A Method for Assessment of Recyclability of Aluminum from Incinerated Household Waste

Mertol Gökelma, Ingrid Meling, Ece Soylu, Anne Kvithyld, and Gabriella Tranell

Abstract

Aluminum is widely used in daily household consumable goods such as food and drink packaging materials, storage containers, etc. The disposal of such goods into household waste means that this waste stream contains a significant amount of aluminum. Domestic waste is commonly sent to incinerator plants where the organics are combusted while the metallic content stays in the bottom ash, which is subsequently separated into various metal streams. Because of the importance of aluminium in the circular economy, there is a need for efficient recovery procedures for this metal source. This paper discusses the recyclability and the recovery rate of aluminum from the bottom ash through remelting with a molten salt. The remelting experiments were performed under a 50–50 wt% NaCl: KCl mixture with a 2 wt% CaF_2 addition to promote metal coalescence. The oxide thickness and trace element content of the starting metal and the composition of the resulting metal were characterized as these parameters largely determine the recovery rate and recyclability of these secondary metal streams. The laboratory results showed the coalescence efficiency up to 99.5% and the material yield up to 92%. High deviation in oxide content based on the oxide layer thickness measurements was observed which crucially affects the metal losses in recycling.

Keywords

Recycling • Incinerated metal • Bottom ash • Aluminum

Introduction

The global demand for aluminium (Al) has been increasing since the 1950s [1]. This increasing use has led to significant secondary production of aluminium from scrap, which reduces both the production cost and energy consumption [2], with associated lower CO_2 emissions [3]. There are also other important societal advantages of recycling such as resource conservation and reduced costs for waste landfilling.

Al products such as vehicles, building—and household materials are all potential secondary sources. Although recycling from "bulk" secondary sources like cars and building materials—or return scheme products such as used beverage containers (UBC's) is well established, there is a large Al material loss from household materials (foils, food containers etc.), because many countries do not have a dedicated recycling system or very low collection rate. As such, these products are mostly thrown in municipal solid waste, and subsequently end up at incinerator plants or landfills. On a global scale, household wastes contain approximately 4% metal fraction [4].

The output of the incineration process is a bottom ash which contains a mixture of metals and other unburned inorganic materials. The metal content, especially aluminium because of its high oxygen affinity, becomes highly oxidized during the incineration procedure that reaches temperatures up to 1000 °C in different parts of the reactor. This oxidation affects subsequent recycling yield and efficiency. European Waste-to-Energy plants produce almost 20 million tons of incinerator bottom ash (IBA) annually [5]. This ash contains materials in different size fractions. Particle sizes larger than 4 mm constitute 58.3–60.3% of the bottom ash, while the

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fraction of particles smaller than 1 mm constitutes 20–25%. Metallic particles are mainly present in the size range of 16–25 mm diameter [6], making it separable from other materials through a range of methods. Once separated from other materials, ferric (magnetic) materials can be separated from aluminium [7].

Recent research has focused on aluminium recovery yield in the remelting of aluminium from incinerator ashes, which depends on the properties of the input metal and the treatment process (temperature, flux. etc.). The most important challenge is the oxide layer thickness of aluminium pieces after incineration, which affects the efficiency adversely. According to Warrings and Fellner [8], approximately 11 wt% of the aluminium fraction oxidizes during the incineration. There is, however, still a lack of information regarding the properties and thickness of the oxide layer on the particles and a general trend and variation in trace element analysis. The aim of the current work is to investigate aluminium recovery yield and metal quality, as a function of metal particle input composition and oxide layer thickness, as well as salt to metal ratio in remelting.

Experimental Materials and Procedure

Materials

The aluminium fraction (Fig. 1) of the bottom ash after incineration, was acquired from a recycling company.

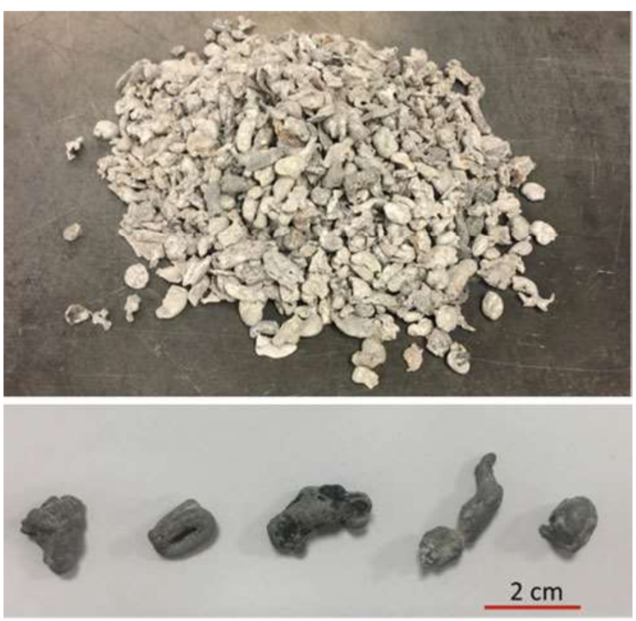

Fig. 1 Aluminium fraction of the bottom ash from an incineration plant

The particle sizes ranged between 5 and 25 mm having aspect ratios, A_R (A_R = Min Feret/Max Feret [9]) ranging between 0.1 to ≈1. Chemical analyses by inductively coupled plasma mass spectrometry (ICP-MS) of the starting material have been carried out and initial bulk composition of the material is shown in Table 1. As seen from the table, there are large variations in composition for all major elements.

Prior to the melting, particles were mounted in epoxy, sectioned and the oxide film characterised in the Scanning Electron Microscope (SEM).

Experimental Procedure and Matrix

A graphite crucible, with 0.57 l t volume was used for the remelting experiments. The crucible was placed in an induction furnace which operated with maximum 15 kW power (Fig. 2). Recycling under a salt flux was chosen since initial experiments of heating the metal pieces up to 850 °C did not break the oxide layer and no coagulation was observed. A 50–50 wt% NaCl:KCl mixture with 2 wt% CaF_2 added was used to improve the coalescence behaviour of aluminium. Besson et al. [10] and Sydykov et al. [11] have experimentally confirmed and reported the promoting effect of CaF_2 on coalescence and 2 wt% addition showed the highest efficiency.

In all experiments, the metal fraction was added after the salt mixture was molten and heated up to 800 °C. During the experiments, the temperature was kept at 800 ± 20 °C. No manual stirring was applied to make the parameters representative and to obtain comparable results.

Experiments were performed in three sets, each with three parallels, changing the salt/scrap ratio and the charging procedure (gradual vs. batch) as shown in Table 2. Gradual charging was performed in 5–7 charges to be sure that each piece had direct contact with the salt flux. 100 grams of salt mixture was molten in all experiments. After all aluminium pieces were charged, the melt was held at temperature for 5 min before the crucible was taken out from the furnace to cool. The recycled aluminium was removed from the crucible by crushing and washing.

Results

Characterization Results

The aluminium fraction samples were first characterized with different aspects such as bulk density, mass, elemental composition and oxide layer thickness. Bulk density was measured to 0.918 g/cm^3, with an average particle mass of 0.64 ± 0.40 g counted in 70 pieces. The oxidized

Table 1 Elemental analysis of aluminium fraction of the bottom ash after incineration in wt%

	ICP-MS	
	wt%	St. dev
Si	1.91	2.10
Fe	0.76	0.52
Cu	0.46	0.64
Mn	0.24	0.13
Mg	0.04	0.03
Cr	0.01	0.01
Zn	0.37	0.46
Ti	0.03	0.01
S	0.01	0.007
Ni	0.01	0.01
Pb	0.015	0.019
Sn	0.006	0.007
Na	0.003	0.006
K	0.0007	0.001
Y	0.1 ppm	0.1
U	0.6 ppm	0.1
Al	88.96	1.81

Fig. 2 Induction furnace used for the recycling experiments

aluminium surface is shown in cross section in Fig. 3. EDS analysis reveals an Al_2O_3 chemistry with a high carbon content resulting from the sample carbon coating.

Figure 4 shows the thickness measurements of the oxide surface. 16 oxide thickness measurements were performed on 3 random samples and average thickness for each sample was measured as 256, 247 and 284 µm with a standard deviation of 43, 55 and 28 respectively.

The oxide content was calculated according to Eq. 1, by using equivalent sphere diameter of the samples and the calculation shows lower oxide volume than the real, since the sphere will have less surface area than any irregular shape.

$$\text{oxide content in } \% = \frac{m_{oxide}}{m_{oxide} + m_{metal}} * 100 \qquad (1)$$

where,

$$m_{metal} = \rho_{Al-oxide} * 4/3\pi (r_{material} - oxide\ thickness)^3$$

$$m_{oxide} = \left(\rho_{Al-oxide} * 4/3\pi r^3_{material}\right) - m_{metal}$$

A minimum of 8 wt% oxide is present in the samples which can increase up to 15 wt%, based on the measured oxide thickness layer in different samples. Hu et al. reported up to 9 wt% oxide loss after incineration of can bodies at 910 °C for 60 min which is comparable with the calculations in the current work [12].

Yield Results

The remelting results were evaluated by coalescence efficiency (CE) and material yield aspects. The calculations were done by using Eqs. 2 and 3. A single 0.64 g molten aluminium piece that solidifies in spherical form will have a diameter less than 7 mm. Therefore, metal droplets over 7 mm were taken as coagulated droplets in Eq. 1.

Table 2 Experimental matrix

Exp #	Salt/scrap wt ratio	Number of charges	Scrap (g)
1	2	5	50
2	2	5	50
3	2	5	50
4	1	7	100
5	1	7	100
6	1	7	100
7	1	1	100
8	1	1	100
9	1	1	100

In all experiments, approximately 100 g salt was used in total

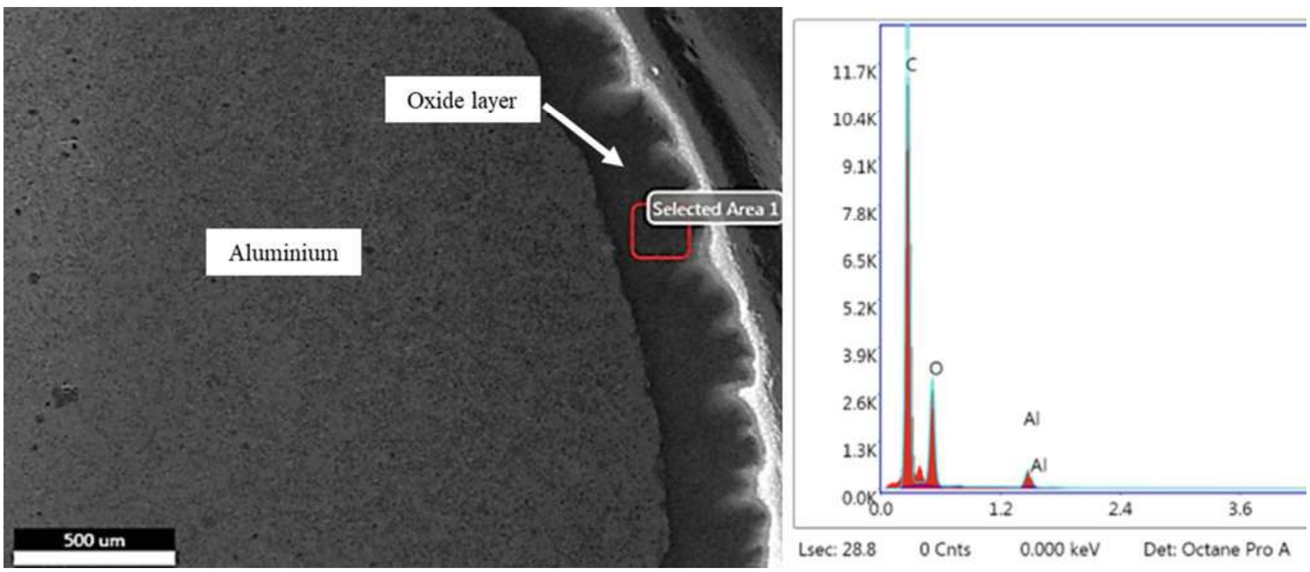

Fig. 3 SEM picture of an edge of the aluminium after incineration and EDS analysis of the oxide layer

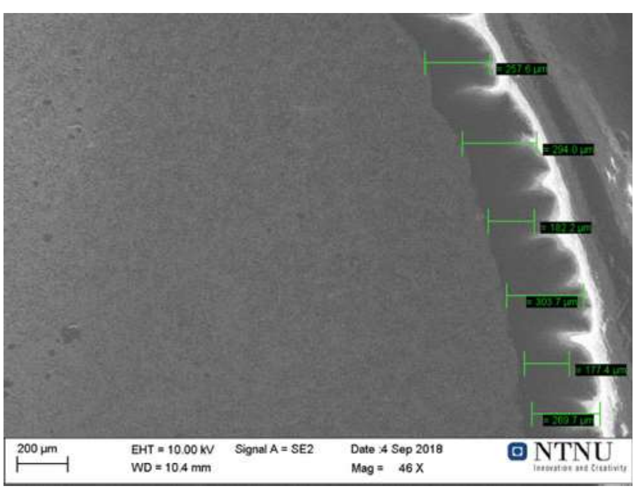

Fig. 4 SEM pictures showing the oxide thickness of aluminium pieces from the bottom ash

$$\mathrm{CE} = \frac{m_{>7mm}}{m_{total}} * 100 \quad (2)$$

where $m_{>7mm}$ is the weight of particles that has a diameter larger than 7 mm and m_{total} is the total amount of recovered metal.

$$\text{Material Yield} = \frac{m_{total}}{m_{input\ material}} * 100 \quad (3)$$

Here, $m_{input\ material}$ is the total charged scrap for recycling.

The results of yield experiments are shown Fig. 5. The coalescence efficiency results vary between 94.19 and 99.44 with a standard deviation of 1.89. The material yield (i.e. the metal) was calculated to between 83.6 and 91.8%, with a standard deviation of 2.6. The yield results correspond very well with the measured oxide content, indicating that essentially all metallic content is recovered during the remelting process. Similar material yield was obtained by different researchers: Hu et al. reported a yield ranging between 77 and 93 wt% for incinerated waste (household waste in Netherlands) with different packaging types (thin foils, foil containers and beverage cans) in a +2 mm fraction [12]. Biganzoli et al. reported remelting yield in the range of 76–87 wt% for +5 mm fraction (household waste in Italy) [13].

As it is seen in Fig. 5, trial 1 shows a very high CE with 99.4% and trial 8 a lower CE with 94.3%. Figure 6 shows coagulated and non-coagulated solidified droplets of these trials. Many small non-coagulated droplets can be observed in trial 8 which resulted in a lower CE.

Remelted metal composition:

The recycled metal from the bottom ash was analysed by ICP-MS after 6 different batches recycled under salt flux. The results are shown in Table 3. A high variation of results is observed in all elements which is expected in household waste where a monotype waste product is impossible to obtain.

Discussion

In the current laboratory investigation, the effect of salt/scrap ratio was negligible to coagulation and material yield, in agreement with Capuzzi et al. [14]. However, the salt/metal ratios in the current study are not representative of those used in industrial scale and hence, the critical point for salt/scrap interface coverage/contact was not reached. Both ratios used in the current study are high in comparison with the industrial practice due to lack of stirring during the procedure in contrast to the rotary furnaces to promote salt-oxide contact and associated high CE/material yield.

The charging procedure did not make a noticeable difference to the CE results. The coalescence efficiency was measured to, on average, 97, 98 and 97% for the sets 1, 2 and 3 respectively. Charging in batch rather than in gradual amounts did not reduce the interactions between the surface area of oxide and the salt mixture, thus the CE remained high.

The oxide layer thickness seems to be a more important effect among the parameters, as reflected in the deviation

Fig. 6 Coagulated and non-coagulated droplets after recycling (Trial 1 and 8)

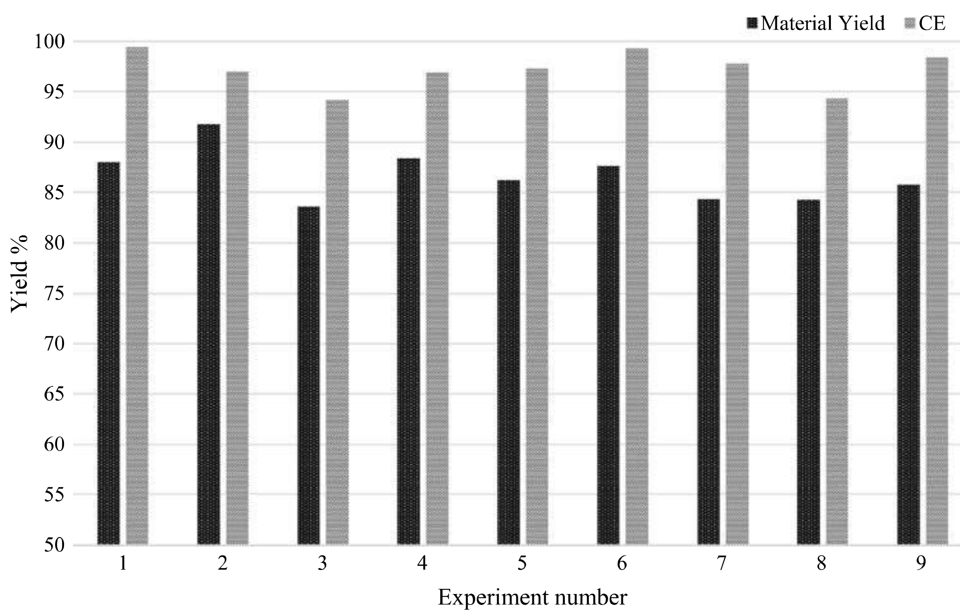

Fig. 5 Summary of material yield and coalescence efficiency results

Table 3 Elemental composition of recycled aluminium

	wt%	St. dev		ppm	St. dev		ppm	St. dev
Al	97	3	Ni	160.50	150.1	Y	0.53	0.2
Fe	0.423	0.10	Cr	168.08	50.6	Ti	0.24	0.02
Mn	0.318	0.06	Pb	248.49	256.1	U	0.81	0.10
Cu	0.308	0.07	Sn	70.71	57.3	Na	0.81	6.37
Zn	0.248	0.14	S	34.37	8.4	Ge	0.23	0.04
			Cd	5.16	9.1	As	0.29	0.08
			Sb	4.00	2.5	Ba	0.03	0.03
			Cd	5.16	9.1	Hg	<0.002	
			Mo	2.94	0.3	K	<1	
			W	1.33	0.7			

between material yield results. Material yield results show losses between 8.22 and 16.41 wt%, which correspond to the measured/calculated oxide contents of the initial metal pieces.

While the remelting appears reasonably unproblematic with high yields, the resulting metal contains alloying elements such as Cu, Zn in quite high concentrations, making direct use of the metal in wrought alloys problematic. In addition, elements like Pb and Cd are especially critical for food containers or packaging. The Fe content is also limiting for wrought alloys since removal of Fe is not possible in current industrial refining procedures. However, the remelted metal can be a source for select cast alloys, such as 200 or 300 series alloys. The standard maximum concentration for minor elements is 500 ppm and the measured level of Pb in the current material can be a potential difficulty, as long as no dilution is applied, since one of the six batches showed Pb slightly over the concentration limit.

This work focused on the melt purity and recyclability of the aluminium fraction from the bottom ash but the cleanliness, in terms of non-metallic inclusions and hydrogen content, was not investigated.

Conclusions

The aluminium fraction of the bottom ash from incinerated Scandinavian household waste was investigated for recyclability in terms of material yield and output composition, varying salt/metal ratio and charging procedure. The results were correlated to the determined initial oxide content of the material. Results of the study may be summarised as:

- The oxide content of the aluminium fraction ranged between 8 and 15 wt% based on the measured oxide thickness layer in different samples. The material yield as metal showed similar variations (approx. 84–92%) in different tests, seemingly corresponding to the variation in oxide content of the input scrap.
- The high oxide content of the material requires the use of salt in remelting to break the thick oxide layer and coalesce the metal.
- The metal remelted under salt showed a good coalescence behaviour up to 99% without any external stirring. The porous structure of the initial material (density: 0.918 g/cm^3) might have promoted the salt-oxide interaction and resulted in a good coalescence behaviour.
- The elemental composition of the remelted metal indicate content of a wide range of elements which may prohibit the use of this material in wrought alloys. However, the recycled material can be used for select cast alloys in more or less diluted form. However, the level of Pb and Cd in the cast alloy needs verification in order to stay within acceptable and legal limits.

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