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Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology

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ABSTRACT

This paper discusses how the recycling of aluminum will change between now and 2050, focusing on the introduction of next-generation vehicles and scrap sorting. To evaluate the recycling potential, aluminum demand and discard in Europe, the United States, Japan, and China are estimated by material flow analysis (MFA). The MFA distinguishes between wrought and cast alloys so that the chemical composition of each flow is taken into account. A comparison of demand with discard is used to evaluate the amounts of primary aluminum required and scrap that cannot be recycled because of a high concentration of alloying elements. The results of these investigations show that the introduction of electric vehicles leads to a decrease in the demand for cast alloys, which generates 6.1 Mt of unrecyclable scrap in 2030. The results also indicate the effectiveness of scrap sorting in the future: if scrap sorting is carried out for end-of-life vehicles, it mitigates the generation of unrecyclable scrap and reduces the primary aluminum requirement by 15–25%.

1. Introduction

Current trends in energy supply and consumption are generally regarded as unsustainable: International Energy Agency (IEA) estimates that energy-related greenhouse gas (GHG) emissions will more than double by 2050. The vehicle industry, one of the high CO_2-emitting sectors, has been developing next-generation vehicles such as hybrid electric vehicles (HEVs), electric vehicles (EVs), and fuel cell vehicles (IEA, 2009). These vehicles are expected to consume less fossil fuel and emit less CO_2 during the use phase than conventional vehicles with internal combustion engines (ICEVs) (Lave et al., 2000; Samaras and Meisterling, 2008). In recent years, several governments have announced sales targets for these vehicles, and IEA has proposed a global scenario named “BLUE Map scenario,” which aims at “cutting CO_2 emissions levels in 2050 to 30% below 2005 levels” for the transport sector”. (The overall target for the scenario is a 50% reduction in global energy-related CO_2 emissions by 2050 compared to 2005 levels.) According to IEA (2009), this ambitious objective can be achieved by the rapid penetration of next-generation vehicles, improvements in energy efficiency, and some other technological developments. Thus, the introduction of next-generation vehicles has often been evaluated from the viewpoint of energy consumption and climate change.

However, the effect of such vehicles on the resource management of metals has not been discussed thoroughly. The expansion of the world economy in the last century has increased an importance of securing various metals (Erdmann and Graedel, 2011), and a still larger amount of metal usage is expected for developing countries. In response to this problem, a number of technologies and policies have been developed to promote the three Rs (reduce, reuse, and recycle); therefore, anthropogenic material stocks and flows are of current interest (Gerst and Graedel, 2008; Graedel et al., 2004; Johnson et al., 2005; Reck et al., 2008; Wang et al., 2007). Researches of the material flow analysis (MFA) have found that the vehicle industry plays a prominent role in the material cycle for various metals (Saurat and Bringezu, 2008, 2009; Tabayashi et al., 2009). A notable example is aluminum, whose use has expanded as a means of lowering fuel costs, with a consequent increase in aluminum consumption and recycling.

Aluminum is usually used with the addition of a few elements, in the form of an alloy. The Japanese Standard Association defines 40 or more alloy types (JSA, 2003), and these alloys are commonly categorized into two types according to the concentration of alloying elements: wrought alloys (less than ca. 5%) and cast alloys (ca. 15%). In current aluminum recycling, cast alloy production receives most of its scrap from end-of-life products because it can tolerate a high concentration of foreign elements. This recycling system (called down-cycling or cascading) works well as long as the demand for cast alloy is sufficiently greater than the quantity of scrap generated. However, a recent increase in scrap generation from end-of-life vehicles, buildings, and other products may

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dictate a change in the recycling system. Gesing (2004) simulated the mass balance in the transport sector and concluded that there would be a large amount of scrap that could not be absorbed by cast alloy production, while not being suitable for wrought alloy production because of its high concentrations of foreign elements. The author stated that "*The transportation sector will become a net producer of aluminum scrap rather than, as is the case at present, a consumer*." Gesing also raised the possibility that the expansion of cast alloy demand, economic principles, and technologies in the future would mitigate the generation of this "unrecyclable scrap." In particular, scrap sorting by alloy type is considered to be an effective means of reducing unrecyclable scrap. If wrought alloys in end-of-life products are identified and collected without much contamination, they can be used as a source for wrought alloy production. To carry out the sorting in a simple, quick, and inexpensive manner, several techniques such as X-ray transmission analysis, apparent density, and three-dimensional sensing, combined with neural network analysis, have been under development (Gaustad et al., 2012; Koyanaka and Kobayashi, 2011; Mesina et al., 2007).

The purpose of this paper is to provide insight into aluminum recycling in the near future, with a focus on clarifying how the next-generation vehicles will affect it. The extent to which scrap sorting can enhance recycling is also discussed. Aluminum demand and discard in Europe, the United States, Japan, and China are modeled using MFA. Then, the necessary amount of primary aluminum and the generation of unrecyclable scrap are derived for three separate scenarios of vehicles and scrap use. The results show the limitations of the current recycling system and confirm the validity of scrap sorting.

2. Methodology

The present status of the anthropogenic aluminum cycle has been illustrated by some MFA studies (Boin and Bertram, 2005; Chen et al., 2010; Liu et al., 2011; Martchek, 2006). In the previous publication (Hatayama et al., 2009) we projected the aluminum in-use stock, demand, and discard up to 2050 for Japan, the United States, Europe and China, using dynamic MFA. In that study we calculated the concentrations of foreign elements in scrap, considering the alloy types used in respective end uses, and then evaluated the potential for reduction in primary aluminum consumption using multimaterial pinch analysis. These approaches are employed in the present paper for an evaluation of the recycling potential.

2.1. Material flow analysis

The analysis in this paper targets Europe, the United States, Japan and China, which accounted for 80% of world aluminum consumption in 2005 (WBMS, 2008). The consumption data distinguished two types of alloys, namely, wrought and cast alloys, which were classified into eight end use categories: building, vehicles (ICEVs, HEVs, and EVs), transportation (excluding vehicles), container and packaging, machinery, electrical equipment, consumer durables and other products. The product lifetime distribution and yield ratios in the fabrication process were given for each end use (listed in Supplementary Material).

Aluminum demand in the future was calculated based on the forecast of in-use stock. Materials are of use to consumers as a product in use; therefore, product demand arises when consumers feel a deficiency in existing in-use products. For this reason, some researchers gave importance to the concept "stocks drive flows," and the same concept was adopted in this paper (Hatayama et al., 2010; Müller, 2006). We assumed that the per capita stock follows the logistic curve as a country develops:

$$s_t = \frac{s_{\text{sat}}}{1+\exp(\alpha-\beta\times \text{GDP}_t)} \quad (1)$$

where s_t is the per capita stock in year t, s_{sat} is the saturation value of per capita stock, α and β are parameters, and GDP_t is the per capita gross domestic product (GDP) in year t. For each end use except vehicles, the parameters α, β and s_{sat} were determined using nonlinear regression on the data plot of the historical relationship between GDP_t and s_t (t = 1980–2005) in each region. Then, substituting the determined α, β and s_{sat} in Eq. (1), the in-use stock of aluminum from 2006 to 2050 was estimated for each end use using GDP and population projections (EIA, 2008; The United Nations). Aluminum consumption and discard were derived so as to satisfy the stock increase on the basis of mass balance (details are described in Hatayama et al. (2009)). Eq. (1) was applied to six end uses, excluding vehicles and transportation. For vehicles, our forecast was based on the IEA's scenario (described in Section 2.3.1). For transportation, the consumption was assumed to be constant from 2005 onward.

Although most MFA studies only try to capture the quantitative aspect of the anthropogenic material cycle, this study also considered the qualities of the material: we considered what types of alloys are used in each end use. This experiment made it possible to calculate the composition of scrap because, if scrap sorting is not carried out, the scrap is a mixture of those alloys (Hatayama et al., 2007). This approach can calculate the amount and the composition of scrap for every end use and evaluate the recycling potential with multimaterial pinch analysis.

2.2. Multimaterial pinch analysis

In current aluminum recycling, the use of old scrap (scrap from end-of-life products) in wrought alloy production is quite limited. However, appropriate separation and blending of scrap can make it possible for wrought alloy production to receive more scrap. The aluminum recycling process consumes old scrap, new scrap and primary aluminum as "source," and produces secondary aluminum alloys that meet the quantity and quality required by society (considered here as a "sink"). In this process, various types of source must be mixed in consideration of constraints in impurities. This type of optimization problem has often been an important issue in the design of plant-level heat exchanger networks and pinch analysis was developed to solve it (Linnhoff and Hindmarsh, 1983). By applying this technique to material recycling (named multimaterial pinch analysis in Hatayama et al. (2009)), we derived the optimized recycling, where the amount of recycled scrap is maximized and at the same time virgin material consumption is minimized. In multimaterial pinch analysis, primary aluminum consumption (s_{primary}) must be minimized under the following conditions.

$$ss_i \geq sc_i \quad (2)$$

$$s_{\text{primary}} + \sum_i sc_i = \sum_i d_i \quad (3)$$

$$u_{kj} \geq \frac{\sum_i (e_{ki}\cdot sc_i \cdot r_{ij})}{\sum_i (sc_i \cdot r_{ij})} \quad (4)$$

where ss_i is the supply of scrap i, sc_i is the consumption of scrap i, d_j is the demand of alloy j, e_{ki} is the concentration of foreign element k in scrap i, r_{ij} is the proportion of the scrap i recycled into alloy j, and u_{kj} is an acceptable concentration of element k in alloy j. Scrap i represents the old or new scrap from each end use in each region and alloy j represents the wrought and cast alloys for each end use in each region. For element k, four major additives

Table 1
Future scenarios.

	HEVs and EVs	Scrap sorting
Scenario I		
Scenario II	+	
Scenario III	+	+

Technologies marked with "+" are introduced in each scenario.

(Si, Fe, Cu and Mn) were selected here. The values of *ss*, *d* and *e* are given by dynamic MFA, and the *u* values are defined based on the industrial standards. Then, minimized $s_{primary}$ is solved through linear optimization with variables sc_i and *r*. The multimaterial pinch analysis in this paper aims to achieve the minimization of total primary aluminum requirement throughout regions. Therefore the optimization problem was solved considering all the sources (ss_i) and sinks (d_j) in four regions, where trade of scrap was an available measure to increase the scrap use.

In Eq. (4), we assumed that the foreign elements in the aluminum scrap are not removed during the smelting process. Although some elements, like Mg, can be removed to some extent, we deem the assumption acceptable for those four elements (Si, Fe, Cu, and Mn). Removal of these four elements from scrap is thermodynamically impractical. Furthermore, incorporation of other material parts (e.g., iron clips in aluminum window frames) into the waste management processes is not taken into account.

Thus, multimaterial pinch analysis shows how far we can reduce the primary aluminum consumption by trade, blend and dilution of scraps. It can be a convenient index for evaluating energy consumption in the aluminum industry, because primary aluminum is well known for its large energy requirement during the smelting process. Concurrently, the analysis points out the scrap that cannot be recycled because of highly concentrated foreign elements. It represents the overall efficiency of secondary resource use; further, it illustrates which product would become a "scrap producer." This paper represents the recycling potential of aluminum by the amount of (minimum) primary aluminum requirement and unrecyclable scrap. The total amount of unrecyclable scrap is represented as Eq. (5).

$$\text{Amount of unrecyclable scrap} = \sum_i (ss_i - sc_i) \qquad (5)$$

2.3. *Future scenarios*

To clarify the influence of next-generation vehicles and scrap sorting on future aluminum recycling, three scenarios are envisioned (Table 1). These scenarios are characterized by the following factors, both of which are related to the vehicle sector. The other seven end uses share the same conditions in these scenarios.

2.3.1. *Introduction of next-generation vehicles*

In the IEA's BLUE Map scenario, target sales of HEVs, EVs, hydrogen fuel cell vehicles and other types of vehicles are shown up to 2050 for each type (IEA, 2009). The scenario envisages the HEVs and EVs occupying 80% of the passenger vehicle sales therefore we represent future vehicles by HEV and EV. The penetration rate of HEVs and EVs was assumed to be as shown in Fig. 1 for Japan, the United States, and Europe, and a five-year delay was applied to developing China. The number of total vehicle sales for the BLUE Map scenario was obtained from the World Business Council for Sustainable Development (Fulton and Eads, 2004); therefore, the number of HEVs and EVs introduced in scenarios II and III was calculated using the penetration rates in Fig. 1. In scenario I, by contrast, all vehicles are conventional ICEVs. The number of vehicles used in each region was estimated using the existing model (Dargay et al., 2007).

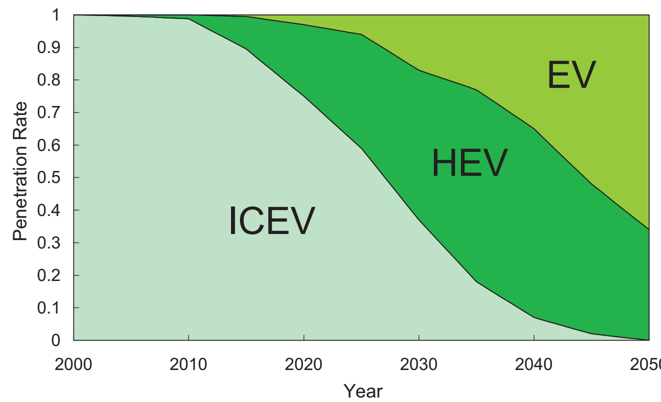

Fig. 1. Penetration rate of next-generation vehicles, 2000–2050.

Future aluminum demand for vehicles was calculated from the number of vehicles and the weight of aluminum per unit. The aluminum usage in vehicles has been increasing as a means of reducing vehicle weight. However, HEV and EV have different aluminum components, because their drive systems are different from those of a conventional ICEV. At present, the engine blocks used in ICEVs are the largest consumer of aluminum cast alloys. However, for example, since an EV is not equipped with an internal combustion engine, the weight of aluminum cast alloys used is lower than for a conventional ICEV. On the other hand, aluminum wrought alloys are expected to be used for the power-supply box in EVs. We discussed the material composition of HEV and EV with experts in industry and postulated the weight of wrought and cast alloys used in each vehicle type. Compared to ICEV, we assumed more cast alloy use for HEV while more wrought alloy use and less cast alloy use for EV.

2.3.2. *Scrap sorting*

Current aluminum recycling is dominated by cascading. One reason, as mentioned in Section 2.2, is the presence of irremovable foreign elements in the scrap. Just as critical is that the varieties of alloys used in a product are often collected without separation. Metals in end-of-life products are separated through several processes, such as magnetic separation, eddy-current separation and sink-float separation. However, it has been difficult to identify the alloy types in these processes. The composition of smelted aluminum scrap therefore becomes different from any type of alloys, a strong indication for straightforward cascading into a cast alloy. Scrap sorting techniques are expected to avoid undesirable blending of alloys in the scrap and achieve "alloy to alloy" recycling.

In the analysis, scenario II and III are characterized by whether discarded scraps are sorted according to alloy types. Whereas different types of alloys in a product are collected and smelted together in scenario II, scenario III assumes that the aluminum alloys used in ICEV, HEV and EV are recovered separately. It leads to an increase in scrap use and to a reduction in primary aluminum requirement.

3. Results

The dynamic MFA provided the information on the source and sink of recycling: scrap volume and its compositions for respective end uses, and production demand for respective alloy types. Then, the minimum requirement for primary aluminum and the generation of unrecyclable scrap were calculated using multimaterial pinch analysis for 2030 and 2050.

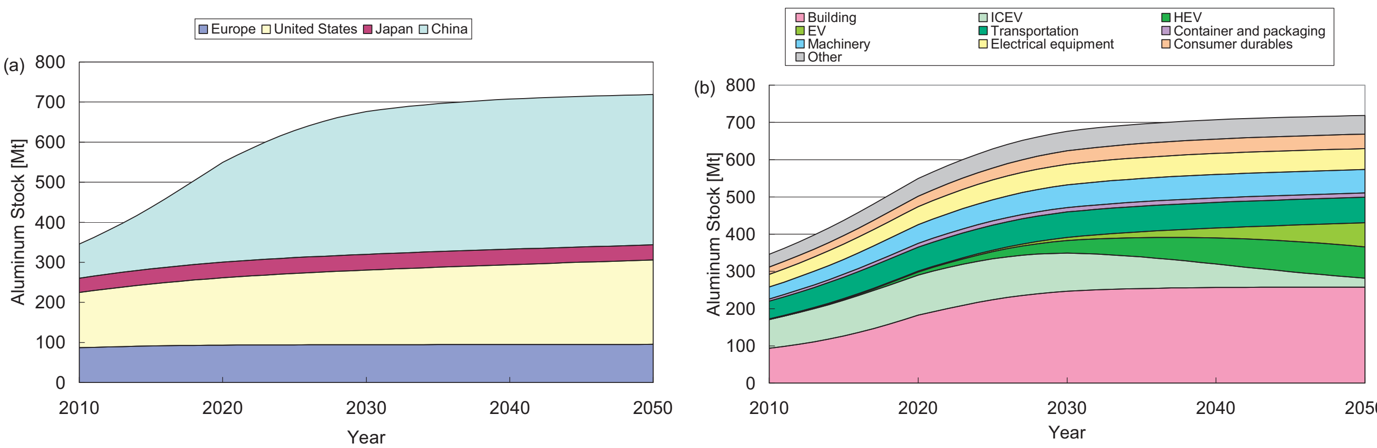

Fig. 2. Forecast of in-use aluminum stock by 2050: (a) by region and (b) by end use.

Aluminum stock, demand and discard were estimated as shown in Figs. 2–4 for scenarios II and III. (It should be noted that the word "discard" is referring to an old scrap. The estimation of a new scrap is presented in Supplementary material.) The stock reaches 720 Mt (million ton) in 2050, which is double that in 2010. The demand also grows to 60 Mt at 2020s and then stabilizes. The stock in China grows from 86 to 375 Mt, which prompts the annual demand to increase up to 40 Mt. Meanwhile, for Europe and Japan, aluminum stock and demand show only a slight increase. Aluminum discard in 2010 was estimated to be 18 Mt, less than half of the aluminum demand. However, the amount of aluminum discard gradually rises to the level of aluminum demand and reaches 50 Mt in 2050. As shown in Figs. 3b and 4b, vehicles will occupy 25% of aluminum demand and discard. On demand side, HEVs and EVs increase their presence from 2020s and exceed ICEVs in ca. 2030. In contrast, ICEVs are dominant until the middle of 2040s on discard side. In the material life cycle, a change in material use at supply side is not reflected immediately on the waste stream.

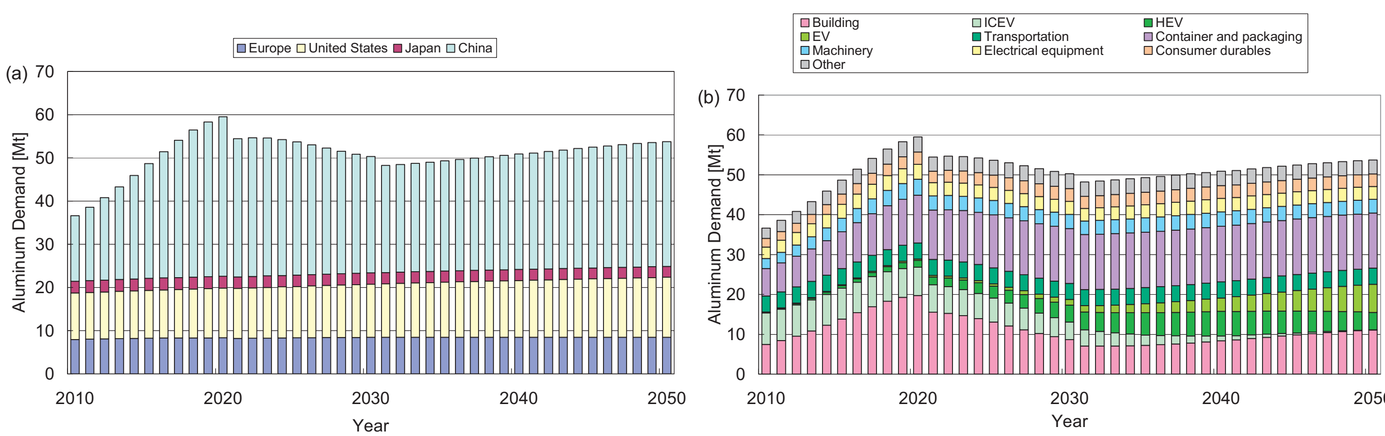

Fig. 3. Forecast of aluminum demand by 2050: (a) by region and (b) by end use.

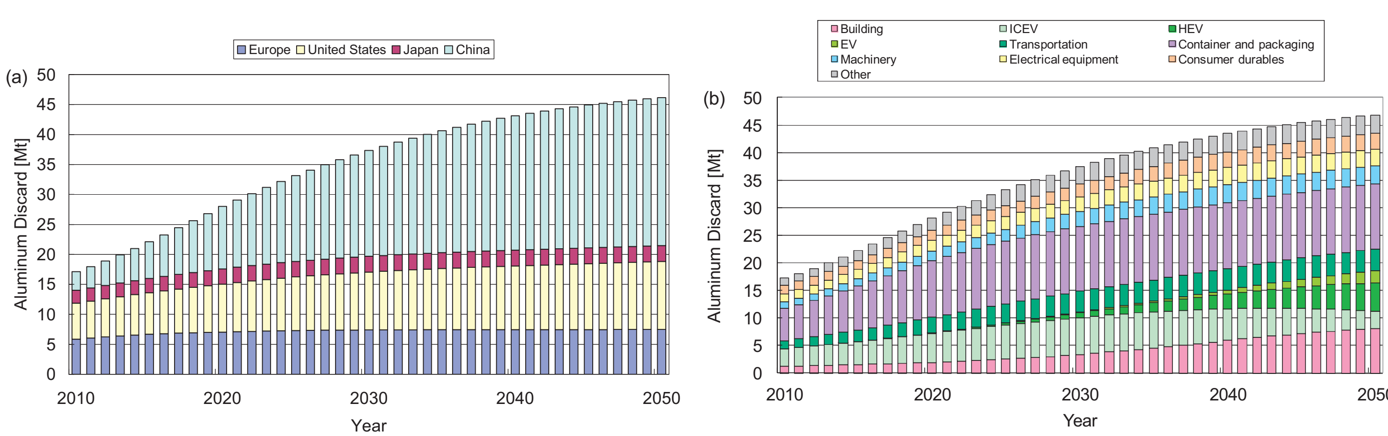

Fig. 4. Forecast of aluminum discard by 2050: (a) by region and (b) by end use.

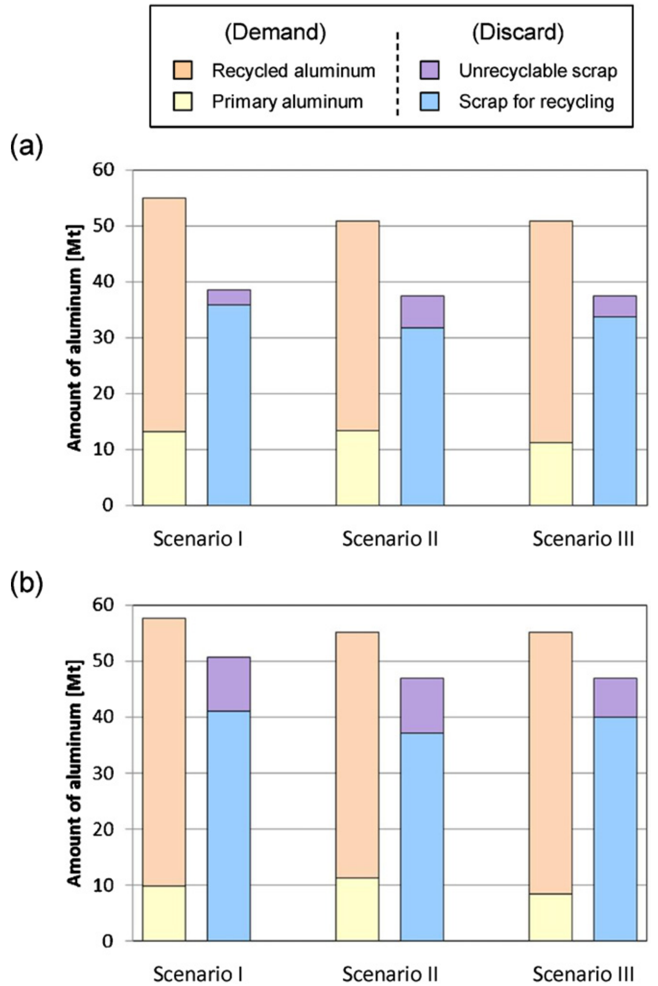

Fig. 5. Sources and sinks in the optimized aluminum recycling for (a) 2030 and (b) 2050.

The results of the multimaterial pinch analysis for 2030 are shown in Fig. 5a. In scenario I, the global aluminum demand and discard in 2030 are 55 and 39 Mt, respectively. Of the discard, 36 Mt of the old scrap is available for secondary aluminum, whereas 2.9 Mt cannot be recycled because of the high concentration of alloying elements.

In scenario II, global aluminum demand and discard in 2030 are 51 and 38 Mt, respectively. Compared to scenario I, unrecyclable scrap in 2030 increases to 6.1 Mt. In this scenario, the year 2030 is in transition from ICEVs to HEVs and EVs; the penetration of EVs is rapidly growing, while most of the end-of-life vehicles are still ICEVs. This means that the demand for cast alloy decreases, even though vehicle scrap still contains a high percentage of cast alloys (70% in 2030). If scrap sorting is not carried out, the scrap from end-of-life vehicles is so contaminated that it would only be suitable for producing cast alloys. Fig. 6 shows the aluminum demand for vehicles by alloy type with the plot of aluminum discard from vehicles. In 2030, the amount of scrap does not exceed the cast alloy demand in scenario I; therefore, the vehicle sector would behave as a “scrap consumer”. However, in scenario II, the vehicle sector becomes rather a “scrap producer,” because the rapid penetration of EVs suppresses cast alloy demand. This gap between source and sink results in the generation of a large amount of unrecyclable scrap.

In scenario III, the primary aluminum requirement in 2030 would be 15% lower than in scenario II. By means of scrap sorting, 2.4 Mt of wrought alloy scrap will be separately collected from end-of-life vehicles in this scenario. This wrought alloy scrap can easily be used to produce the same type of wrought alloys; therefore, scrap sorting leads to a reduction of 1.9 Mt in both primary aluminum requirement and the generation of unrecyclable scrap.

The result for 2050 (Fig. 5b) indicates that the primary aluminum requirement will decrease by 15–25% compared to 2030, because there will be a large amount of aluminum discard available for recycling. At the same time, the increase in discard leads to a 1.7–3.4 times increase in unrecyclable scrap. The increase in vehicle scrap will enhance the effectiveness of scrap sorting, reducing the primary aluminum requirement by 25%.

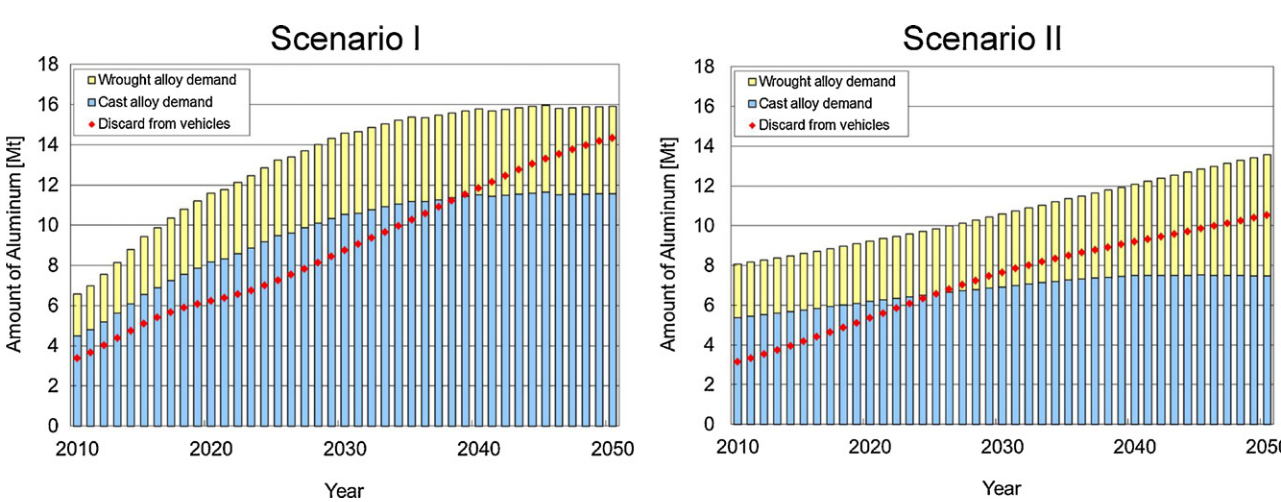

Fig. 6. Demand for vehicles (ICEVs, HEVs and EVs) by alloy type. Scrap from vehicles is also plotted.

4. Discussion and conclusions

This paper presents the prospects of aluminum recycling by 2050, quantitatively analyzing the influence of next-generation vehicles and scrap sorting. First, dynamic MFA was used to estimate the stock and flow of aluminum in Europe, the United States, Japan, and China by 2050. The MFA indicated that the increase in aluminum stock and demand in the future are almost all derived from developing China, while aluminum usage in developed countries already seems mature for traditional products. The influence of the next generation appears as a suppression of cast alloy demand, which leads to at least 6.1 Mt of unrecyclable scrap in 2030. In the situation where the amount of scrap (source) grows to the level of the demand (sink), scrap sorting becomes an effective measure to promote recycling. If scrap sorting is applied to end-of-life vehicles, a 15–25% reduction in primary aluminum consumption can be expected in the future.

Aluminum usage in the products has been increasing, owing to its properties such as light weight, high corrosion resistance and good formability. However, the introduction of EVs would become the first case that reduces the intensity of aluminum usage in major sectors. In terms of the anthropogenic aluminum cycle, a suppression of cast alloy demand would constrain a scrap use in the secondary production. This shift will raise the importance of the improvement in waste management and recycling processes, especially in a developed society. As Fig. 5 shows, actually, the benefit from scrap sorting was expected to be larger in 2050 (25% reduction in primary aluminum) than in 2030 (15% reduction in primary aluminum). The recycling technologies such as scrap sorting in separation process, removal of impurities in smelting process and design for disassembly in manufacturing process will probably contribute on the resource conservation, energy saving, and CO_2 reduction.

However, it should be noted that what we analyzed in this paper is the “potential” of recycling. In other words, optimization of the recycling flows with multimaterial pinch analysis was conducted on the assumption that all the aluminum contained in the end-of-life products would be available for recycling. In 2005, the quantities of aluminum scrap recovered in Europe, the United States, Japan, and China were 2.8 Mt, 3.0 Mt, 1.0 Mt, and 0.5 Mt, respectively (WBMS, 2008). When compared with Fig. 4, the scrap collection rate was found to be far from 100% (Supplementary Material: calculation of collection rates). The low collection rate has led to the cascading in the current recycling system and a decreasing motivation for scrap sorting, because the demand for cast alloys has been sufficiently greater than the scrap collected. If the collection rate does not improve in the future, scrap sorting may not be as effective as estimated in this study. However, in that case, a large amount of aluminum contained in end-of-life products will not be recycled and will thereby be dissipated regardless of its recyclability. Scrap sorting will certainly be important in aluminum recycling; in addition, it is also important to encourage the recovery of aluminum from various end-of-life products in order to enhance the effectiveness of scrap sorting. Such an evolution of aluminum recycling can be economically feasible in the developed world (Gaustad et al., 2011). The recycling potential shown in this paper could be refined by modeling the metal price, as well as the costs of collection and sorting, in the analysis.

This paper indicates the possibility that the amount of primary aluminum production in the future can be reduced to less than the current level by using greater quantities of scrap. A reduction in the primary aluminum production would help mitigate the energy consumption and the CO_2 emissions associated with the aluminum production process. However, CO_2 emissions are also affected considerably by emission factors. CO_2 emission factors of primary aluminum [kg-CO_2/kg] depend on electricity mix, age of plant (newer plants are more energy-efficient), and related technologies in producer countries. For example, the emission factor in China is now estimated as 18.2 (Gao et al., 2009), which is more than double the 8.6 value in Europe (EAA, 2008). Low CO_2 emissions can be achieved by the improvement in the emission factor in low-efficiency countries, while higher CO_2 emissions might ensue when aluminum production converges on low-efficiency countries. The electricity mix in the producer country is also significant: the utilization of natural energy has a positive effect on CO_2 emissions, while the avoidance of nuclear plants may have a negative one.

The development of the technology used in electric generation and aluminum smelting processes has decreased energy intensity and accompanying CO_2 emissions. Nevertheless, the aluminum industry is regarded as a large CO_2 emitter because drastic economic growth has been increasing primary aluminum consumption for decades. In the coming decades, however, the amount of scrap available for recycling will increase; therefore, it should become possible to satisfy demand with a small amount of primary aluminum. The growth of the aluminum industry and a reduction in environmental load can be achieved compatibly in the future.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2012.06.006.

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