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Environmental modelling of aluminium recycling: a Life Cycle Assessment tool for sustainable metal management

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ABSTRACT

The uncontrolled mixing of metals and their alloys during the different life cycle phases, combined with the melt purification constraints during remelting, pose great challenges during their end-of-life (EoL) treatment. In practice, open-loop recycling is typical and more common for metals than closed-loop recycling; especially in the case of aluminium, the industry operates in a cascade recycling approach. Associated with open-loop recycling are various types of material losses; loss of original functional quality, dissipation of scarce resources and the final need for dilution of the resulting metal impurities with primary materials. Thus, an environmental assessment tool is presented within this paper, aiming to support decision making related to the sustainable management of metal resources during secondary aluminium production. A material blending model aims at the minimization of the above mentioned losses in order to meet the product quality requirements. The goal of the study is threefold: i) to assess the environmental impact calculation of aluminium recycling, ii) to express, quantify and integrate dilution and quality losses into Life Cycle Assessment (LCA) studies, and iii) to determine the optimum material input for the recycling process from an environmental perspective. Different recycling options or strategies can be evaluated and compared based on avoided environmental impact. Case studies focusing on major post-consumer scrap streams are used to illustrate application areas and highlight the importance of altering and optimizing the raw material input. Finally, policy issues and opportunities for environmentally conscious metal management are discussed.

1. Introduction

Metals, compared to other materials, have the highest potential for systematic recycling due to: i) their high economic value, ii) the large scrap volumes enabling economies of scale, as well as iii) their distinctive feature of excellent recyclability. Nevertheless, the contamination of the metal streams each time that re-circulates from residuals (alloying and foreign elements), especially those for which the removal from the melt is problematic (cf. Section 2.1), makes processing more difficult.

For Aluminium (Al) more than 450 alloy designations/compositions have been registered by the Aluminium Association Inc. (Davis, 1998). While iron (Fe) mainly occurs as foreign/impurity element (also known as tramp element), typical alloying elements for aluminium are: silicon (Si), copper (Cu), Zinc (Zn), magnesium (Mg) and manganese (Mn). Two major categories can be defined with respect to the concentration of the alloying elements: i) high purity wrought alloys (alloy content up to 10 wt.%) and ii) cast alloys with much higher, especially for Si, tolerance limits (alloy content up to 20 wt.%). Due to the mixture and/or accumulation of the alloying elements during the different life cycle stages, these elements can no longer be considered as valuable elements, but rather as contaminants (Nakajima et al., 2011).

Environmental considerations need to be integrated with many types of decisions. Ferretti et al. (2007) examined the aluminium supply chain, proposing a model to determine the supply mix, i.e. molten and solid alloy, incorporating both economic and environmental aspects. LCA is widely used in the aluminium industry (Rebitzer and Buxmann, 2005; Tan and Khoo, 2005; Liu and Müller, 2012) and provides a comprehensive methodology (ISO, 2006) that can be a valuable tool to identify the environmental burdens and benefits, of altering the raw materials (primary and waste material) in the recycling process from a holistic perspective. Major bottleneck in standard LCA is that quality degradation of metals during recycling cannot be properly described and quantified (Amini et al., 2007). Conventional LCA studies ignore the down-cycling aspect and account the metal inputs and the produced secondary metals as equivalent in terms of quality, assuming that they are recycled

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Nomenclature

sc, Al, e Index for scrap, primary Al and alloying elements material batches respectively
M_{sc}, M_{Al}, M_e Available batch masses
m_{sc}, m_{Al}, m_e Selected mass from each batch in the pre-melt mixture
$\overline{e}_e$, $\overline{e}_{sc}$, $\overline{e}_{Al}$ Mean or expected mass fraction values of alloying element *e* in each batch
M_p Desired mass of the produced target alloy p
e_p^{max}, e_p^{min} Max. and Min. mass fraction tolerance limits of the target alloy *p* for element e
SL, ML % scrap lost (SL) during collection, separation and processing (cleaning, pressing etc.) phase and % melting losses (ML)
I_e, I_{Al} I_{sc}, I_{pr} Single point environmental impact per tonne of: alloying element e production (I_e), primary aluminium production (I_{Al}), scrap collection, sorting and preparation phase (I_{sc}). I_{pr} is the impact of the recycling process per mass of produced alloy excluding material inputs. (cf. Table A.1)

within closed alloy loops. However, instead of closed alloy loops most of the aluminium scrap is recycled in open loop cycles, where we cannot justify complete substitution of primary aluminium and alloying elements, since the inherent properties (chemical composition) of the metal input alter. Interrelationships between inherent properties and recycling maps for metal are provided in the work of Dubreuil et al. (2010). Thus, besides the amount of the metal input, also its composition must be taken into account in the environmental impact assessment of the recycling phase.

Comprehensive reviews (Reuter et al., 2005; Gleich et al., 2006) discuss central issues related to the sustainable material use, recycling technologies and policies as well as the limits of metal recycling determined by thermodynamics, economics and process technology. One of the most critical and challenging steps in metal recycling operations is the logistic of material clustering based on the residuals concentration (Yellishetty et al., 2011). Johansson and Luttropp (2009), introduced the concept of Material Hygiene (MH). The definition of MH is 'to act, in every step of the product lifecycle, towards greater amounts and increased purity of useful material from recycling, possible to use on the same quality level as before or degraded as little as possible'. In line with the MH concept, this study presents a decision support tool for the sustainable metal utilization during the metallurgical recycling phase, aiming at the minimization of material down-cycling and maximization of the scrap usage.

2. Aluminium recycling and its challenges

2.1. Melt refining and metallurgical limitations

Recent studies based on thermodynamic analysis (Nakajima et al., 2011, 2012) indicate which elements can be removed and in how far impurity can be controlled during metallurgical *recycling* of various base metals, such as, aluminium, steel, copper and magnesium. These studies indicate that melt purification options are much more limited for aluminium compared to other base metals, like copper and steel. In particular, Nakajima et al. (2012) examined the removability of 45 elements (most of them occur as tramp elements) for the case of aluminium simulating the remelting process under varying oxygen partial pressure and temperature conditions. Among the examined elements, only six can be removed either by evaporation in the gas phase or through the oxidation mechanism in the slag phase. Regarding the contamination by the typical alloying elements of Al, only Mg and Zn can be removed to an appreciable extent during remelting. Consequently, the residual elements remain in the metal phase during remelting and the purification of the melt from them is either technically very difficult or essentially impossible to achieve. Moreover, while a post electrolysis process can recover most of the elements that remain in the metal phase for copper, this is not the case for aluminium. Compared to the primary production of aluminium, consuming approximately 14 kWh/kg, the three layer electrolytic process for aluminium refining is more energy intensive with energy consumption between 17 and 18 kWh/kg (Gaustad et al., 2012).

Fluxing is the most common and widely used melt purification treatment in the industry. In an experimental study, nearly half of the magnesium content was removed from the Al scrap after remelting with a salt flux treatment (Mashhadi et al., 2009). Furthermore, a flotation/de-gassing melt treatment, purging gases containing chemical reactive components such as chlorine gas, can also be an effective solution in removing Mg apart from hydrogen, Na, Ca and Li (Reuter et al., 2005). Zinc, a major alloying element in the 7XXX alloy series, can be recovered using distillation technologies (Ohtaki et al., 2000). Finally, other technologically advanced melt/chemical separation technologies, like fractional crystallization and unidirectional solidification are still in a research or early development stage (Gaustad et al., 2012). Therefore, from technical and economic point of view, these technologies are still questionable and currently not viable for scrap purification at large scales.

2.2. Quality constraint on subsequent metal uses

Castro et al. (2004), Amini et al. (2007) and Nakamura et al. (2012) highlighted three types of losses during metal recycling: material, quality and dilution losses. Material losses include physical losses during scrap preparation/separating processes (e.g. from shredding) and melting losses such as oxidation losses as well as residues and slag waste that are landfilled. Quality losses occur when the quality (meaning composition) of the produced secondary metal does not match with the input material. Dilution losses occur when high purity metal is required to lower the contaminants (residuals) concentration to the desired limits of the target alloy. Amini et al. (2007) used an Exergetic Life Cycle Assessment approach to quantify these losses for the case of aluminium recycling; while Nakamura et al. (2012) focused on ferrous materials from the End-of-Life Vehicles (ELV).

Quality and dilution losses can result in scrap under-utilization depending on the target alloy. Fig. 1 presents a Sankey diagram that visualizes the above mentioned losses during Al recycling, for the case of producing the 1 tonne of the 380.0 alloy by utilizing old scrap from the 6XXX (except 6061 and 6063) alloy series. The best case scenario of maximum scrap usage and minimum primary resource consumption is presented (example taken from the case studies section). Yet, despite these studies and the extensive Life Cycle Inventory (LCI) for aluminium, compiled from industry-wide generic data (Leroy, 2009; EAA, 2008; IAI, 2007), an environmental assessment tool for the sustainable metal use during recycling that integrates these losses is still missing.

2.3. Open and closed loop aluminium recycling circuits

Nowadays, the refining limitations along with contamination challenges are addressed by the secondary Al industry either by dilution (also called sweetening) of the contaminants with primary