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Life cycle carbon benefits of aerospace alloy recycling

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ABSTRACT

The goal of this project is to determine the reductions in greenhouse gas (GHG) emissions associated with the recycling of aerospace alloys. This study is based on an aerospace recycler that sells much of its high-performance alloy scrap directly to remelters that produce these alloys for aircraft engine component manufacturers, with significant potential environmental benefits arising from the substitution of recycled materials for virgin materials. The project team explored existing sources of environmental data for all of the metals that make up aerospace alloys, and ten common alloys were chosen as case studies. Certain metal elements, including niobium, rhenium, tungsten, and zirconium, did not have any robust environmental impact information, and for these GHG emissions factors from primary production were modeled using a variety of statistical and industrial data sources. The project team then investigated the forms of metal inputs into alloying operations to ensure that the model reflects actual industrial practices and that the alloy scrap substitutes for virgin materials. GHG emissions are also incurred through alloy scrap collection and processing, and so a carbon footprint was performed for alloy recycling operations in order to determine these burdens. Overall, the recycling of aerospace alloys for reuse in the aerospace industry represents significant reductions in GHG emissions for each of the ten alloys considered, while emissions associated with collection and processing are <5% in comparison. Certain elements occur in small quantities in aerospace alloys, such as rhenium (Re) and tantalum (Ta), but due to their high carbon intensity they significantly influence the final results.

1. Introduction

The issue of energy use and associated greenhouse gas (GHG) emissions from air transportation has traditionally focused on fuel combustion. Accordingly, most of the efforts to improve the environmental performance of aircraft have been in making them more efficient in flight through lightweighting, improving combustion efficiency or gearing ratios in engines, or redesigning wing aerodynamics (Greene, 1992). Aerospace companies have also begun to target embodied energy and associated greenhouse gas emissions as important environmental indicators. Public reporting is increasingly common, and the International Aerospace Environmental Group has released preliminary guidance on how aerospace companies should measure and report GHG emissions (IAEG, 2013).

Modern aircraft are technological marvels, relying on advanced materials and thousands of precisely engineered components. The most energy and carbon-intensive materials in aircraft are found in the engines. Turbine blades and other engine components must operate flawlessly in an extremely challenging technological environment with high shear forces and temperatures. Because of a zero tolerance for failure, engine components are manufactured to high precision with high-purity materials, many of which are expensive and/or limited in their market size. For these same reasons, secondary (recycled) metals have rarely been used due to impurity risk. However, not reusing the alloys in engine components also means that engine producers must secure long-term contracts for the primary (virgin) supply of these metals from suppliers, and markets that can be subject to geopolitical instability, natural hazards, or price volatility (Alonso et al., 2007). The concept of metal criticality captures these supply risks, such as how essential a metal is to a certain technology (engine components in this case), without technologically suitable substitutes, as well as

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environmental risks associated with metal production (Erdmann and Graedel, 2011; Graedel et al., 2012).

1.1. The business of recycling aerospace alloys

Dismantling and recycling demonstrations by individual companies and the formation of the Aircraft Fleet Recycling Association have spurred aerospace metal recycling efforts in recent years (Asmatulu et al., 2013a) and helped to set targets for overall aircraft recycling. A demonstration by Airbus as part of the Process for Advanced Management of End of Life Aircraft (PAMELA) program revealed that 85% of the total mass of materials in obsolete aircraft could potentially be recycled, led by aluminum alloys (Airbus, 2014). This theoretical level of recycling is far above current rates. A detailed study of aerospace manufacturers in the aviation hub of Wichita, USA, revealed that 20% of recyclable materials are actually recycled (Asmatulu et al., 2013b).

Engine parts specifically have typically been recycled for their nickel content for inclusion into stainless steels. While nickel and some of the alloying elements from engines confer useful material properties in steels, others do not beneficially contribute, and elements such as copper and tin are considered tramp elements that are detrimental to steels (Reck and Graedel, 2012). Direct, closed-loop recycling of aerospace metals decreases their criticality by providing a local, predictable supply with lower risks of disruption, while reducing costs and avoiding the substantial environmental burdens associated with metal mining and processing (Eckelman et al., 2013). From a resource point of view, switching to a closed-loop recycling system allows the specialty alloys in engine components to be reused in engine components for the specific physical characteristics to which they were originally designed. As engines are commonly leased and individually tracked in a clear chain of custody, they are relatively free of contamination and can be a source of revenue for the engine and/or airline companies involved, with post-consumer sales typically to specialty metal recyclers.

Large metal recycling firms process hundreds of separate alloys and there is significant interest in quantifying the environmental benefits of its business, specifically in estimating the avoided GHG emissions associated with closed-loop recycling of each alloy. As the alloys are not downcycled, the avoided emissions will be greater than for scrap recyclers that engage in mixed metal recycling. These measures may serve the company and its business partners as a future basis for monetary or regulatory instruments associated with carbon, as a differentiating characteristic in the highly competitive scrap market, and by demonstrating corporate leadership by understanding the sustainability of its operations in general.

1.2. Metal cycles and global aviation scrap

Metal recycling is driven by market forces, but the supply of scrap aerospace metals is challenging to predict. Airbus projects that over the next 20 years, 40,000 aircraft will come out of service, but it would also be useful to understand how these levels will shift year-to-year, what specific alloys will be present, and the dynamics of scrap generation in other economic sectors that may affect global supplies of aviation-relevant scrap. Anthropogenic metal cycles are an important tool in forecasting scrap supplies and assessing the global stocks and flows of a metal, allowing for a comprehensive snapshot of resource use and serving as a basis for scenario modeling (Chen and Graedel, 2012). Global and/or national metal cycles have been created for several elements used in aerospace alloys, including aluminum (Liu and Müller, 2013), nickel (Reck et al., 2008), chromium (Johnson et al., 2006), cobalt (Harper et al., 2011), tungsten (Harper and Graedel, 2008), copper (Graedel et al., 2004), iron (Wang et al., 2007), and zinc (Graedel et al., 2005), as well as for several alloys including stainless steel (Reck et al., 2010) and brass (Daigo et al., 2009). Metal cycles provide detailed information on the size and spatial allocation of production, use, and recycling flows (Cullen and Allwood, 2013). Such information can be used to calculate a wide variety of resource sustainability indicators such as recycling rates (Reck and Gordon, 2008) or the number of times a metal is cycled through the global economy (Eckelman and Daigo, 2008). Such cycles can be linked with life cycle assessment (LCA) models to show the magnitude and location of multiple environmental impacts associated with anthropogenic metal use, including life cycle energy and water demand, deterioration of air and water quality, or increasing toxicity burdens (Eckelman et al., 2012).

1.3. Environmental benefits of metal recycling

Recycling activities require capital and natural resources, but avoid the energy-intensive mining, concentrating, smelting, and refining activities required for primary materials. For this reason, metals can often be recycled or reprocessed for additional uses at environmental and economic costs that are much lower than those for primary metal. A compendium of estimates of energy savings from metals recycling can be found in Eckelman et al. (2013), ranging from 55 to 98%, depending on the metal. Similar reductions in water use, air and water emissions, and waste generation also accompany recycling compared to producing virgin materials. Much research domestically and internationally has been devoted to metal recycling, both from the perspective of LCA in quantifying environmental benefits (Classen et al., 2009; Dubreuil et al., 2010) and in terms of technological potentials and barriers (Allwood et al., 2010; Gaustad et al., 2012; Reck and Graedel, 2012). The metals industry has made declarations on recycling objectives and principles to guide practices and accounting procedures (Atherton, 2007), and has sponsored extensive research into scrap recycling rates and energy benefits of recycling (Johnson et al., 2008).

Despite considerable recycling potentials, little published work has examined the environmental benefits of recycling in the aerospace industry. Asmatulu et al. (2013b) estimated the energy savings and GHG emissions reductions associated with recycling of materials from manufacturers, covering a broad range aircraft components, electronic equipment, and finishings, but did not include engines nor any non-ferrous metals beyond aluminum and copper. Several of the metals contained in engine components, such as rhenium and tantalum, require more than an order of magnitude more energy to produce than aluminum, with similarly large potential benefits alloy recycling after engines or components become obsolete. The elemental composition of an aerospace alloy obviously affect savings from recycling and substitution for primary metals, but there are very few studies that account for this (c.f. Johnson et al., 2008). The sorting, cleaning, and processing operations of recycling facilities are seldom included in assessment, in part because measured data are difficult to obtain.

In this work we present an in-depth accounting of energy and environmental savings from recycling of aerospace alloys, covering ten of the most important alloys used in aircraft engines. The present study was carried out in cooperation with a large aerospace metals recycler that has several facilities in the United States and several other countries. These serve as collection and/or processing plants, mostly for aircraft-grade aluminum and nickel-bearing alloys from engine components. Over the past several years, this recycling firm sold much of its alloy scrap directly to the smelters that supply aircraft engine component manufacturers, thus creating a closed-loop recycling system. Here we determine the GHG emissions reductions of such a closed-loop approach to