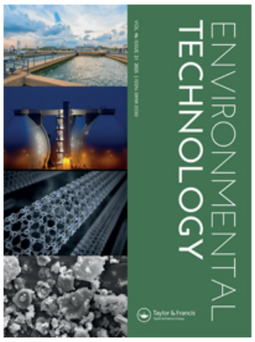

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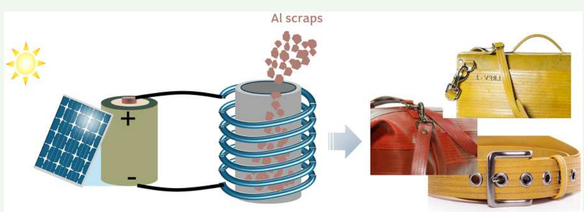
Low cost small scale recycling aluminium cans for energy conservation and environmental sustainability

Man Zhang [a,b], Keren Zhou[c], Theo Saunders[a], Gang Wang[d], Kresse Wesling[e], Jianguo Liu[c], James Busfield[a], Emiliano Bilotti[a] and Haixue Yan[a]

[a]School of Engineering and Materials Science, Queen Mary University of London, London, UK; [b]School of Mechanical Engineering, University of Leeds, Leeds, UK; [c]School of Environment, Tsinghua University, Beijing, People's Republic of China; [d]State Key Laboratory of Advanced Refractories, Sinosteel Luoyang Institute of refractories Research Co. Ltd, Luoyang, People's Republic of China; [e]Eako Ltd, Kent, UK

ABSTRACT
A smart, low-cost small-scale aluminium (Al) beverage cans recycling technology is needed to solve the problem of abandoned cans around the world. In this research, a small-scale Al recycling system which is clean, safe, sustainable, easy to use and low cost, has been developed. It uses natural solar energy as the power source, a smart induction furnace to quickly melt the Al cans and two filters to purify the generated gas during the melting. High value-added products can be obtained by direct casting. Life cycle assessment (LCA) is used to evaluate the environmental performance of the newly developed system compared with the traditional Al recycling technology. Results have shown that the low-cost small-scale Al recycling technology performs better in environmental categories such as climate change, ozone depletion and eutrophication, while the traditional recycling method shows advantage in acidification, eutrophication (terrestrial), and eutrophication (marine). This low cost small-scale Al recycling system is easy to duplicate and to operate. It is a promising sustainable technology to support the large-scale recycling technology by low cost and easy processing, engaging and empowering more people in communities, households and small enterprises, in undeveloped areas.



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Aluminium recycling; low-cost small scale; life cycle assessment; solar energy; high value-added products

1. Introduction

Aluminium (Al) recycling is becoming increasingly important as it offers environmental and economic benefits for reduced emission and waste disposal, resource regenerating and energy savings [1–5]. Currently, 30% of the aluminium produced worldwide now comes from secondary sources which are based on the recycling of Al scrap metals [6]. There are well developed high efficiency technologies in secondary Al industry for Al recycling with the goal of improving manufacturing ability and process materials closer to the desired end-products [2]. Such large-scale Al recycling factories have large capacity (2–120 Mt) [7] and diverse raw materials sources, including components from buildings, automobiles and beverage cans. The energy efficiency of large-scale Al recycling furnace is between 15 and 90% depending on the type of furnaces being used [8,9]. However, large-scale Al recycling factories need large capital investment and the Al scraps are recycled by downgrading and dilution due to difficulties in refining [9]. This technology cannot cover regions that are not well developed and cannot create job opportunities for less educated people due to the complexity in operation. A new technology that is low cost, easy to duplicate and easy to use is needed urgently.

Al beverage cans account for around 10% of total aluminium consumption by end-use [10]. Consumption of soda and beer in aluminium cans reaches 1.8×10^{12}

CONTACT Man Zhang sjumzhan@leeds.ac.uk School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, UK; School of Mechanical Engineering, University of Leeds. Woodhouse Lane, Leeds, LS2 9JT, UK
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cans every year [11]. While the recycling rate of Al cans in Germany is 99% in 2019, that in Cyprus is less than 30% due to limited Al recycling factories [12]. The beverage cans that are not recycled go to landfill. The negative impacts of this litter include: total loss of material value, financial burden on local councils, and the annual death of approximately 3 million small mammals [13]. These negative impacts are obviously in striking contrast with the intention and commitments of the United Nations Climate Change Conference (COP27) [14,15]. The environmental problems caused by littered cans, which are difficult to recycle by large-scale technology, is pushing the aluminium industry to be in a position to continue its growth while optimising its environmental performance. A new technology that can be used by undeveloped areas and can work as a supplementary method in developed areas for large-scale recycling factory is needed to solve the problem of 'abandoned' aluminium.

In this paper, a simple technology is developed to recycle littered Al cans with low cost in small scale based on sustainable clean energy. Life cycle assessment (LCA) [16] is conducted on both traditional large-scale Al recycling technology and the new developed sustainable small-scale Al recycling technology to evaluate the environmental influences. The results indicate that our developed low-cost small-scale recycling technology is a good additional method to recycle materials in terms of reducing CO_2, waste disposal, regenerating resource and energy saving.

2. The low-cost and small-scale recycling process

The aim of this research is to build a sustainable, simple and safe system that can be used by a normal household, community or a small-scale enterprise to convert littered Al cans into high value-added products. Figure 1 illustrates the overall picture of the small-scale Al recycling system. The energy used to pre-treat and melt the Al scraps is sourced from solar energy. Photovoltaic panels were used to harvest solar energy which was converted into electricity and stored in rechargeable batteries. The generated electricity was used to drive an induction furnace to quickly melt the Al scrap to save staff time and minimise oxidation. The Al melt was directly cast into different ingots, including high-valued fashion products with different shapes, such as belt buckles, jewellery and decorations (Figure 1(b)). Moreover, the electricity within the batteries was also used for alternative daily household consumptions which makes this system multi-functional.

The recycling process of the small-scale technology include: (1) energy collection; (2) Al can collection: (3) pre-processing; (4) melting and (5) casting. Each of the processes will be explained below.

(1) Energy collection. More than 99% of the energy used in this system is from solar energy which is captured by four solar panels and then converted into electricity. The output voltage and energy power of each solar panels are: 12 V and 100 W. The generated DC electricity was stored in car batteries with max. voltage of 12 V (a low voltage was used to enhance safety) and capacity of 80 Ah. Theoretically, it takes 0.8 days (assuming an average daylight time of 12 h) to fully charge four car batteries using four solar panels that are connected in series. Work efficiency of the solar panels varies depending on the seasons and geographical location. The solar irradiation incident in London in July is 4.74 kW/h/m^2/day which is 7 times higher than an equivalent day in January. However, in cities nearer the equator, such as Cairo, the solar irradiation incident in July was 7.88 and 3.19 kW/h/m^2/day in January

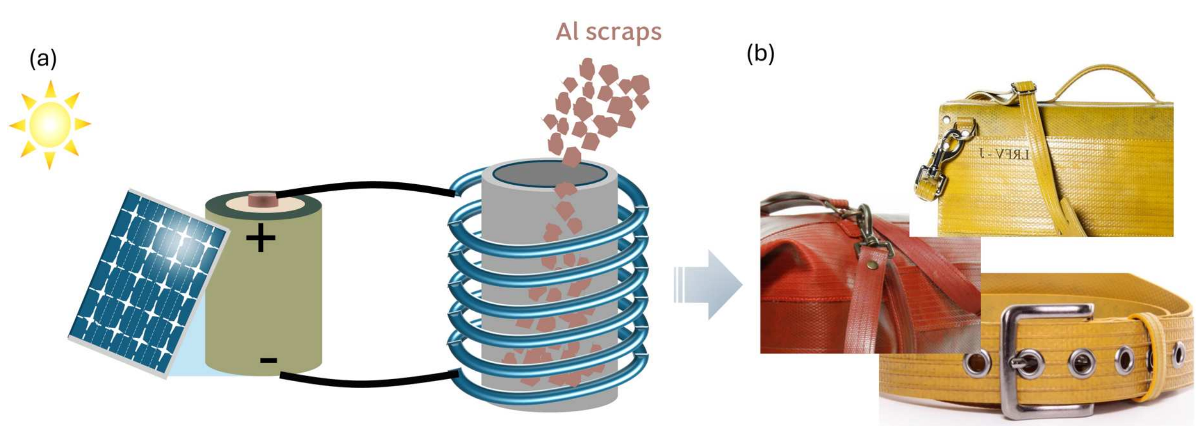

Figure 1. (a) Illustration of the small-scale recycling of Al beverages cans system; (b) hardware made by recycled Al cans in fashion products.

[17]. This means the system works better in sunny regions of the world. It is worth noting that the electricity within the car batteries can be used for other purpose, including lighting, heating, cooking or pumping water.

(2) Al can collection. As this small-scale Al can recycling system is designed for use by the general public, the sources of Al cans are diversified. The Al cans could come from daily household consumption, recycling bin or street. Figure S1 shows an advertisement encouraging the community to donate Al cans in Kent, UK. Compared with conventional large-scale recycling, the composition of the raw material is relatively fixed, which helps avoid downgrade recycling.

(3) Pre-process. This step involves shredding, cleaning and drying. The Al cans are shredded into scraps using a shredder. The scraps are washed manually (or use ultrasonic cleaner depending on the degree of contamination) using recycled water and then dried under natural sunlight within 1 h.

(4) Melting. The heart of the small-scale recycling system is an induction furnace, the illustration of which is shown in Figure 2. An image of the real setup is shown in Figure S2. The core unit of the system is the melting and casting part, which is depicted as Figure 2(a). The melting system mainly consists of a sealed chamber, with details shown in Figure S3. The Al scraps which are fed into the graphite crucible are heated to melt by copper coils outside of a sealed glass chamber. The sealed chamber can effectively avoid direct contact of melt metal liquid with the operator and reduce the oxidation of Al during the melting process. To protect the induction furnace, both water cooling and air cooling are used in the system. The water is circulating and after passing through the copper coil it returns to the water tank. The capacity of the graphite crucible is 50 g Al scraps (~5 Al beverage cans with volume of 330 ml each) and it takes about 12 min to melt the Al scraps. This setup is designed to be safe and easy to operate.

(5) Casting. Sand casting is used to demonstrate a simple method of metal casting. The sand-casting kit with a specific pattern is placed in the safety box which has a protective front wall and two filters on both sides to purify the pollutant gas, which comes from the polymer coating layer of Al cans, generated during melting and casting of Al. Casting can be finished easily by lifting the stainless steel rod on the top of the lid. During operation, the lid of the casting chamber should be closely sealed to avoid the leakage of harmful gases and possible direct contact with high-temperature molten liquid. Moreover, enough time should be left to allow the casted ingot to cool down after casting. The detailed working mechanism and assembly process is shown in the supporting information, from Figures S3 to S14. The final cast products are diverse, with geometric features depending upon the pattern being used.

3. LCA research methodology

3.1. Goal and scope definition

To evaluate the effect of this recycling process on human wellbeing and the natural environmental, life cycle

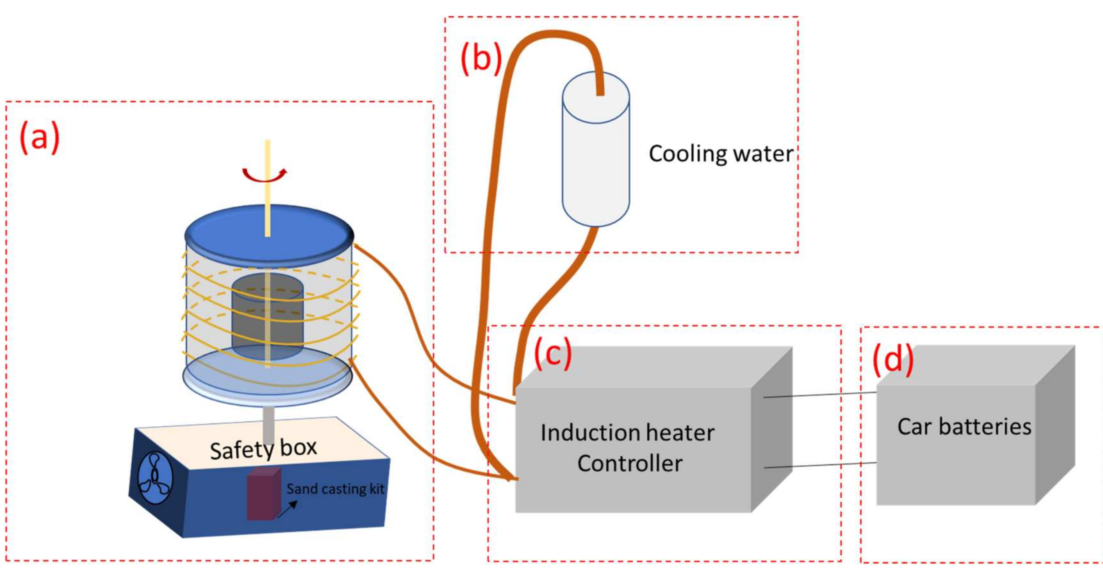

Figure 2. Illustration of the induction furnace. (a) melting and casting system; (b) cooling system; (c) induction heater controller; (d) re-chargeable car batteries.

assessment (LCA) was used to evaluate the environmental impacts throughout the entire chain of the recycling process. A comparison between the herein proposed small-scale recycling and traditional large-scale recycling was carried out. In this study we defined a function unit as the mass of Al can scrap that can be melted using the small-scale Al recycling machine at a time, which is 50 g Al. We focused on the small-scale low-cost recycling machine so the process of can production and manufacturing were not considered.

The process of small-scale recycling: Materials used in assembling the machine and the energy system are calculated as the main input. While during the operating procedure, no artificial energy but solar energy and cooling water are utilised. The main output is cast Al products which can substitute original Al.

The process of large-scale recycling: 70% of the Al is recycled through remelting, while the remaining 30% residue is disposed by landfill. The materials and energy consumed are considered as input. The main output is cast Al products which can substitute original Al.

Figure 3 illustrates the boundaries defined for both systems. \ Machine construction, energy system construction, energy consumption and the product substitution are included in the system boundaries for the small-scale recycling process as presented in Figure 3(a). The traditional large-scale Al recycling of aluminium beverage cans is chosen for comparison (Figure 3(b)).

3.2. Inventories and database

The material consumption by machine and energy system construction, the energy consumption, substitute products and traditional treatment methods are listed in Table S1 for the life cycle inventory calculation. Different parts of the machine are calculated by their raw materials. Most parts of the machine are estimated to be used repeatedly more than 1000 times, while the graphite crucible should be substituted after 20 uses.

The environmental life cycle assessment method used in this study was developed by the International Reference Life Cycle Data System (ILCD2014). The ILCD is developed by JRC and DG ENV, providing guidance and data network for greater consistency and quality assurance in applying LCA. Characterisation factors considered include climate change (global warming), terrestrial acidification, eutrophication (terrestrial, fresh water, marine), photochemical ozone formation, ozone depletion, ecotoxicity (freshwater), human toxicity (cancer effects and non-cancer effects) and ionising radiation. The LCA data of material and energy consumption were selected from Ecoinvent database version 3.8, as indicated in Table S2.

4. LCA results and discussions

The LCA results of using our small forge machine to recycle Al beverage cans were summarised in Figure 4. Among all the component parts of the forge machine, car batteries are the main negative factor to the environmental impact. The production of aluminium ingots by using the small-scale recycling technology is the main positive factor contributing to environmental impact. Under the influence of aluminium production and substitution for primary aluminium, 0.509 kg CO_2-eq per function unit can be reduced. Although the construction of the machine brings a lot of greenhouse gas (GHG) emission, disposing 50 g can fragments using the new technology still results in a 0.315 kg CO_2-eq GHG reduction. The recycling of Al can through the new technology also reduces 3.74×10^{-8} kg CFC-eq ozone depleting compounds, 1.23×10^{-4} kg P-eq, 1.41×10^{-4} kg N-eq,

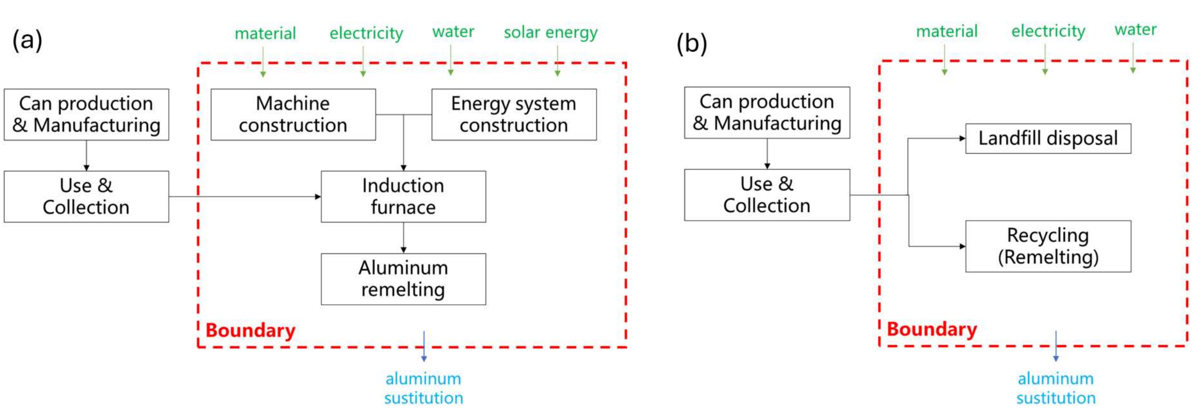

Figure 3. System boundary for Al recycling system. (a) small-scale recycling; (b) traditional large-scale recycling.

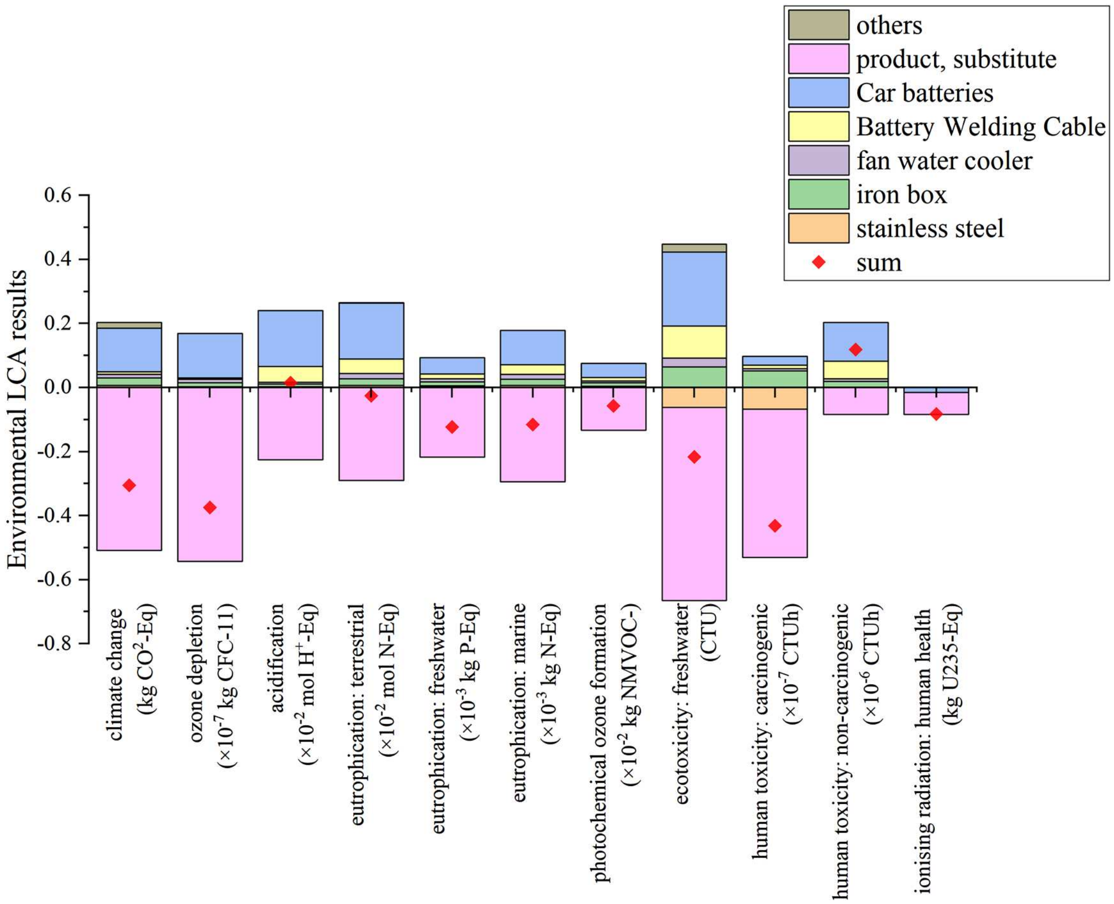

Figure 4. LCIA results of application of the small-scale recycling technology.

4.32×10^{-4} kg NMVOC and 8.28×10^{-2} kg U235-eq ionising radiation. In the acidification category, the small-scale recycling brings 1.47×10^{-4} mol H^+-eq acid gas emission due to the production of the machine. In the toxicity category, various pollutants have different emission characteristics. Carcinogenic compounds are reduced and non-carcinogenic compounds increase through the small-scale recycling.

A comparison between the small-scale technology and traditional large-scale recycling process is shown in Figure 5. The current recycling rate of Al beverage cans is about 70% [9]. The traditional treatment of cans includes 70% recycling and 30% landfill. The low-cost small-scale Al recycling system performs better in impact categories such as climate change, ozone depletion, eutrophication: fresh water, human toxicity: carcinogenic and ionising radiation. The small-scale machine can increase 11.6% GHG reduction compared with traditional recycling. While traditional large-scale treatment performs better in acidification, eutrophication: terrestrial and eutrophication: marine. The results can be influenced by the number of times that the small-scale machine can be used and the recycling rate using the traditional pathway.

5. Casting by small-scale recycling technology

The recycled Al beverage cans are melted by the induction furnace and made into high valued-added products by sand casting. The castability of the liquid Al and the mechanical properties of the casted ingots are largely related to the composition of the raw materials. In regard to the Al beverage cans, the composition of the lid and the base/sides of the cans are different due to their special requirements for mechanical properties. Table 1 shows the compositions of aluminium beverage can alloys [18]. Al products have a wide range of coatings, such as paints, lacquers and inks to improve

Table 1. Compositions of aluminium beverage can alloys.

		Weight of elements%		
	Alloy	Al	Mn	Mg
Lid	5182	95.2	0.35	4.5
Sides and base	3004	97.8	1.2	1.0

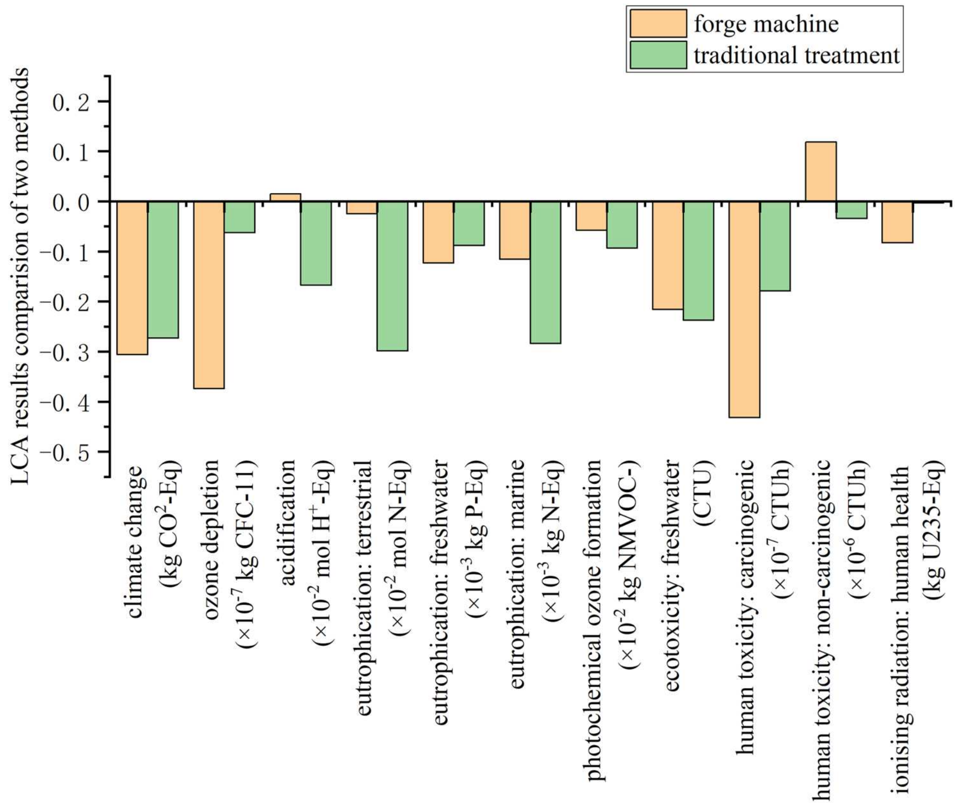

Figure 5. Comparison of the small-scale recycling system and traditional large-scale Al recycling system.

corrosion resistance and appearance. Different elements (such as Cr, Co, Pb, Mg, etc.), plastic and oil might exist in the coating layer. At high temperature, the burning of the coating layer will generate pollutant gas and the residue after burning will remain in the liquid Al, which will influence the mechanical property of the final product [9].

In order to improve the recovery of aluminium and reduce the chemical impurities within the liquid Al, salt flux with a composition of 47.5 mol% NaCl, 47.5 mol% KCl and 5 wt% NaF was added into liquid Al [19]. It is the oxidation of metals at high temperature that generates this large amount of dross. The molten chlorides and fluorides can break the oxide links and accelerate the wettability with oxides and inclusions, subsequently liberating the pure Al [20]. The influence of the percentage of flux on the amount of Al recovered from dross is studied, as is shown in Figure 6. When the flux is added at a low level, e.g. 1 and 3 wt%, large Al particles can be found in the dross. When the amount of flux added into liquid Al is increased then the residual Al particles are reduced, and the particles become smaller. Moreover, a maximum of 70% Al be recycled when 5 wt% of salt flux is used. Thus, 5 wt% of salt flux is chosen as the optimum value.

Standard samples for the tensile test measurement are prepared by sand casting. Three Al beverage cans are shredded into scraps and melted at 790°C before casting. The microstructure of the as-casted sample is observed by using an Optical microscope (Olympus BX60). Prior to the observation of microstructure, the sample was ground and polished. The polished sample was etched by acids (50 ml H_2O + 2.5 mlHNO3 + 4 mlHCl + 1 mlHF) for 4mins. As is shown in Figure 7(a), the sample does not show any traces of dendrites, indicating an appreciating cooling rate during casting. However, as indicated by red circles in Figure 7(a), the black particles might doss impurities, which could potentially reduce mechanical properties of the casted ingots. The tensile test measurement was carried out by using a Instron tester (Instron 5900R84). The fracture strength of the sample is 140 MPa, which is lower than typical Al 3004 alloy with a fracture strength of 180–240 MPa [21]. The reduction in fracture strength in this research might be related to the doss impurities which can be the origin of cracks when the sample is subjected to external force. Despite the reduction in fracture strength, the casted samples are strong enough in low load-bearing applications, such as D-rings and buckles, the requirement for stress is normally between 10–

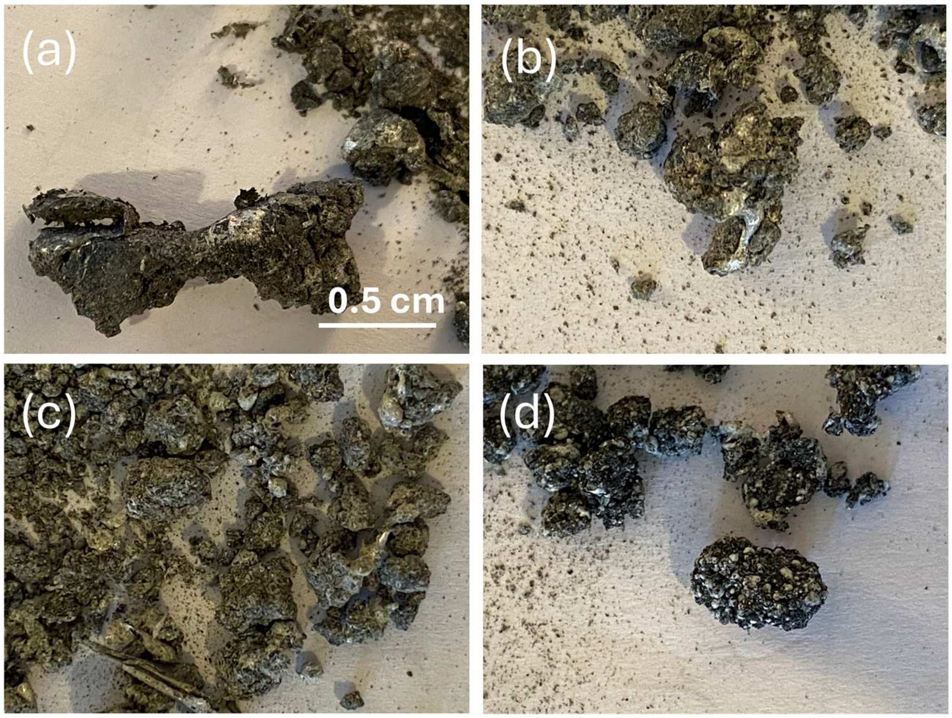

Figure 6. Photo image of dross with the addition of different amount of flux. (a) 1 wt%; (b) 3 wt%; (c) 5 wt%; (d) 8 wt%.

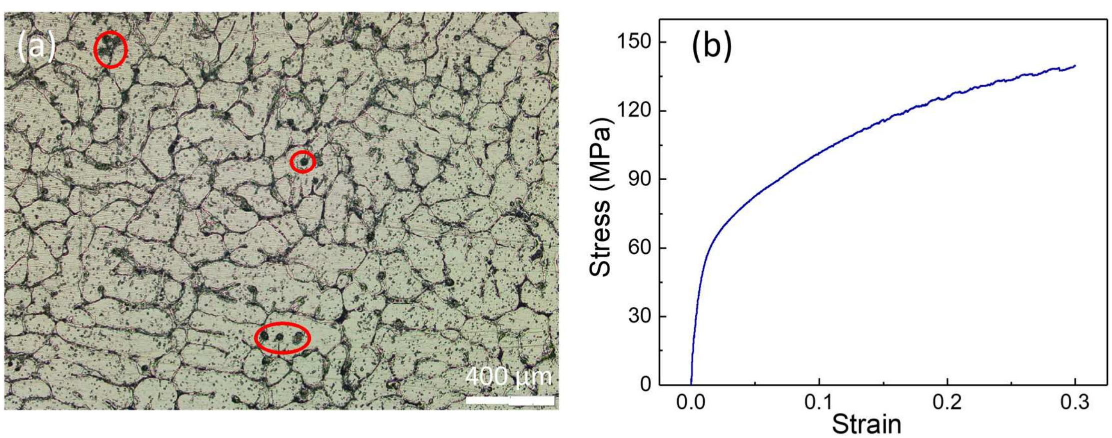

Figure 7. (a) Optical microstructure of casted Al ingot (200X); (b) a typical stress – strain curve of the cast Al sample at room temperature. The red circles in *a* highlight impurity.

50 MPa. Examples of the casted products are shown in Figure S15.

5. Conclusions

A novel, sustainable, small-scale Al recycling system has been developed to recycle abandoned Al cans. The system is run on solar energy and is low cost and easy to operate. LCA results demonstrate that this system shows advantages in environmental aspects including climate change, ozone depletion and eutrophication, compared with the traditional large-scale Al recycling method. Moreover, the work is designed to have an impact to involve more people around the world in Al recycling and convert environmentally unfriendly litter into different products including high value-added products. This small-scale technology also provides an additional recycling method in underdeveloped areas where the large-scale recycling technology is normally not available.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

All data generated or analysed during this study are included in this published article.

ORCID

Man Zhang http://orcid.org/0000-0002-1094-7279

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