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Downcycling in automobile recycling process: A thermodynamic assessment

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ABSTRACT

Current metal recycling techniques for end-of-life vehicles (ELV) are based on mechanical treatments to mainly recover steel, aluminum, copper, and zinc alloys. Such techniques facilitate compliance with the ELV European Directive (2000/53/EC) target of achieving recyclability quotes of up to 85%. However, a vehicle can use more than 60 metals, some of them considered critical by international institutions, which end up downcycled as part of alloys or ultimately in landfills. This paper undertakes an assessment of the downcycling degree of minor metals in conventional vehicles using a SEAT Leon III model as a case study. Downcycling is assessed from a thermodynamic point of view using thermodynamic rarity, an indicator that is used as a weighting factor for the metals used in the car. The thermodynamic rarity of metals is a function of the quality of the minerals from which they stem, considering their relative abundance in Nature and the energy intensity required to extract and process them. The results demonstrated that, even if the quantity of downcycled metals only represents 4.5% of the total metal weight of the vehicle, in rarity terms, this figure increases to approximately 27%. This indicates that an important portion of high-quality metals becomes functionally lost. The most downcycled vehicle subsystems are in order: (1) accessories, (2) electrical and electronic equipment, (3) exhaust system, and (4) engine. Further, the most downcycled parts are: speed sensor, control unit, antenna amplifier, airbag circuit, temperature and rain sensors, front pipe, particle filter, and turbo parts.

1. Introduction

At present, the vehicle sector generates approximately 5% of the world's industrial waste, either from vehicles or the plants that produce them (Zorpas and Inglezakis, 2012). Each year in Europe, end-of-life vehicles (ELV) generate between 7 and 9 million tonnes of waste (European Commission, 2017a) and hence, the treatment of ELV and the impact of discarding their residues are subjects of worldwide concern (Simic and Dimitrijevic, 2012). As stated by Arda et al. (2017), a stable supply of raw materials is crucial for the transition to a sustainable and circular economy. This becomes even more important considering that, by 2030, up to 1.85 billion vehicles are expected to be added to the current fleet (Simic and Dimitrijevic, 2013), requiring massive amounts of raw materials (Hernandez et al., 2017).

In order to reduce waste originating from ELVs and increase their recyclability, in 2000, the EU enforced the ELV Directive (2000/53/EC). It aims to reduce the waste generated by ELVs and also to protect the environment by promoting the reuse and recycling of ELV components. According to the ELV Directive, from January 1, 2015, recovery requirements should achieve the target of at least 95% (with a maximum energy recovery of 10%) and a minimum of 85% of the total material has to be reusable and recyclable. Consequently, nowadays, a common vehicle has recyclability rates higher than 85% for any equipment version (Millet et al., 2012).

However, the future compliance of these recycling targets is challenged by the changing material composition of cars (Ortego et al., 2017). Examples of the changes in vehicle material composition over time are: the replacement of Fe by Al alloys for parts such as the head cylinder or gearbox case, body-in-white, and wheels (Hatayama et al., 2012; Løvik et al., 2014; Van Schaik et al., 2002); the increased use of plastics for the interior of the car (Juska, 2007); the transition from conventional internal combustion engines to hybrid-electric and fully electric powertrains (Eurostat, 2015); the evolution from manual to automated control of vehicle functions owing to an increased number of car electronics (Restrepo et al., 2016). Current vehicles require more electrical and electronic devices, which demand an increasing amount of different metals such as Li, Co, Mn, Ni, and different rare earths to manufacture batteries (Simon et al., 2015); Nd, Pr, and Dy to build permanent magnets (Riba et al., 2016); Ag, In, Ta, or La to manufacture electronic components (Andersson et al., 2016). As a result of this

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vehicle evolution, currently, more than 60 metals are used in a vehicle (Ortego et al., 2017).

Furthermore, some of these metals such as light rare earth elements (REE), Co, Ga, In, Mg, Nb, Ta, or V are also considered critical from several perspectives such as vulnerability, economic importance, supply, or ecological risks (Achzet and Helbig, 2013; Alonso et al., 2007; European Commission, 2014, 2017b). Critical metals in passenger vehicles are mainly found in the embedded electrical and electronic devices (Du et al., 2015; Widmer et al., 2015). Moreover, critical metals are also used as alloying elements in aluminum and steel alloys constituting the body-in-white and powertrain of the vehicle (Løvik et al., 2014). The number of embedded electrical and electronic devices and the alloy types depend on characteristics such as vehicle equipment, power source, and model, which define the vehicle type (Modaresi and Müller, 2012). Moreover, the future widespread adoption of electrical powertrains will encourage the development of large-capacity batteries, which will also increase the demand for some metals such as lithium (Grosjean et al., 2012; Kushnir and Sandén, 2012; Scrosati and Garche, 2010) or cobalt (Schmidt et al., 2016; Väyrynen and Salminen, 2012).

Focusing on ELV recycling processes, they are typically aimed at isolating hazardous content, selling spare parts, recovering and recycling some regulated parts such as batteries, tires, or catalytic converters, and recycling the metallic compounds existing in the largest quantities such as steel and aluminum alloys (Andersson et al., 2016). Focusing only on ELV metals, recycling plants (shredders) are mainly designed to separate ferrous (steel) and non-ferrous (aluminum, copper and zinc) fractions, which are subsequently sent to smelters as secondary sources. Such an operation entails the loss of most alloy elements (Ohno et al., 2015) either because they are downcycled or because they end up in the automobile shredder residue (ASR), ultimately becoming landfilled.

The concept of downcycling is understood as *"to recycle something in such a way that the resulting product is of a lower value than the original item"* (Merriam-Webster, 1995). Metal downcycling in ELV processes is a topic of concern; as demonstrated by Andersson et al. (2016) from a total of 17 metals investigated, only Pt from catalytic converters is functionally recycled. Moreover, as demonstrated by Ohno et al. (2014), approximately 60% of Ni, Cr, and Mo contained in light duty vehicles unintentionally ends up as the metal source in steel-making process.

As a result, these metals are lost during smelting; dissolved in the molten metal during smelting; or diluted as contaminants when they exceed the maximum content allowed for a specific alloy (Amini et al., 2007).

Another example is the case of nickel—only 40% of its content in automobiles is reused for its nickel content in steel plate rolls; another 40% is downcycled into other metals and becomes unavailable to the nickel recycling loop; finally, approximately 20% ends up in landfills (Nickel Institute, 2016). This occurs because metals are recycled in open/cascade recycling loops where dilution and quality losses occur (Maurice et al., 2017).

Indeed, and as demonstrated by Van Schaik and Reuter (2007), commercial recycling systems never achieves 100% material recovery during physical separation, high temperature metal production or thermal processing. These losses are intrinsic to any process and many of them are unavoidable as stated by the second law of thermodynamics (Valero and Valero, 2015). The physical limitations posed by the combination of materials, together with the intrinsic efficiency of the current recycling technologies have been analyzed by different authors including Castro et al. (2004, 2007); Reuter et al. (2006); Ignatenko et al. (2007, 2008); Gutowski and Dahmus (2005) or Gutowski (2008). According to Reuter (2016), one of the key drivers of a true circular economy is metallurgy and recycling and the understanding of entropy in each of its facets.

It should be stressed that recyclability assessments are intricate and work intensive because products are complex combinations of materials changing rapidly and continuously over time and that have an effect on the metals and other materials obtained after their recycling (Meskers et al., 2008; Van Schaik et al., 2003). This is why, considering that a car is made up of over 1000 different car parts, it is advisable to rank them according to the intrinsic value of the materials contained in the given component. Once ranked, recyclability assessments can be subsequently performed to those car parts selected as more valuable from a material point of view and so find ways to improve the eco-design of the product.

In depth recyclability assessments of vehicles have been performed by Van Schaik et al. (2002, 2003), and Van Schaik and Reuter (2007), who developed dynamic and fuzzy rule models to predict the liberation behavior and therefore the quality of e.g. recyclates as a function of design choices. This in turn provides a technology based feedback to the designer on the consequences of material combinations, connections and joints as defined in the design stage of the product. A useful software to undertake such analyses is HSC Sim 9 simulator (Outotec, 2017), which also allows to quantify the environmental impact via Life Cycle Assessments as well as through exergy.

This paper uses a methodology based on an indicator called thermodynamic rarity that allows to assess the physical value of systems based on their material contents. It must be noted that this methodology does not take into account the chemical relationships among metals, which affects the recyclability of the system. That said, with the method we can provide a quantitative number of the material losses that take place in ELV recycling processes, considering not only the quantity but also the quality of the materials. It also allows to identify those car components where deeper recyclability analysis and subsequent eco-design efforts should be placed. The methodology is applied to a segment A vehicle (SEAT Leon III) to which a hypothetical conventional ELV recycling operation is applied.

2. Research framework

As demonstrated by Ortego et al. (2017), a mass-based assessment of metal content in a vehicle excludes minor but very valuable elements that are increasingly gaining importance in the automotive sector. In order to overcome this deficiency, an alternative indicator based on the second law of thermodynamics was proposed. The aim of the new indicator, called "thermodynamic rarity," is to allocate a physical value to minerals and subsequently to metals according to their relative abundance in Nature and the energy intensity required to extract and process them to obtain the refined raw material. Consequently, commodities of precious metals such as platinum or gold are several orders of magnitude greater in terms of rarity than common metals such as iron, aluminum, or lead. Thermodynamic rarity combines the advantage of mass-based approaches—in that it is an indicator strictly based on the physical aspects of the commodity and hence is universal, objective, and stable—and that of monetary-based approaches, in that mineral rarities are closer to the societal perception of value.

The methodology is based on the recognition that the physical value of minerals is mainly due to their chemical properties and their degree of scarcity in the crust. The scarcer a resource, the greater its extraction costs and these, in turn, increase exponentially as the ore grades become depleted (Valero and Valero, 2015). Thermodynamic rarity incorporates two aspects. The first and the most evident one is the exergy cost (kJ) required to extract and process a given mineral from the cradle to the gate (i.e., until it becomes a raw material for the manufacturing industry). The second is the hypothetical exergy cost required if the given mineral must be restored to its initial conditions of composition and concentration in the original mines from a completely dispersed state (Valero and Valero (2015)). The latter is named exergy replacement cost, whereas the former is named embodied exergy cost. Notably, as minerals become depleted, exergy replacement costs decrease, indicating that the "bonus" granted by Nature for having minerals concentrated in mines and not dispersed reduces, indicating that real