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CAST SHOP FOR ALUMINUM PRODUCTION

Recycling/Cast Shop

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LIFE CYCLE ASSESSMENT OF SECONDARY ALUMINIUM REFINING

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Abstract

This paper presents a life cycle assessment (LCA) of various technologies for refining of post-consumer aluminum scrap. The goal is to identify the environmental performance of relevant refining technologies compared to the production of primary aluminum. The assessment is based on a given scrap composition and given purity limits to meet the technical requirements of a certain aluminum product which is currently produced from primary aluminum. From an environmental perspective low-temperature electrolysis and fractional crystallization are the preferred refining methods. This is due to the low energy use in these methods, and that the environmental impact is mainly caused by the energy used during refining. Since the assessment is based on a specific scrap composition and specific purity requirements, it is suggested that other possibilities to reduce environmental impacts are investigated, for example better sorting processes or production of wrought alloys more suitable for recycling. Such methods are likely to be more relevant when the use of aluminum has increased even further and more stable sources of scrap are established.

Introduction

Aluminum is a very useful material in many areas due to properties like strength and low density. Aluminum is in addition very suitable for recycling both because the properties of the material are not altered when re-melted (EAA, 2004, Kahveci and Unal, 2000) and because recycling of aluminum only uses about 5-10 % of the energy required to produce primary aluminum (Schlesinger, 2007, EAA, 2004). The high energy (13-15 kWh/kg requirement (Petrucci, 2011)) to produce primary aluminum is mainly due to the chemical difficulty of extracting pure aluminum from its oxide form. Because aluminum is very reactive, its oxide form is very stable. Oxidation is a common refining method for metals (Nakajima et al., 2010), but it does not work for aluminum due to aluminum's strong affinity to oxygen. Therefore alternative refining methods must be applied.

There are two main production routes for aluminum products, cast and wrought alloy production. Wrought alloys typically allow fewer impurities and are generally characterized by low content of alloying elements (EAA, 2004). Cast alloys typically allow higher contents of impurities. Due to the low tolerance for impurities, wrought alloys are mainly produced from primary aluminum or new scrap, or in some cases old scrap diluted with primary metal. When wrought alloys are recycled, they are mainly re-used in cast alloys. This is due to the accumulation of alloying elements and tramp elements when a variety of alloys are collected and melted together. The current technology for recycling of aluminum is cascade recycling or downcycling. This means that the collected post-consumer scrap is melted, with some degree of dilution with primary metal, and re-used for products having lower purity demands (Gaustad et al., 2012, Nakajima et al., 2010, Sillekens et al., 2002, Modaresi and Müller, 2012). This is economically preferable since it does not require much sorting of the scrap or any expensive refining process. Cascade recycling does not cause any problems so far, since the availability of post-consumer scrap is currently relatively low (EAA, 2004, Schlesinger, 2007). The availability is low since the lifetime of aluminum products is generally high and much of the extracted aluminum is bound up in products still in use. When recycling aluminum there is currently only a need to re-melt it to re-use it. Hence when it is stated that recycling of aluminum only uses a small fraction of the energy needed for primary production, it is referred to the energy needed to re-melt the aluminum scrap. Since the melting point of aluminum is relatively low, the energy needed to recycle aluminum is very low compared to primary production. The same low energy use may however not be the case if there is a desire to recycle post-consumer scrap back to products demanding high purity aluminum alloys. It is predicted that the use of aluminum will continue to grow fast (EAA, 2004, Kevorkijan, 2002, Schlesinger, 2007), and this implies that the scrap availability will increase in the future. This might imply that the market for downcycled scrap might saturate and excess scrap will be available. This possibility makes it interesting to investigate opportunities to recycle post-consumer scrap back to products demanding higher purity standards than those currently utilizing old aluminum scrap. It is of interest to predict when the low-grade scrap market will saturate and the use of old scraps for other purposes might get economically and environmentally preferable. It is suggested by Modaresi and Müller (2012) that this will occur in the near future, depending on which dilution rate and separation methods are used. EAA (2004) suggest that it will be economically viable to introduce separate collection of wrought alloys from cars in 2013. Rombach (2002) on the other hand suggest that it is only the volume of available scrap that will increase during the nearest decade, and not the share of available scrap compared to the production of scrap containing alloys. He does not however reflect on whether or not this will happen in a more distant future. Kevorkijan (2002) states that due to improved economy the demand for scrap will always exceed the supply. However, he mention the possibility of this changing in the future, stating that there might be a point in the future when the increase in old scrap supplies will be greater than the growth of aluminum demand. The fact that the low-grade market might saturate in an either near or distant future makes it interesting to develop opportunities to recycle post-consumer scrap back to products demanding higher purity standards than those products currently utilizing old aluminum scrap. The work presented in this paper has been structured around three main objectives; 1) Identifying possible refining technologies to remove specific alloying elements present in post-consumer scrap, 2) establish life cycle inventory for the relevant technologies and 3) evaluate the environmental benefit of recycling post-consumer scrap back to

Table 1: Scrap composition and desired level of removal. The scrap composition is given in wt.% Alloys 1-7 represent the alloys that are to be produced from the post-consumer scrap. The desired rate of removal for each element is given in braces.

	Si	Mg	Fe	Cu	Mn	Zn
Scrap composition	6.11	0.53	0.53	1.66	0.23	0.86
Alloy 1	1.05 (83 %)	0.81	0.25 (53 %)	0 (100 %)	0.54	0 (100 %)
Alloy 2	1.98 (68 %)	0.88	0.23 (57 %)	0 (100 %)	0.59	0 (100 %)
Alloy 3	3.73 (39 %)	0.84	0.23 (57 %)	0 (100 %)	0.58	0 (100 %)
Alloy 4	5.51 (10 %)	0.84	0.23 (57 %)	0 (100 %)	0.58	0 (100 %)
Alloy 5	1.03 (83 %)	0.82	0.66	0 (100 %)	0.51	0 (100 %)
Alloy 6	1.02 (83 %)	0.75	0.25 (53 %)	0.91 (45 %)	0.54	0 (100 %)
Alloy 7	1.02 (83 %)	0.79	0.65	0.88 (47 %)	0.5	0 (100 %)

wrought alloys, compared to primary aluminum production, using LCA. The compositions used in this paper are summarized in Table 1. The first row in this table gives the scrap composition used. The scrap composition is based on ELV scrap (End-of-Life-Vehicles) from work by Kirchain and Cosquer (2007). The alloys to be produced from the scrap are presented as alloys 1-7 in Table 1. They are based on a report by Gudbrandsen-Dahl et al. (2013), which suggest various alloys which could be produced using post-consumer ELV scrap. Alloys 1-7 are developed based on the standardized wrought alloy AA6082. Industrial pure aluminum was used as a base for these alloys, and the alloying elements were added in different concentrations and then the alloys were property tested. Large variations for all elements were not tested, and due to this the limits are zero for Zn and Cu for some of the suggested alloys. Thus alloy 1-7 are not produced from scrap, but the idea is that they *could* be produced from ELV scrap.

Life Cycle Assessment (LCA) Methodology

Life cycle assessment is a method used to identify the environmental performance of a product. It considers the entire life cycle of the product, from the extraction through production, use and disposal and/or recycling. Different variants of the methodology exist; for example only selected parts of the life cycle can be investigated. In this paper a cradle-to-gate analysis is carried out. This covers the extraction of the raw material through some processing up to the stage when the product is ready to be used in further production.

There are four phases of an LCA study;

(a) Goal and scope definition
(b) Life cycle inventory (LCI)
(c) Life cycle impact assessment (LCIA)
(d) Interpretation

The first phase consists of defining the goal and scope for the assessment. The goal of the assessment states what it is desirable to accomplish and the scope states within which limits the goal should be achieved. The scope more specifically consists of defining the functional unit for which the LCA is modeled and the system boundaries. The second phase is setting up the inventory for all the processes included within the system boundaries. The inventory consists of mapping and quantifying the inputs (e.g. energy and material consumption) and outputs (e.g. emissions and waste) of all the included processes. The third phase is the impact assessment phase, which comprises converting the inventory into more graspable environmentally relevant information. This information aims to reflect the potential impacts caused by the emissions and resource uses have on the environment. This is often done by assigning the various stressors contributions to different impact categories. A stressor is a broader term for emissions including for example resource depletion and water use. Impact categories are for example Global Warming Potential (GWP) and Human Toxicity Potential (HTP). One stressor can contribute to more than one impact category, and one impact category can be influenced by many stressors. To make results readable and useful the contribution from each stressor to the same impact category are converted to equivalents. For example all contributions to GWP are converted to kg CO_2- equivalents. The last phase is the interpretation, which mainly consists of discussing the results and putting them into context. Interpretation should also be conducted continuously during the LCA. When this is done, the other three phases can be adjusted to fit the specific functional unit and hence enhance the quality of the assessment.

Refining Technologies

The refining technologies identified to be included in this study are based on the scrap composition given in Table 1. A criterion that must be met by the refining methods is that they are able to remove some, or all, of the excess alloying elements present in the post-consumer scrap. It is preferable if the processes are continuous, since this more easily can be up-scaled to industrial use, and continuous processes are generally more efficient. In Table 1 it is seen that excess Si, Fe, Cu and Zn have to be removed to meet the finished alloy criteria.

Iron has detrimental impacts on the strength and ductility of aluminum alloys making it brittle and weak (Zhang et al., 2011, Ashtari et al., 2012, Dewan et al., 2011), and is therefore very important to remove. Unfortunately iron is also the most pervasive impurity element in aluminum alloys. Zhang et al. (2011) discuss methods to neutralize the detrimental effects of Fe, and they conclude that three-layered electrolysis is the most efficient way to remove Fe so far. They also conclude that the three-layered electrolysis is an efficient way to remove Si. Fe and Si are generally the elements requiring most effort to remove. Si can also be removed using fractional crystallization.

Electrolysis

Electrolysis is when an electric current is used to separate molecules by forcing an otherwise non-spontaneous process (Petrucci, 2011). A general positive attribute is that electrolysis can produce very pure aluminum (Schwarz and Wendt, 1995). Other positive aspects are that electrolysis can be applied to any scrap composition, and that there is close to zero metal loss. Negative aspects are that electrolysis in general has high energy use and the potential use of toxic chemicals. In this paper two main types of electrolysis are included. The traditional three-layered electrolysis, called Hoopes process, and the more experimental low temperature electrolysis. Hoopes process has high energy requirement (17-18 kWh/kg (Kamavaram and Reddy, 2003)), and is mainly used on primary aluminum to produce extremely pure aluminum. This process can produce aluminum with a purity of >99.7 % (Gaustad et al., 2012). It is assumed that this energy requirement includes both the energy to maintain the required temperature throughout the process and the actual energy consumed by the process. Schwartz and Wendt (1995) state that this process is able to achieve a purity level comparable to primary aluminum even for scrap with a purity as low as 70 %. Kjos et al., (2011) conducted an experiment to see if the three-layered electrolysis could be adjusted to fit aluminum scrap and possibly reduce the energy requirements if the purity demands of the refined aluminum were lowered. An energy use of 5-8.5 kWh/kg was achieved. Low temperature electrolysis is electrolysis performed in solid state. Kamavaram and Reddy (2003) conducted an experiment which only used 3 kWh/kg and achieved a purity level of 99.89 %.

Fractional crystallization

Fractional crystallization is a segregation method which utilizes the fact that most elements are more soluble in liquid state of a solvent than in solid state of the same solvent. The solvent being aluminum in this context. The basic idea is to melt the metal and to gradually let it solidify causing the tramp elements to accumulate in the liquid fraction. Fractional crystallization was developed mainly to remove Fe and Si from primary aluminum to be able to produce extreme purity alloys (Sillekens et al., 2002). Clear advantages with this method are no use of additional chemicals and that the main energy need occurs when melting the scrap. Some energy might be required to keep the aluminum liquid, so the solidification can be controlled. The main disadvantage with this method is the low production yield and that the process is currently non-continuous (Zhang et al., 2011). The yield issues arise because some amount of aluminum must be left in liquid state, and are thus not part of the desired output of the process which is the purified aluminum. A commonly known version of this technique is the Alcoa fractional crystallization process. Kahveci and Unal (2000) experimented with an extension of Alcoa's technology, so it could be used to process aluminum scrap. The desire was to be able to recycle aluminum scrap back to an alloy similar to the alloy which the scrap originated from. Kahveci and Unal (2000) state that for this method to be economically feasible, high yields of recyclable alloys must be available. With a yield of 50 %, Kahveci and Unal (2000) were able to achieve approximately 85 % removal of Si, 80 % removal of Fe, 50 % removal of Cu and 45 % removal of Zn. Sillekens et al. (2002) state that fractional crystallization is a possible solution to recycle various scrap aluminum on an industrial scale and at the same time limit the energy use. They conducted an experiment on binary systems with a yield of 20 % and where able to remove 87 % of the Si content, 97 % of Fe, 83 % of Cu and 13 % of the Zn. Sillekens et al. (2002) state that the refining performance is not dramatically affected by the initial content of the alloying element, and thus the process can be repeated with a similar purifying effect. Since fractional crystallization apparently does not remove Cu and Zn to the desired level, another refining step has to be included.

Distillation

Distillation is a process where the substance to be purified is held at different temperatures to vaporize elements with a lower boiling point than the solvent. Gaustad et al. (2012) states that distillation holds much promise for removal of tramp elements in scrap metal, since the elements can be re-collected in a high purity state. Zn is the only element with a lower boiling point than aluminum in the context of this paper. Gaustad et al. (2012) mention a study that was able to reduce the Zn content by 97 %. The desired removal of Zn is 100 % according to Table 1, which is very unrealistic; therefore it is assumed that 97 % is satisfying. A negative issue with distillation is the presumably high production of dross due to the high temperature which is required.

Based on this various methods of electrolysis, fractional crystallization and distillation are the refining methods included this study.

System Definition

The system to be assessed in this LCA is a production route for post-consumer aluminum scrap which includes a refining step. The aim is that this production route shall be comparable to the production route of primary aluminum to allow a sensible comparison. A general flow of aluminum through secondary production based on post-consumer scrap can be viewed as follows; first the metal scrap is collected, sorted and shredded. Then the metal is sold to remelters or refiners. Remelters are those who melt and re-use the metal as it is, while refiners apply a refining step to produce a specified alloy composition. It is the refiner's approach which is relevant in this context. At the refiners the molten metal is fed into a holding furnace where the alloy content and concentration is adjusted by either adding desired alloying elements and/or removing excess alloying elements. The general idea for the system defined in this paper s to include the processes which are separate from a corresponding production step in primary production. After the finished alloy exit the foundry it is considered the same whether it is produced from primary metal or refined post-consumer scrap. Hence the use phase can be excluded. Figure 1 illustrates which processes are included within the system boundaries. The arrows illustrate the flow of aluminum between the included processes. The collection process includes sorting and shredding.

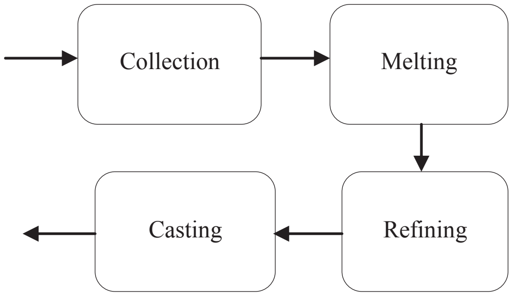

Figure 1: System flowchart

Goal

The goal of this assessment is to investigate refining methods which makes it possible to utilize post-consumer scrap in production of aluminum products that have strict requirements to chemical purity. A further goal is to establish whether applying these methods are environmentally preferable compared to using primary aluminum to produce the same products.

Scope

The functional unit in this study is set to be 1 kg of refined aluminum which meets the purity criteria set in Table 1 for alloy 1-7. The system boundaries are set to include the four processes displayed in Figure 1. The impact categories included are global warming potential, ozone depletion and mineral and fossil depletion.

To do this assessment five different production scenarios have been developed. These scenarios utilize different refining methods to produce 1 kg of aluminum which meet the purity criteria given in Table 1. All scenarios are based on the general flowchart in Figure 1. The scrap is collected, sorted and shredded using a standardized method. The scrap is melted according to the requirements of the applied refining method. The casting is the same for all production scenarios. The assessment does not include addition of alloying elements.

Inventory

The inventory is based on various research papers, some thermodynamic calculations and a series of reasoned assumptions. The inventory is structured into five production scenarios which represent the plausible production routes to meet the requirements of the functional unit. General assumptions are that there is approximately 2% loss during the melting process due to dross formation and the electricity used is based on a European energy production mix.

Scenario 1a: Utilizing Hoopes process to refine the scrap. It is assumed 95 % yield from this refining method.

Scenario 1b: Utilizing the adjusted three-layered method. This is basically the same scenario as scenario 1a, but the energy consumption is highly reduced.

Scenario 2: Utilizing low temperature electrolysis as refining method. This scenario is very similar to both scenario 1a and 1b, but here the energy consumption in the refining step is even more reduced. Since the refining takes place in solid state, the melting stage in Figure 1 is omitted. The same yield, 95 %, is assumed here.

Scenario 3a: Utilizing fractional crystallization together with dilution to be able to meet the purity requirements set in Table 1. A 50 % yield from the fractional crystallization process is assumed here, causing a requirement of more scrap than the previous scenarios to produce 1 kg of refined aluminum. 80 % of primary metal is used to dilute the scrap.

Scenario 3b: This is the same scenario as 3a, but here distillation is utilized instead of dilution to meet the purity criteria given in Table 1.

The primary metal production process used for comparison is taken directly from the ecoinvent database v2.1 from 2009, and is named *Aluminium, primary, at plant/RER U*. This process is based on work done by EAA (European Aluminium Association) with reference year 2000.

Results

Figure 2-4 visualize the results as bars representing the contribution to the included impact categories. Each bar is the total contribution from each production scenario together with a bar which represents primary production. Each bar is divided into zones which represent the contribution from each process included in the scenario. Scenario 1a is omitted from the presented results because it is assumed highly unlikely that this method will be considered as a refining method for scrap when an adjusted method more suitable for scrap is available.

It is very clear from these graphs that the refining step is the main contributor to all impact categories. A further analyze of this reveals that the contribution from the refining step is mainly due to the energy used during refining. Another clear result is that primary production contributes more to all the included impact categories, per kg produced, than all the secondary production scenarios. This indicates that it is interesting to pursue the idea of including a refining step to post-consumer scrap to be able to utilize it in production of products that have high purity requirements.

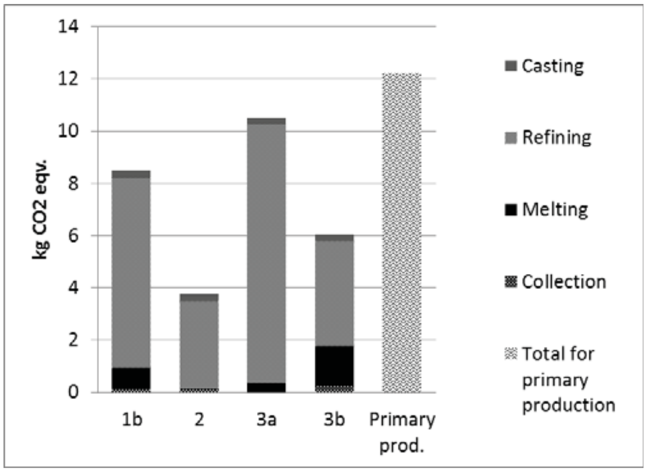

Figure 2: Impacts to global warming potential (GWP) per kg aluminum produced from each scenario.

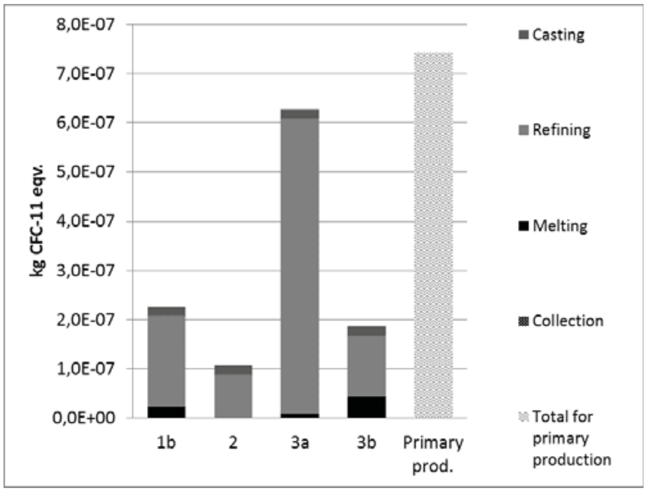

Figure 3: Impacts to ozone depletion potential per kg aluminum produced from each scenario.

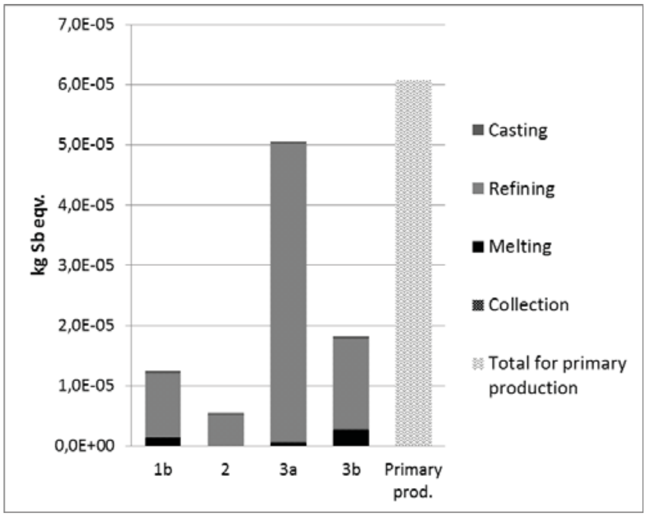

Figure 4: Impacts to mineral and fossil depletion per kg aluminum produced from each scenario.

Discussion

It is clear that the environmental impact assessment prefer the refining methods with the lowest energy use. The specific results of this LCA indicate that the adjusted three-layered electrolysis and low temperature electrolysis are the preferred refining methods. An important note when reading these results is that fractional crystallization is not used as a refining method alone, it is in combination with either dilution with primary metal or distillation which are both very energy demanding. Scenario 3a utilizes 80 % primary metal, and therefore 80 % of the impacts associated to this scenario can be allocated to primary production. Without the need for dilution or distillation, fractional crystallization would be the refining method with the lowest environmental impacts, and thus the preferred refining method from an environmental perspective. It is therefore evident that the specific results from this LCA are of limited relevance as they are based on the limitations introduced in the introduction. It is unlikely that the specific scrap composition used a basis here have to be recycled back to one of the suggested alloys 1-7 in Table 1. Another issue is *when* these refining methods hypothetically would be put in use. If they are not relevant in the nearest future, it can be considered likely that some changes in energy production might have occurred. If the energy production is much cleaner in the future, the energy required during refining might not cause such a large share of the environmental impacts and other issues must be considered. Such issues might be the use of chemicals during electrolysis or yield from the applied refining method.

Despite the disputable relevance of the specific results obtained here, conducting an LCA like this does shed light on some important issues which may be very relevant for the industry of recycled aluminum. The results show a clear relation between the energy requirement of a process and the environmental impacts associated with the same process. It is also evident that an effort to match the scrap composition better to the alloy to be produced from the scrap would be desirable as this would reduce the need for refining steps with a high energy demand. For example recycle a scrap composition with high Si content, as in this case, back to an alloy which allows or require a high Si content. It can be challenging to do this, since this requires the scrap to be sorted properly and large amounts of scrap must be available for this to be economically preferable. From Figure 2-4 it can be read that the collection process (which includes sorting and shredding) is responsible for a very small share of the total environmental impacts associated with each scenario. The collection is actually less than 2 % for all scenarios. This indicates that it might be interesting to invest more energy in this process if this result in energy saved during the refining step. Since this paper want to explore options to reduce the environmental impacts when refining is required, better sorting is a relevant suggestion if the use of aluminum increases rapidly causing more scrap to be available in the future.

Conclusion

The aim of this study was to identify possible solutions for refining of secondary aluminum, and to do an environmental impact assessment of these refining methods. The results show that the main impacts associated with each of the identified refining possibilities are due to the energy use. Therefore one conclusion must be that the refining methods with the lowest energy use are preferred from an environmental perspective. The best alternative would be fractional crystallization without any additional refining step.

An overall impression based on this work is that there might be a large potential in improving the sorting of post-consumer scrap. It was found for all scenarios that this process is only responsible for a very small share of the total impacts to all included impact categories. So an alternative to further improvement is to find a better balance between the sorting step and the refining step of the production route relevant for this paper. A third opportunity to improve the production route is to develop alloys or products which are more suitable for recycling. This can be done by for example broadening the use of existing alloys or possibly merging alloys with similar qualities. This last suggestion will ease recycling by reducing the need for refining by making it more plausible that more scrap can be melted as re-used as it is.

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