Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

A Material Flow Model for Impurity Accumulation in Beverage Can Recycling Systems

Amund N. Løvik[1], Daniel B. Müller[1]

[1]Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, NO-7491, Norway

Keywords: Aluminum, Recycling, UBC, Impurity, Accumulation

Abstract

Recycling of aluminum is beneficial due to reduced energy inputs, greenhouse gas emissions and raw material costs. Beverage cans are currently the second largest source of old scrap, and could become even larger with improved collection. However, impurities such as iron, titanium or lead may impede end-of-life recycling at higher levels, especially in closed-loop systems where they can accumulate over time. A generic material flow model for impurity accumulation in a simple recycling system is presented here. Sensitivity analysis was used to investigate the effect of key parameters on dynamics of accumulation and concentration at steady state. It was found that it takes longer to reach steady state at high collection rates, and that the steady state concentration is disproportionally higher. Increasing the U.S. beverage can collection rate from today's 54% to the goal of 75% may cause more than a doubling of impurity concentrations unless better scrap treatment and remelting are developed in parallel or the scrap is used in other applications.

Introduction

Primary production of aluminum is energy intensive and causes large emissions of greenhouse gases (GHG). Ingot production from secondary sources can cut the energy input by more than 90% [1], and process related GHG emissions are essentially eliminated. Considering the limited potential for energy and emission improvements in the primary production chain [2], it is clear that increased recycling is the most important measure for a more sustainable aluminum industry. Beverage cans represent one of the largest end uses, and due to the short lifetime it is the second largest source of end-of-life aluminum scrap globally [3]. However, the recycling rate is low in many countries, especially for those without a deposit scheme for collection. The collection rate is above 80% in several European countries [4], but only about 50% in the U.S. [5], the largest consumer of this product. Hence, there is a large potential for increased recycled content if better systems for scrap collection are developed.

Like any type of end-of-life scrap, used beverage cans (UBC) come with impurities such as other metals or glass from commingled collection systems, dirt, or titanium dioxide particles from the lacquer used for decoration [6, 7]. Due to the repeated recycling of the material, these impurities may accumulate over time in the system if not properly controlled in the scrap beneficiation processes. The concentration of impurities in remelted material is adjusted by diluting with primary aluminum or higher quality scrap. With a higher recycled content, the possibility for dilution is smaller, and impurities that are unproblematic today may become constraints to recycling in the future.

Previous material flow models of aluminum recycling that include quality differences have mainly focused on complex systems, such as automotive aluminum, with long lifetimes, a large number of alloys and several scrap streams [8-13]. In all of these works, optimization models were used to determine maximum scrap utilization, given the demand for various alloys, supply of scrap of different types, and the composition of these. The results are calculated numerically year by year. This is a powerful way to assess recyclability in complex systems, but because of the numerical methods the models depend on quantified parameters and have a limited capacity to explain the underlying drivers for accumulation. None of these studies include real measurements of scrap compositions, and most ignore external contaminants (e.g. free iron particles) entirely. Only one study considered the accumulation of impurities or alloying elements over time due to repeated recycling of the same material [9]. It was assumed there that the concentration of each alloying element in remelted material increases by a certain fraction, the "accumulation ratio", for each loop. This approach overestimates the accumulation effect, since it assumes that the flow of impurities into the system is proportional to the concentration of impurities already there.

An analytical model of accumulation can lead to better understanding of the mechanisms causing it and inform about possible future developments without knowing the real level of scrap contaminations. This is more easily done with a simple system such as beverage can recycling where there is only one type of scrap and the lifetime is short. We therefore developed an analytical, dynamic substance flow model for a generic impurity in a simple UBC recycling system, and performed a sensitivity analysis to investigate the effect of collection and contamination rates on steady state impurity concentration and the time it takes to reach it.

Methods

System definition

The system of interest for this work is defined as shown in Figure 1. It is a simplified representation of a closed system of aluminum beverage can production, use and recycling. No statistics exist that specify the destination of scrap, but it has been claimed that 95% of collected UBC scrap in the U.S. is used for production of new cans [14]. This is largely consistent with the Aluminum Association's estimate of recycled content in beverage cans [15], after adjusting for production scrap.

The beverage cans are manufactured from two parts, the lid and the body, which have different material compositions. The body is made from an alloy (AA3104) with around 1% manganese and 1% magnesium, while the lid is made from one or two alloys from the 5xxx-series with higher magnesium content [16]. During use and collection, the cans may pick up impurities such as steel, glass and dirt. These impurities and compounds from the lacquer may contaminate the aluminum metal upon remelting (X_{01}). Some of the material is lost due to incomplete

collection of UBCs, or because of remelting losses (X_{30}). The recycled material is used in the production of new bodies (X_{32}) [17] after a delay equal to the average time spent from production of the can material until it arrives at the remelting facility as used scrap. Primary aluminum and alloying elements are added for lid production (X_{01}) and for adjusting the composition and mass of the body (X_{02}). It is assumed that the impurity may also be an alloying element in the lid, and that it is not closely controlled in the production of the body material, i.e. it is allowed to accumulate.

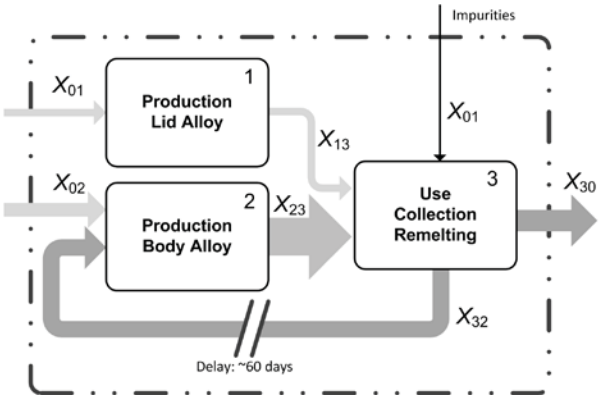

Figure 1. System definition for aluminum beverage can production and recycling, with impurity accumulation. X_{ij} are material flows. The can consists of two parts, the body and the lid, where only the body material is produced from end-of-life scrap.

Mathematical model description and parameter estimation

The goal of the model is to investigate how the collection rate and contamination rate affect the accumulation of an impurity in the body material when the overall mass flows are constant, i.e. to find the concentration in X_{23} after n recycling loops and in steady state. For simplicity, the impurity inflow, X_{01}, is defined as impurities ending up in the recycled material X_{23}; i.e. contaminations that appear in UBCs which are removed before or during remelting are not considered. Model parameters are summarized and defined in Table 1. The concentration of the impurity in flow X_{ij} is expressed as c_{ij}.

The lid's average share of the total can weight is reported from 18 to 22% [18-20]; 20% was used as a representative value. The end-of-life (EOL) recycling rate, as defined here, depends on the collection rate, the yield during scrap pre-processing (shredding), and the yield during remelting. These are respectively estimated as 54.2% (USA 2011) [5], 99% [19] and 95% [19], giving an overall EOL recycling rate (RR) of 51%. Note that the collection rate is here defined as the amount of cans entering recycling divided by the amount of cans sold (i.e. it takes into account import unfilled of cans), as suggested by the Container Recycling Institute.

It was recently estimated that typical titanium content from lacquer in UBCs is 0.4% of the can weight [6]. As a conservative estimate it was assumed that one quarter of this ends up as an impurity in the remelted aluminum.

Table 1. Model parameters and definitions.

Symbol	*Description*	*Definition*	*Value*
w_{lid}	Mass share of the lid	$w_{lid} = \frac{X_{13}}{X_{13} + X_{23}}$	0.20 [18-20]
RR	End-of-life recycling rate	$RR = \frac{X_{32} - X_{01}}{X_{23} + X_{13}}$	51% (USA 2011) [5, 19]
h	Rate of impurity contamination	$h = \frac{X_{01}}{X_{32} - X_{01}}$	assumed = 0.1% [6]
c_{lid}	Conc. in lid material	$c_{lid} = c_{13}$	assumed = 0
$c0_{body}$	Initial conc. in body material	$c0_{body} = c_{23}^{n=0}$	assumed = 0

Assuming that the inflow of impurities is small compared to the aluminum flows ($X_{01} << X_{32}$), the concentration in the body material after n loops can be expressed as a function of the concentration after $n - 1$ loops:

$$c_{23}^{n} = \theta + RR \cdot c_{23}^{n-1} \tag{1}$$

where

$$\theta = \frac{RR}{1 - w_{lid}} \cdot (w_{lid} c_{lid} + h) \tag{2}$$

This gives:

$$c_{23}^{n=1} = \theta + RR \cdot c0_{body} \tag{3.a}$$

$$c_{23}^{n=2} = \theta \cdot (1 + RR) + RR^2 \cdot c0_{body} \tag{3.b}$$

etc. After n loops, the concentration can be expressed as:

$$\begin{aligned} c_{23}^{n} &= RR^n \cdot c0_{body} + \theta \sum_{i=1}^{n} RR^{i-1} \\ &= RR^n \cdot c0_{body} + \theta \frac{1 - RR^n}{1 - RR} \end{aligned} \tag{4}$$

The steady state concentration is found by letting $n \to \infty$:

$$c_{23}^{ss} = \theta \frac{1}{1 - RR} \tag{5}$$

Note that the results are only valid as long as the amount of recycled material is less than or equal to amount required for body production, i.e. in this case $RR \leq 0.80$. For higher recycling rates, the material will either have to be used in lid production or in other applications.

A sensitivity analysis was performed on the concentration over time by quantifying the system for different recycling rates and assuming a constant value for the contamination rate, h = 0.1%. The steady state concentration was calculated as a function of recycling rate, and a sensitivity analysis with respect to contamination rate was carried out.

Results

Steady state concentration of impurities

The steady state concentration in the body material as a function of end-of-life recycling rate is shown in Figure 2 for different values of the contamination rate. As the recycling rate grows toward 100%, the concentrations are approaching infinity, as can be seen in (5), where the denominator goes to zero. However, as long as only the body material absorbs scrap, it is not possible to go beyond 80%. For a given recycling rate, the steady state concentration is directly proportional to the contamination rate, h. The curve shape is thus independent of this parameter.

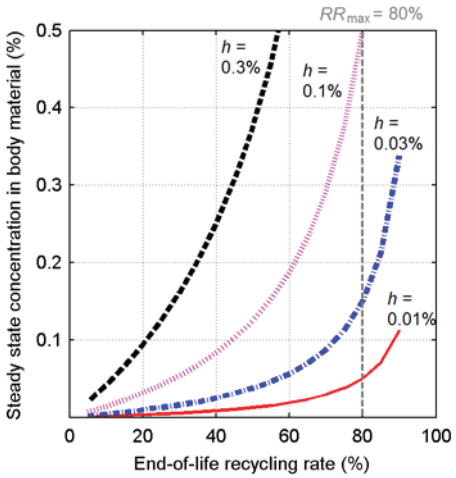

Figure 2. Steady-state concentration of an accumulating impurity in the can body, as a function of end-of-life recycling rate, shown for different values of the contamination rate, h.

Dynamics of impurity accumulation

The concentration in the body material as it develops over time is shown in Figure 3 for different values of the recycling rate. For recycling rates less than ~55%, the concentration will stabilize relatively fast: After 5 loops through use and recycling, the material has already reached its steady state composition, as can be seen by the plateau. At higher recycling rates the accumulation takes longer, and the steady state level increases disproportionally. It takes about 15 loops before steady state is reached with a 75% recycling rate.

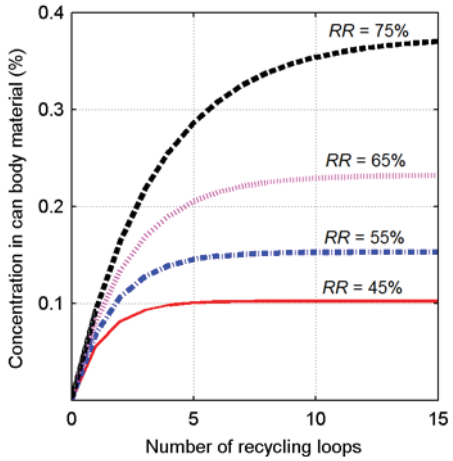

Figure 3. Concentration of an accumulating impurity in the can body material as a function of the number of recycling loops, shown for different values of the end-of-life recycling rate, RR. Accumulation lasts longer for high recycling rates, and reaches progressively higher steady-state levels.

Discussion and conclusions

Model limitations

The model presented here is a highly simplified representation of real recycling systems, and was used to demonstrate some fundamental properties of impurity accumulation. It is therefore useful to ask whether the same conclusions would hold in reality.

Production scrap was not included in the model. The effect of this simplification depends on whether the impurity enters the system in the production chain or in the use/end-of-life management stage. For example, an impurity contained in the lacquer may already be present in some of the manufacturing scrap, although most of the production scrap is generated before this stage. Similarly, iron contamination may originate from equipment used for remelting and scrap handling. In such cases, the accumulation will be intensified by the generation and recycling of new scrap. If on the other hand the impurity only enters the system in the use phase or during collection, the recycling of new scrap does not significantly influence the steady state concentration, as long as the collection and recycling of it is close to 100% and done in a closed-loop fashion (recycling into the same alloy).

It was assumed here that collected cans are recycled into new cans in the same region. In reality, UBC scrap is also used in other products, and may be exported to other regions, thereby redirecting the impurities associated with it as well. Industry associations and other institutions that publish recycling rates do not distinguish between different uses of the scrap, and this information is generally not available in statistics. It is therefore possible that the recycling rate of UBCs, as it is normally defined, increases without any effect on impurity levels in cans. Hence, the conclusions from this work apply to closed-loop systems. While this may be a good approximation for beverage can recycling in the U.S. today, most aluminum alloys are recycled in an open-loop fashion, with cast alloys for automotive applications being the main scrap absorbers [21, 22]. However,

increased scrap supply from products with long lifetimes may necessitate a higher degree of closed-loop recycling in the future [23].

In the quantification of the system all parameters were set as constant over time. The validity of this assumption may be assessed by looking at Figure 3. It can be seen that accumulation, at current U.S. recycling rates, happens over a relatively short period of time. The Aluminum Association claims that each recycling loop may take as little as 60 days [24]. Even assuming an average of twice this time, the steady state concentration is reached within less than two years, while the consumption of aluminum beverage cans in the U.S. has been stable over a period of 10 years [25]. In regions with rapidly growing consumption, additional primary material is needed to account for the growth that occurs between one recycling loop and the next, leading to a somewhat lower impurity concentration until consumption stabilizes. This is also the reason why the results here cannot be directly extrapolated to other markets such as building or transport, where lifetimes are much longer and consumption growth higher.

The example calculations included only a rough estimate of the contamination rate, h, for one element (titanium). The inflow of impurities, X_{01}, is not directly observed in reality, but may be estimated by mass balance. This would require knowledge of the average composition of can lid and body materials that are used in the given region, and measurements of the composition of remelted material. Individual producers routinely check the composition of their material, but such information is not publicly available. At the moment it is therefore difficult to draw conclusions about specific impurity elements and their current and future levels. Because scrap compositions are determined by the practices of all producers in the system, a higher level of knowledge requires a coordinated effort by the whole industry.

Conclusions

Despite the aforementioned limitations, the model can provide some fundamental insights into the accumulation of impurities in a closed-loop recycling system. Most importantly, the steady state concentration will increase more rapidly than the recycling rate. As an example, consider the goal of the Aluminum Association of reaching 75% recycling for UBCs [26]. This corresponds to a 71% end-of-life recycling rate, *RR*, as it is defined here. From today's level of 51%, the resulting change in steady state impurity concentration can be calculated with Equation 5, or observed in Figure 2. Such increase in recycling rate will lead to a steady state impurity concentration which is 2.35 times today's level. A single producer may be able to produce with this level of recycled content today, but if the whole industry did so, the quality of scrap would be affected by accumulation. This implies that better control of impurities in scrap handling, preprocessing and remelting must be developed in parallel with increased collection, unless significantly higher concentrations can be tolerated.

The results also indicated a time frame for reaching steady state concentrations in impurity accumulating recycling systems. At current U.S. recycling rates, this occurs within approximately 5 recycling loops. Considering the relatively slow rate of change of parameters in the system, it is likely that impurity levels are presently in steady state, i.e. not accumulating over time. Rapid changes in collection rate, contamination, or the introduction of new alloying elements in the lid may be followed by a transition period to a new steady state concentration. The time needed depends on the collection rate, but will in general be less than 15 recycling loops, or assuming that each loop takes 120 days, less than 6 years.

Acknowledgment

We thank Andres Tominaga for help with data gathering and literature survey.

References

1. International Energy Agency, *Energy technology transitions for industry*. 2009, Paris: IEA Publications.
2. J.M. Allwood, J.M. Cullen, R.L. Milford, *Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050.* Environ Sci Technol, 2010. **44**(6): p. 1888-1894.
3. International Aluminium Institute, *Global aluminium recycling: a cornerstone of sustainable development*, 2009.
4. Container Recycling Institute. *Aluminum Used Beverage Can recycling Rate: Europe, US, and Canada 2010*. [10.12.2013]; Available from: http://www.container-recycling.org/index.php/factsstatistics/aluminum/125-aluminum-data.
5. *Calculating the Aluminum Can Recycling Rate*. [10.11.2013]; Available from: http://www.container-recycling.org/index.php/calculating-aluminum-can-recycling-rate.
6. N. Li, K. Qiu, *Study on Delacquer Used Beverage Cans by Vacuum Pyrolysis for Recycle.* Environ Sci Technol, 2013.
7. W.B. Steverson, *MRFs and UBCs: a concern yet an opportunity*, in *Light Metals 1995*, J. Evans, Editor 1995, TMS-AIME.
8. R. Kirchain, A. Cosquer, *Strategies for maintaining light metal reuse: Insights from modeling of firm-wide raw materials availability and demand.* Resources, Conservation and Recycling, 2007. **51**(2): p. 367-396.
9. G. Gaustad, E. Olivetti, R. Kirchain, *Toward sustainable material usage: evaluating the importance of market motivated agency in modeling material flows.* Environ Sci Technol, 2011. **45**(9): p. 4110-7.
10. H. Hatayama, et al., *Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology.* Resources, Conservation and Recycling, 2012. **66**: p. 8-14.
11. H. Hatayama, et al., *Dynamic Substance Flow Analysis of Aluminum and Its Alloying Elements.* Materials Transactions, 2007. **48**(9): p. 2518-2524.
12. A. van Schaik, et al., *Dynamic modelling and optimization of the resource cycle of passenger vehicles.* Minerals Engineering, 2002. **15**(11): p. 1001-1016.
13. A. van Schaik, M.A. Reuter, K. Heiskanen, *The influence of particle size reduction and liberation on the recycling rate of end-of-life vehicles.* Minerals Engineering, 2004. **17**(2): p. 331-347.

14. J. Green, M. Skillingberg, *Recyclable aluminum rolled products.* Light Metal Age, 2006(August).
15. The Aluminum Association, *Aluminum: The Element of Sustainability - A North American Aluminum Industry Sustainability Report.* 2011.
16. Hydro Aluminium Rolled Products Packaging and Building. *Coil for aluminium beverage cans*. [10.21.2013]; Available from: http://www.hydro.com/pagefiles/55888589/BeverageCans.pdf.
17. D.A. Doutre, *LiMCA and its Contribution to the Development of the Aluminum Beverage Container and UBC Recycling*, in *2011 Guthrie Symposium Proceedings* 2011.
18. S. Yoshida, H. Baba, *A New Used Aluminum Beverage Can Recycling System.* Proceedings of the 12th International Conference on Aluminium Alloys, 2010.
19. PE Americas, *Life Cycle Impact Assessment of Aluminum Beverage Cans.* 2010, Washington, DC, USA: Aluminum Association, Inc.
20. A. Detzel, J. Mönckert, *Environmental evaluation of aluminium cans for beverages in the German context.* The International Journal of Life Cycle Assessment, 2009. **14**(S1): p. 70-79.
21. A. Gesing, R. Wolanski, *Recycling light metals from end-of-life vehicle.* JOM, 2001. **53**(11): p. 21-23.
22. S.K. Das, J.A.S. Green, J.G. Kaufman, *The development of recycle-friendly automotive aluminum alloys.* JOM, 2007. **59**(11): p. 47-51.
23. R. Modaresi, D.B. Müller, *The role of automobiles for the future of aluminum recycling.* Environ Sci Technol, 2012. **46**(16): p. 8587-94.
24. The Aluminum Association. *U.S. Aluminum Can Recycling Reached 54.2 percent in 2008*. 2009 [10.12.2013]; Available from: http://www.aluminum.org/AM/.
25. Container Recycling Institute. *Aluminum can sales and recycling in the US*. 2006 [12.10.2013]; Available from: http://www.container-recycling.org/index.php/factsstatistics/data-archive.
26. The Aluminum Association. *Aluminum Can Extends Lead as Most Recycled Beverage Container*. 2012 [10.12.2013]; Available from: http://www.aluminum.org/AM/.