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Toward the efficient recycling of alloying elements from end of life vehicle steel scrap

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A B S T R A C T

There has been a sharp increase in the production of automobiles over the past decade. In 2010, one billion automobiles were in circulation worldwide. The automobile industry is one of the largest metals consumers and plays an important role in their sustainable use. Steel materials, including alloy steels that contain alloying elements (AEs) such as manganese, chromium, nickel, and molybdenum, are the main component of automobiles. The recycling of end-of-life vehicles (ELVs) significantly affects the cycling of iron, steel, and AEs. Currently, ELV recycling is performed using the electric arc furnace (EAF). In this method, losses of AEs are likely to occur because their presence is rarely considered. This study evaluated the environmental and economic benefits of alternative ELV recycling schemes, which allow more efficient utilization of AEs found in ELV-derived steel scrap (ELV-dSS). The AE contents in ELV-dSS (as car-parts) were estimated by means of a waste input–output material flow analysis (WIO-MFA) model extended for the detailed analysis of automobile composition. Using Japanese data, it was found that sorting ELV-dSS by parts can result in a significant recovery of AEs; more specifically, a 10-fold saving in AEs was achieved by sorting exhaust parts. The recoverable mass of AEs from sorted ELV-dSS was found to correspond to 8.2% of the annual consumption of AEs in Japan, as virgin resources in EAF steelmaking. ELV-dSS sorting was found to be significantly effective in the conservation of AE resources.

1. Introduction

The proficient management of resources is indispensable for realizing a sustainable society. Metals are considered as essential resource in the modern society, and their efficient use is a key for sustainable development (Gaustad et al., 2011; Graedel et al., 2012; Reck and Graedel, 2012). Reck and Graedel (2012) noted that the recycling of metals from end-of- life (EoL) products has become more complicated and challenging due to the complex structure and composition of contemporary functional products. Metals are typically used in combination and/or alloyed with other products. Unintentional alloying and dissipation may occur as a result of the thermodynamic properties of metals in recycling (Nakamura et al., 2011; Ohno et al., 2014). Efficient recovery of metals from EoL products requires careful deliberation of the recycling methods (Reck and Graedel, 2012).

The automobile industry is one of the largest metal consumers (Nakajima et al., 2013; Nakamura et al., 2011; Ohno et al., 2014). The production of automobiles has been increasing with global population growth. The International Organization of Motor Vehicle Manufactures (OICA) estimated that by 2010, there were one billion automobiles worldwide (International Organization of Motor Vehicle Manufactures (OICA), 2012). Thus, the automobile industry plays a vital role in the sustainable use of metals. The main component of automobiles is steel materials; therefore, the recycling of end-of-life vehicles (ELVs) could significantly affect the cycling of iron and steel.

There have been many studies regarding the material flow analysis (MFA) of iron and steel (Daigo et al., 2007; Michaelis and Jackson, 2000; Mueller et al., 2006; Pauliuk et al., 2012; Wang

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et al., 2007). The studies have mainly been concerned with the quantity-based flow and cycling of iron and steel, highlighting the importance of steel recycling in terms of the depletion of high-grade iron ore and CO_2 emission reductions. On the other hand, some recent studies have correctly identified the need for quality assurances, in order to guarantee sustainable material cycles for iron and steel (Hatayama et al., 2014; Nakajima et al., 2013; Nakamura et al., 2011, 2012; Pauliuk et al., 2012; Reck et al., 2010).

Owing to the complex usage of metals in automobiles, several problems have been identified in the recycling process of ELV-derived steel scrap (ELV-dSS). The most typical problem is the mixing, and contamination, of other metal materials into ELV-dSS. In the current basic ELV treatments, the non-reusable parts (e.g. air-conditioner coolants and airbags), copper contaminated sources (e.g. wire harnesses), and the reusable components (e.g. the engine) are removed, while the rest of the parts are shredded together to reduce the volume of scrap (Ohno et al., 2014). After shredding, non-ferrous metals are magnetically separated from ferrous metals; the magnetic ferrous materials are collected as carbon steel and recycled as an iron source for electric arc furnace (EAF) steelmaking. Copper removal is an important step in the ELV treatment as it is one of the most concerned contaminants in the recycling of steel: Copper has adverse effects on the workability of steel materials and has an accumulative tendency as the cyclic use of steel depending on thermodynamic distribution during steel recycling (Daigo et al., 2005; Hatayama et al., 2014; Houpert et al., 1997; Nakamura et al., 2011). If ELV-dSS contains a known concentration of copper, it must be diluted to below regulatory limits by adding pure iron during the EAF steel recycling process (Hatayama et al., 2014; Nakamura et al., 2012). Contamination in steel may also be caused by alloying elements (AEs), such as chromium (Oda et al., 2009), which are added to enhance certain properties of steel materials. These AE-enriched steel materials are known as alloy steels, and the various available types are consumed in large quantities by the automobile industry (Nakajima et al., 2013). Although AEs are intentionally added to produce alloy steels, they are a source of contamination in the recycling process. They are often considered unwanted constituents (International Organization for Standardization (ISO), 1987). Furthermore, some AEs tend to oxidize into steelmaking slag, depending on their thermodynamic distribution (Nakamura et al., 2011). In these cases, AEs are dissipated, representing the loss of an otherwise potentially valuable resource (Nakamura et al., 2012).

Alloy steel materials are often present in large quantities in automobiles. For example, high-tensile steels are used in the vehicle frame and stainless steels are used as exhaust parts. AEs are likely to be lost during current ELV recycling, which involves shredding and mixing car-parts of varying composition (Ohno et al., 2014). A solution proposed for this problem is the design of recycling-oriented automobiles, which incorporate the metal combinations that cause less contamination during recycling into their design, in accordance with the thermodynamic distribution tendencies of the metals (Castro et al., 2004; Froelich et al., 2007; Millet et al., 2012). However, this solution does not take into account scrap from conventional vehicles, for which materials cannot be easily recycled separately. Therefore, an appropriate treatment process for efficient ELV-dSS recycling must be developed (Ohno et al., 2014).

Nakamura et al. (2012) estimated that significant reductions in CO_2 emissions could be achieved by preventing copper contamination in ELV-dSS and reducing the need for the dilution of copper by the addition of pure iron. Current recycling methods of ELV-dSS operate under strict precautions for the prevention of copper contamination. ELV-dSS with low concentrations of copper has been recycled as an iron source in the EAF steelmaking process (Matsubae et al., 2014a). On the other hand, little, if any, attention has been paid to AE concentrations in current ELV-dSS treatments (Ohno et al., 2014). Recent studies have highlighted the importance of developing an efficient recycling system that prevents the loss of indispensable AEs (Nakajima et al., 2013; Nuss et al., 2014; Ohno et al., 2014). Given the difficulties of removing AEs from the steel matrix under present technological and economic conditions, this study aimed to propose a process of disassembling and collecting parts with similar compositions to minimize losses of AEs, and then evaluate the efficiency of the proposed sorting approach.

This study consists of two parts: first, the AE contents in automobiles and ELV-dSS are estimated by extending the waste input–output material flow analysis model (WIO-MFA model); second, the efficiency of ELV-dSS sorting is evaluated. The WIO-MFA model is a useful top-down approach for estimating nationally averaged material composition of various products (Nakamura and Nakajima, 2005; Nakamura et al., 2007). Japanese data were selected due to the availability of high-resolution input–output (IO) data in terms of metals, while the model itself is applicable to any economy. However, even for Japanese IO data, the resolution is not high enough to allow the material composition estimation of individual automobile parts and components (Nakajima et al., 2013; Ohno et al., 2014). To cope with this problem, substantial disaggregation and rearrangement of automobile related sectors was conducted for the Japanese IO data. This resulted in the highest-resolution IO-based estimates ever available for AE contents of automobile parts and components. Development of this information base enables us to evaluate the AE saving potential and benefits of sorting ELV-dSS.

2. Method and data

2.1. WIO-MFA

WIO-MFA enables the estimation of the flow of individual materials associated with the flow of commodities by assessing the material composition of commodities based on IO analysis. Using the IO table adjusted for MFA, the material composition matrix C_{MP} can be calculated using the following equation.

$$C_{MP} = \tilde{A}_{MP}\left(1 - \tilde{A}_{PP}\right)^{-1} \quad (1)$$

here (i, j) element of $\tilde{A}_{MP}$ and $\tilde{A}_{PP}$ represent the coefficient of input i to produce one unit of output j accounting for yield losses during production processes, $\tilde{A}_{MP}$ denotes the input of materials (M) for the production of products (P), and $\tilde{A}_{PP}$ represents the input of intermediate products (P) for product production (P).

The (i, j) element of the matrix C_{MP} represent the volume of material i that comprises one unit of product j. Thus, the column sum of this matrix gives the mass of one unit of output when $\tilde{A}_{MP}$ is measured in mass. When the unit of a product is expressed physically, as one ton for instance, the column sum of the corresponding composition matrix is also one ton. When the product is expressed in monetary form, as one-million Japanese yen, the column sum of the corresponding composition matrix represents the mass per one-million Japanese yen. For further details on the methodology, see Nakamura et al. (2007).

In previous studies, a high-resolution WIO-MFA table for the simultaneous flow analysis of steel AEs was developed based on the Japanese IO table for 2000 and 2005 (Nakajima et al., 2013; Ohno et al., 2014). These models and data were extended to automobile-related sectors in the present study.

2.2. Disaggregation of the automobile industry into component sectors

Aggregated sectors in the IO table occasionally lead to unclear results. Since the car-parts sector is highly aggregated in the IO