4   | 0.14 | Matrix |
| 2095       | 4.2   | 1.1   | 0.9   | /    | /    | 0.4   | 0.14 | Matrix |
| 2096       | 2.3–3.0 | 1.3–1.9 | 0.25–0.9 | /    | /    | 0.25–0.6 | 0.14 | Matrix |
| 2097       | 2.5–3.1 | 1.2–1.8 | 0.35  | 0.1–0.6 | 0.35  | /    | 0.14 | Matrix |
| 2099       | 2.4–3.0 | 1.6–2.0 | 0.1–0.5 | 0.1–0.5 | 0.4–1.0 | /    | 0.05–0.12 | Matrix |
| 2195       | 3.7–4.2 | 0.8–1.2 | 0.9   | <0.25 | <0.25 | 0.25–0.6 | 0.14 | Matrix |
| 2196       | 2.5–3.3 | 1.4–2.1 | 0.25–0.8 | 0.35  | <0.35 | 0.25–0.6 | 0.04–0.18 | Matrix |
| 2197       | 2.5–3.1 | 1.3–1.7 | 0.25  | 0.1–0.5 | <0.05 | /    | 0.12 | Matrix |
| AF/C-458   | 2.7   | 1.7   | 0.3   | 0.3   | 0.6   | /    | 0.05 | Matrix |
| AF/C-489   | 2.7   | 2.1   | 0.3   | 0.3   | 0.6   | /    | 0.08 | Matrix |

There are four main routes for the recovery of aluminum-lithium alloy scrap: separate lithium into pure metal, extract lithium into lithium compounds, transform aluminum-lithium alloy into other grades of aluminum-lithium alloy, and smelt alloys with salt flux and regenerate it into the original grade alloy. At present, the methods for extracting pure lithium from aluminum-lithium alloys mainly include vacuum distillation, three-layer liquid electrolysis, hierarchical solidification. Except for distillation, all these methods are obtained by obtaining lithium halide and then combining with other metallurgical methods to get pure lithium.

This kind of closed-loop reuse of aviation metal materials can satisfy part of the supply demand of raw materials, reduce the interruption risk of raw material supply, reduce costs, and avoid the huge environmental burden caused by metal mining and processing [25].

2.2.3. Recycling of titanium alloys.

Titanium alloys are widely used in the aviation field because of their high strength, good corrosion resistance and good heat resistance. However, compared with other common structural materials, the smelting process of titanium is complicated and the production cycle is long, which makes the manufacturing cost very expensive. Norgate et al. found that for every kilogram of titanium produced, the energy consumed is 361 MJ, which is significantly higher than that of aluminum (211 MJ/kg) and steel (23 MJ/kg) [26].

Limited by the fact that domestic titanium resources are not abundant, China has conducted research on titanium alloy scrap recycling very early to meet the increasing demand for titanium alloys. For example, Baoti Group, a technological leader in the scrap recycling industry, drafted relevant standards (GB/T29027-2007) on titanium and titanium alloy scraps, were promulgated and implemented by the state [27]. The dilemma of lack of titanium resources also appears in Europe. ECO Titanium, the first European aerospace titanium recycling business in 2016, was established in France to reduce dependence on imported titanium raw materials and to recycle titanium alloy products more economically and environmentally [28]. Now more mature companies in the titanium recycling field are mostly concentrated in the United States, such as IMT company, Timet's Morgan branch, which have aviation-level certification, titanium alloy processing equipment, process technology and finished product quality.

The recovery of titanium alloy begins with the identification and classification of the scrap grades, and then completes a series of processes such as surface cleaning and crushing. Then, according to the different composition of the titanium alloy, the alloy is reasonably matched to return to the charge for remelting and recycling. The most commonly used structural titanium alloy with multi-purpose for civil aircraft is Ti-6Al-4V. This kind of alloy has a high proportion of aluminum, and titanium and
aluminum are both deoxidizers with excellent metallurgical deoxidizing ability. Particularly, V element is benefit for oxide formation, which can pin the grain boundaries and refine the grains. Application of this type of alloy in iron and steel metallurgy has multiple benefits such as reducing costs and improving quality [29]. Jung-Min Oh et al. proposed that titanium alloy scraps can be used in the powder metallurgy to supply the raw materials required for the production of cemented carbide materials-titanium-containing carbon nitrogen compound by making low-oxygen, high-quality titanium alloy powder [30].

2.3. Recycling of composite materials

As the civil aviation market requires more and more lightweight civil aircraft, some main aircraft manufacturers strive to increase the proportion of composite materials used in aircraft to achieve weight reduction. At the same time, disposal and recycling becomes increasingly severe because a large amount of composite waste was produced during the disassembly process of the current retired aircrafts.

The early treatment method of scrap carbon fiber composite materials was to recycle and use the heat generated by incineration, which will release a large amount of toxic gas during the combustion process, and the ash part of the landfill will also cause secondary pollution to the soil and cause serious harm to the ecological environment. This method has been banned by international orders. Another commonly used disposal method is to convert composite scrap into granules or powder for use by rolling and shredding, but generally it can only be downgraded and used in construction fillers, paving materials, cement raw materials or blast furnace iron making in terms of reducing agent. The cost performance of this method is very low, which greatly wastes high-value carbon fiber materials [31].

Carbon Fiber Remanufacturing Plastic (CFRP) can be decomposed by high-temperature pyrolysis [32], fluidized bed thermal decomposition [33] or super/subcritical fluid method [34]. After extracting pure carbon fiber, it can be applied as new parts of recycled material. The production cost of virgin carbon fiber is about 15-30 US dollars per pound while the production cost of carbon fiber that meets the standard of use through the composite material recycling route is 8-12 US dollars per pound [35]. Carbon Fiber Remanufacturing Company was established in 1997, and this company mainly recycles composite materials and obtains scrap carbon fiber from them, of which about 30% can be reused in composite material manufacturing [36]. Adherent Technologies Recycling Company in the United States has developed a new type of carbon fiber material recycling technology that can completely recycle the carbon fiber materials of the fuselage. The strength of the recycled carbon fiber is only about 9% lower than the original fiber. After recycling, it can be used in the shell of mobile phones and laptops [37]. Last year the International Civil Aviation Organization (ICAO) pointed out in its "Environmental Report" that recycled carbon fiber materials can be used in 3D printing technology, which can reduce raw material waste by up to 95% [38].

3. Design advantages for aircraft manufacturers

The current industry trend of diversified needs will promote the traditional aircraft manufacturers to gradually transform. Incorporate the concept of Reuse-Recycling-Remanufacturing (3R) (as shown in Figure 4) into the aircraft design process. As the aircraft designer, the main manufacturer should not only consider the design criteria for scrap parts recycling, component utilization, incineration and burial after the aircraft’s retirement, but also take into account the possible impact of recycling on the environment [39], mainly from the following aspects:

a) Design is a key stage in determining the choice of materials. More use of recyclable products and green, environmentally friendly, and easily recyclable materials will reduce the use of unconventional composite materials and harmful substances.

b) Aircraft manufacturers are at the upstream of the aircraft's entire life cycle, and have inherent advantages in grasping information such as the composition, proportion and component life of materials in the aircraft manufacturing process. They not only have the potential to provide
information such as disassembly plan guides and material pre-classification, but also provide a reverse boost to new product design optimization and manufacturing technology upgrade through information feedback.

c) With the advent of the post-design era, the main manufacturer in the conceptual design of the aircraft should precede the customer to make the layout from the perspective of operation and profitability, so that the aircraft design can better meet the needs of the entire life cycle and not only limited to functional goals in the operational phase. Increasing the design of disassembly, reuse and remanufacturing will greatly promote the profitability of the civil aircraft industry [40].
d) Aircraft dismantling and recycling is a profitable industry that has emerged. The active deployment and participation of main manufacturers in this industry can greatly enhance their anti-risk capabilities. For example, by recycling high-quality second-hand aviation materials that meet standards and certifications, it can reduce the cost of after-sales service and drive the common development of a series of high value-added industries such as aircraft maintenance, modification, and technical exchange and training [41].

![Figure 4 3R concepts of recycling and manufacturing](image)

4. Conclusions

With the increment of retired aircraft, a large number of domestic and foreign institutions and organizations have participated in the aircraft dismantling and recycling industry. By conducting aircraft dismantling tests, formulating reasonable dismantling procedures and forming mature and standardized industry operating standards, they actively promote the rapid development of the industry.

Whether from the perspective of second-hand aviation materials market, material recycling or environmental benefits, the rapid development of the retired aircraft recycling has always been inseparable from the establishment of relevant laws and standards in various countries. Only by vigorously developing related recycling technologies, expanding reuse channels, and continuously advancing the formulation of various national industry regulations and international standards, can we maximize the economic and environmental benefits during the entire life cycle of an aircraft.

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