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RECYCLING ALUMINUM AEROSPACE ALLOYS

Subodh K. Das and J. Gilbert Kaufman
Secat, Inc., 1505 Bull Lea Road, Lexington, KY 40511

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Abstract

Abstract: For decades, thousands of obsolete private, civil, and military aircraft have been sitting in "graveyards," while the demand for recycled aluminum continues to increase. The aircraft provide an obvious source of valuable metal. However cost-effective recycling of aircraft is complex because aircraft alloys are (a) typically relatively high in alloying elements and (b) contain relatively higher levels of impurities than required of many newer aircraft alloys to optimize their toughness and other performance characteristics. This paper describes (a) potential aircraft recycling process, (b) the technical and logistic challenges, and (c) options to address those challenges in a practical and cost-effective manner. A program addressing these issues is laid out in this paper.

Introduction

Introduction and Scope

For decades, thousands of obsolete aircraft have been sitting in "graveyards," while the demand for recycled aluminum continues to increase. The discarded aircraft provide a large source of valuable metal. However cost-effective recycling of aircraft alloys is complex because aircraft alloys are (a) typically relatively high in alloying elements and (b) contain very low levels of impurities to optimize toughness and other performance characteristics.

Thus recycling of aluminum aerospace alloys represents a major challenge to both the aluminum and aerospace industries. While the recycling of high percentages of aluminum from packaging and automotive applications has been commercialized and become economically attractive [1,2,3], the unique compositions and performance requirements of aerospace alloys have resulted in delaying directly addressing techniques for cost-effectively recycling those alloys.

The purpose of the study described herein was to identify the most attractive means of cost-effectively recycling aluminum alloys used in the production of private, civil, and military aircraft. We will endeavor to define and illustrate the practicality of any new approaches needed, as well as identify opportunities for related alloy development and product evaluation that might make aerospace structure recycling even more attractive.

Aluminum remains the most economically attractive material from which to make aircraft and space vehicles, and new construction proceeds at a prodigious rate. However, the development of newer aircraft structures has proceeded at such a pace that thousands of obsolete civil and military aircraft stand idle in "graveyards" around the USA. Yet it has been impractical to reuse the metal in these planes because of the combination of the differences in compositions of older obsolete aircraft and those of new aircraft, often having special performance requirements requiring specialized alloy compositions.

Driving Forces for This Study

The driving forces for this study to enable large-scale recycling of aluminum aircraft alloys are very clear and very strong.

- The production of aluminum as "secondary metal" (i.e., producing it by recycling) requires only about 2.8 kWh/kg of metal produced while primary aluminum production requires about 45 kWh/kg of metal produced. The 95% energy saving are a powerful economic incentive; and
- The ecological driving force is great too, as recycling results in the emission of only about 4% as much CO_2 as does primary production.

Clearly, it is in the industry's and in the nation's best advantage to maximize the amount of recycled metal that can be regained from obsolete aircraft.

The Ideal Aircraft Recycling Process

Today, in order to meet the performance requirements of aerospace alloy and product specifications, all alloys are produced utilizing primary metal. Typically the specifications for these alloys require that such strict controls on impurities are maintained that recycled metal cannot be used without additional processing.

It is timely to consider a new paradigm in which obsolete aircraft, like obsolete beverage cans and obsolete automotive vehicles, are recognized as valuable sources of aluminum, and an appropriate new commercial scenario developed.

The most desirable recycling scenario would include the following:

a. An aircraft-recycling center would be established, and as aircraft become obsolete they would be flown or delivered to this facility.

b. To the degree feasible economically, the major components of the aircraft would be disassembles and major non-aluminum components would be removed

c. To extent readily practical, the aluminum aircraft components would be pre-sorted by alloy type, most importantly by 2xxx and 7xxx series alloys.

d. The remaining structure would be automatically shredded, sorted, and remelted to provide metal in the most valuable form for reuse.

e. The recycled metal would be cast into ingot or billet of one of a useful set of high-strength aluminum alloy compositions available for a wide variety of non-fracture critical aerospace components, and subsequently fabricated into new end products that meet established performance requirements

Challenges in Achieving Cost-Effective Aircraft Recycling

The principal challenges that must be dealt with in creating this ideal aircraft-recycling scenario include the following:

a. Identifying decision options for dismantling aircraft to simplify recycling;

b. Identifying and optimizing technologies for automated shredding, sorting, and remelting of those 2xxx and 7xxx alloys with relatively high levels of alloying elements (sometimes in excess of 10 percent);

c. Identifying the range of representative compositions likely to be obtained from recycling aircraft components, dependent I=upon the amount of pre-sorting that proves practical.

d. Identifying the combination of performance requirements and compositions that would make useful aircraft components from recycled metal, even though they may not achieve the highest achievable levels of toughness;

e. Identifying useful byproducts to handle elemental residual unable to be used in recycled metal, e.g., Fe.

Some useful progress has already being made in addressing items b and e on this list of challenges. Examples include laser-induced breakdown spectroscopy (LIBS), developed and applied by Huron Valley Steel Corp. (HVSC), which is already being applied to the shredding and sorting of some aluminum alloys [4], and the use of high iron containing aluminum for deoxidizing steel (de-ox) [5].

In general, however, little or nothing has yet been done to apply recycling technology to shredding, sorting, and re-use of recycled metal from obsolete aircraft and space vehicle components. Focusing upon that area was the purpose of this study.

Some Options for Consideration

In the following sections, we will consider

- Dismantling and pre-sorting strategies
- Automated shredding, sorting, and remelting
- Identifying the resulting compositions of recycling aircraft components
- Options for re-use of the metal from recycled aircraft components in new aircraft
- Options for re-use of the metal from recycled aircraft components in non-aircraft applications
- Options for re-use of the metal from recycled aircraft components in aluminum castings

Dismantling and Pre-Sorting Strategies

One of the first things to be considered is the degree to which dismantling prior to shredding is helpful and cost-effective. And assuming that it may be, what are the most useful strategies that might be employed.

To a large extent, aircraft alloys fall into two series, the Al-Cu or 2xxx series and the Al-Zn-Mg or 7xxx series. While automated sorting techniques applied after shredding will unquestionably work, anything that can be readily done to pre-sort those alloys would be helpful.

One technique that seems practical would be to dismantle aircraft into certain logical component groups, as these typically are made of similar alloys of the same series. As example, landing gears, engine nacelles, tail sections, and flaps could be presorted, and wings separated from fuselages. Such separations may be desirable anyway to permit removal of non-aluminum components before shredding.

Guidance in such dismantling and pre-sorting should be available from the aircraft manufacturers who can identify the alloys used in various components of specific aircraft produced over the years. The availability of such manufacturer information will be very useful in establishing procedures for dismantling aircraft components.

An additional consideration, especially if/when manufacturing information is not available, is that it may be possible to take the approach of identifying the various metallic constituents and their chemistry prior to dismantling the aircraft with devices like hand-held mobile spectrometers. Such devices are available that may be used for in-situ identification of alloy types of specific components. Manufacturers include Vericheck Technical Services, Thermo Electron and Spectro. Non-aluminum components may also be readily identified using this technique

Automated Shredding and Sorting

The remainder of this study assumes that the laser induced breakdown spectroscopy (LIBS) technology developed and applied by Huron Valley Steel Corp. (HVSC) [4], scaled up for handling large aircraft components, will provide useful sorting of the aircraft alloys regardless of the degree to which they are pre-sorted. The challenge is determining more-precisely the level of sorting possible: for example, is the process sufficiently discriminating to separate 2014 from 2024? Or separate 7055, 7075, and 7085, for example?

An even more challenging feature that will influence re-use of the recycled metal is to what degree will the LIBS process sort alloys of different impurity levels, defined for example as the level of Fe, e.g., 2024 from 2124 and 2324, or 7075 from 7175 and 7475. The higher toughness alloys 2124, 7175 and 7475 typically have Fe levels in the 0.05-0.20% range while 2024 and 7075 have Fe in the range of 0.35-0.50%. If such differences can be sorted automatically at high speed for an element like Fe, that would greatly add to the flexibility and cost-effectiveness of the re-use of recycled metal.

The authors propose to work with the HVSC scientists to address these issues.

Identifying the Compositions of Recycled Aircraft Alloys

Dependent upon the levels of discrimination achievable in shredding and sorting, a variety of different compositions may result from these operations. A more detailed study is needed to define the representative levels, including some in which sorting is minimal and others where it is the best achievable. This will lay the groundwork for extended studies of re-use of the metal.

Of several basic things that we can be certain of: the metal from recycled 2xxx alloys will be high in Cu, Mg, Mn and Si and the metal from 7xxx alloys will be high in Zn, Cu, and Mg. The compositions of some alloys used for many years in aircraft structures are shown in Table 1; in older aircraft likely to be found in many graveyards, 2024 has been the most widely used 2xxx alloy, 7075 the most widely used of the 7xxx series. Newer aircraft will have more high-purity alloys like 2124, 2324, 7050, 7175, and 7475.

Table 1 – Nominal Compositions of Some 2xxx and 7xxx Alloys

ALLOY	Al	Cu	Fe	Mg	Mn	Si	Zn
2014	~93	4.4	0.7 max	0.50	0.8	0.8	0.15 max
2214	~93	4.4	0.3 max	0.50	0.8	0.8	0.15 max
2024	~93	4.4	0.5 max	1.5	0.6	0.5 max	0.25 max
2324	~94	4.1	0.12 max	1.5	0.6	0.1 max	0.15 max
7050	~89	2.3	0.15 max	2.2	0.1 max	0.12max	6.2
7075	~90	1.6	0.5 max	2.5	0.3 max	0.4 max	5.6
7475	~90	1.6	0.12 max	2.2	0.06 max	0.1 max	5.7
7178	~89	2.0	0.5 max	2.8	0.3 max	0.4 max	6.8

While a high level of discrimination and thus of sorting may possibly be achieved based upon Fe levels in recycled aircraft components, it is more logical at this point to assume that sorting is limited to identifying only 2xxx and 7xxx series alloys, in which case the compositions of recycled metal are likely to represent something like the following in Table 2.

Table 2 – Potential Compositions of some Recycled Aircraft Alloys Assuming Pre-Sorting

ALLOY	Al	Cu	Fe	Mg	Mn	Si	Zn	Others
R2XXX	~93	4.4	0.5	1.0	0.7	0.5	0.1	0.2
R7XXX	~90	2.0	0.4	2.5	0.2	0.2	6.0	0.2

If this is correct and if 2xxx and 7xxx alloys can be sorted successfully leading to compositions as in Table 2, there would appear to be some opportunities to re-use the recycled metal in a 2024-like alloy from the former and a 7075-type alloy from the latter. The properties of these alloys are likely to resemble those of 2024 and 7075, and subject to more thorough performance evaluation there is every reason to conclude that such metal might be utilized in non-fracture-critical aerospace components.

If, on the other hand, 2xxx and 7xxx alloys can not be separated before melting, and assuming an approximately equal amount of 2xxx and 7xx alloys, the recycled metal composition is more likely to look like that in Table 3

Table 3 – Potential Composition of some Recycled Aircraft Alloys Assuming No Pre-Sorting

ALLOY	Al	Cu	Fe	Mg	Mn	Si	Zn
R2+7XX	~92	3.0	0.4	1.8	0.4	0.4	3.0

The characteristics of this composition are difficult to estimate as they do not match any existing registered alloy.

Two other factors should be noted at this stage.

- First, it should be recognized that at least small quantities of several other wrought aluminum alloys like 2219 and 6061 and cast alloys like 201.0, A356.0, and A357.0 may go into the recycle mix.
- Second, aircraft alloys typically have grain-refining elements such as Cr, Zr, and V present in small quantities (~ 0.1 percent or less), and the potential buildup of such elements in addition to Fe, Mg, and Si needs to be the subject of further study. This second factor will become increasingly important as newer aircraft employing later alloys such as 2124, 2048, 7050, 7055, and 7085 enter the obsolete mix.

A further in-depth analysis and mass balance is needed to more precisely determine the compositions of recycled aircraft metal. Secat has proposed to undertake such a study collaboratively with an organization such as HVSC and interested aerospace companies.

Options for Re-Use of the Recycled Aircraft Components in Aircraft

Assuming that the estimated composition in Table 2 based upon pre-sorting of 2xxx and 7xxx alloys are reasonably correct, as noted above it would appear that the resultant alloys could be used for a number of non-critical aircraft components, such a stiffeners, flaps, and other relatively low-to-moderately stressed components made of sheet, plate, or extrusions. These might be used in private, civil, and many military aircraft. Typically these would be components that are not designed based upon fracture mechanics concepts employing fatigue crack growth rates and fracture toughness parameters. The alloys utilized in fracture-critical areas may still have to be fabricated using primary metal.

Therefore another key question to be addressed with further study is whether the percentage of aircraft components that do not require fracture-critical design is broad enough to justify the re-use of compositions likely to result from recycling.

Options for Re-Use of the Recycled Aircraft Components in Non-Aircraft Applications

If the use of these compositions for non-fracture critical components in new aircraft is too tightly limited, i.e., if the number of non-fracture critical components in civil and military aircraft is not large enough to justify re-use of the recycle compositions, it is useful to look at what other opportunities may exist for use of the compositions in Tables 2 and 3?

To aid in addressing that question, the compositions of several wrought 2xxx and 7xxx alloys used in other applications (including 2014, also an aircraft alloy) are presented in Table 4.

Table 4 – Nominal Compositions of Some 2xxx and 7xxx Alloys used in Non-Aerospace Applications

ALLOY	Application	Cu	Fe	Mg	Mn	Si	Zn
2014	RR; Truck Bodies	4.4	0.7 max	0.50	0.8	0.8	0.15 max
2017	Rivets	4.0	0.7 max	0.60	0.7	0.5	0.25 max
7129	Auto Bumpers	0.7	0.3 max	1.6	0.1 max	0.15 max	4.7

Comparing compositions in Tables 2 and 4 illustrates that it may not be too much of a stretch to re-use recycled aircraft metal in certain other products. Further study of this option is justified.

Options for Re-Use of the Recycled Aircraft Components in Castings

Other opportunities for the use of recycled metal from aircraft may include aluminum alloy castings, especially those of the 2xx.0 and 7xx.0 series, Al-Cu and Al-Zn respectively. Examples of some such alloys include the following in Table 5:

Table 5 – Some Aluminum Casting Alloy Compositions

ALLOY	Al	Cu	Fe	Mg	Mn	Si	Zn	Others
201.0	~95	4.6	0.15 max	0.35	0.35	0.10	0.25	0.05 max
242.0	~94	4.1	0.6 max	1.4	0.10 max	0.6 max	0.10	0.05 max
295.0	~94	4.5	1.0 max	0.03	0.35 max	1.1	0.25	0.05 max
710.0	~93	0.5	0.5 max	0.7	0.05 max	0.15 max	6.5	0.05 max
713.0	~91	0.7	1.1 max	0.35	0.6 max.	0.25	7.5	0.05 max.

Even these relatively tolerant limits pose some challenge for direct use of recycled metal reuse. Nevertheless, some opportunity for study of some new alloy options remains, and the properties of the alloys in Table 2 when produced as casting should be studied.

Alternative Products for Use of Excess Alloying Content

It is appropriate to address the fact that as aluminum alloys are recycled there is a trend for the Fe content to increase gradually, primarily through pickup from scrap handling equipment. While aircraft alloys may not be recycled very frequently, as are beverage cans, for example, it is a factor to consider.

With only a few exceptions, Fe is an impurity in all wrought alloys today, and is an ideal candidate for an alternative product if/when it exceeds desirable levels. An excellent example of such a product is the use of high Fe-bearing aluminum as a deoxidizing agent for steel production. Maximization of this capability will benefit both the aluminum and steel industries and add to the life-cycle benefits to aluminum operations.

Another possible approach to the increased Fe content is to make use of the affinity of Zr for Fe, resulting in a heavy particle that sinks to the bottom of crucibles during processing [6]. Combining this Fe-Zr product with Mg and perhaps other undesirable impurities like Ni and V may also improve their impact on resulting recycle content.

Alloys Designed with Aircraft Recycling in Mind

As noted above, an ideal component of maximization of resources in aircraft recycling would be the availability of several new aluminum alloys that would take advantage of the unique characteristics of recycled aircraft metal. Such an approach may call for some "tailored" alloys, enabling broader specification limits on alloying elements likely to be found in recycled aircraft metal, notably the high Cu in 2xxx alloys and Zn in 7xxx alloys.

Adopting the approach of alloy optimization for aircraft recycling requires several steps, potentially phases in a development program:

1. Define the range of expected current and future recycled metal alloy content, utilizing collaborative studies with organizations such as HVSC that are already capitalizing on the economics of recycling. Perform a mass balance to the extent practical indicating the relative volumes of various scrap compositions to be expected;

2. Identify 3-4 basic candidate compositions of alloys that would accept recycled aircraft metal directly, including those listed in Table 2;

3. Determine the performance characteristics of such candidate alloys for a wide variety of applications, including non-critical aircraft components, structural components for bridges and buildings, high-temperature applications, and architectural usage [6-11] including the following determinations:
    - o Atmospheric corrosion resistance
    - o Stress-corrosion crack growth
    - o Toughness, with tear tests and/or fracture toughness tests (for thick sections)
    - o Formability tests, with bulge, minimum bend, and hemming tests

13 – Conclusions and Looking Ahead

There are strong economic and environmental driving forces for aggressively pursuing the recycling of obsolete aircraft, thousands of which exist throughout the world. Based upon the preliminary evaluations from the preliminary study conducted to date, it is recommended that the following steps be taken to establish the cost-effectiveness of recycling obsolete aircraft:

1. Conduct an in-depth study to determine the quantity and character of the obsolete aircraft readily available for recycling, including the alloys utilized in producing those aircraft.
2. Determine the practicality of disassembling and pre-sorting aircraft components by alloy and product form.

3. Conduct trials of the application of technologies such as LIBS for automatically sorting aircraft alloys collaboratively with an organization like HVSC.
4. Carry out a mass balance to estimate from the results of Items 1 and 2 what likely and/or potential compositions may result from various approaches to shredding and sorting components from these aircraft.
5. Define a selection of 2-4 alloys based upon the foregoing mass balance that should be produced, either by a sample remelting of aircraft parts or in the laboratory, and their characteristics thoroughly evaluated, including:
   - Design strengths
   - Atmospheric corrosion resistance
   - Stress-corrosion crack growth
   - Toughness, with tear tests and/or fracture toughness tests (for thick sections)
   - Formability tests, with bulge, minimum bend, and hemming tests
6. Generate a representative set of applications for which the properties and performance generated in Item 5 would be adequate, including:
   a. Non-fracture critical aircraft components
   b. Railroad and highway vehicle construction
   c. Highway structures

Secat has moved forward to establish a collaborative team to provide guidance on the program, including but no limited to:

- HVSC, developers of the LIBS alloy sorting technology
- Representative(s) of the Aluminum Association Recycling Division;
- Aircraft fabricators; and
- Aircraft designers, perhaps through MMPDS, the design committee for the industry

Secat is ideally situated to take the lead in such a study, given its long experience in recycling studies for the Sloan Foundation, the Aluminum Association, and several municipalities [12,13].

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