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Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis

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Abstract

Contaminants cause a decrease in the quality of materials with each recycling step. These quality losses should be minimized to increase the sustainability of resources use. Quality losses cannot be measured using weight-based recovery definitions alone, as the quality degradation cannot be translated by mass measures. Therefore, a better measure of the efficiency of resource use is investigated in the present work. Exergy is a measure of the quality of the energy and of resources in systems. The exergy losses are a thermodynamic measure of exhaustion and thus, of the quality losses in the resource systems. We describe a method to calculate the exergy content and exergy losses of metals during recovery and recycling of a concept car. The exergy losses attributed to recycling (the pollution with other metals) and the consequent need for dilution can be used as indicators of the quality loss of materials and of the efficiency of resource use in product systems.

Keywords: Recycling; Exergy; Quality; Resources

1. Introduction

Life Cycle Impact Assessment of the average passenger vehicle of the Netherlands has been previously performed [1], with emphasis on the current dismantling and recycling practice in the Netherlands. According to the Eco-indicator 99 (EI99) [2], the largest environmental impact of the passenger vehicle's life cycle occurs in the use phase – over 90% – due to the combustion and depletion of fossil fuels. Also, in the other life cycle phases, the use of fossil fuels is the dominant impact, even for the production phase. Resource depletion due to the use of the materials employed in the vehicle causes a comparatively lower environmental impact, namely due to the high recovery rate and efficiency of the metallurgical recycling, that accounts for about 30% the total impacts of the materials. Therefore, the automotive industry has been making efforts to reduce vehicle weight as a way to reduce fuel consumption and hence emissions. The use of lightweight materials can contribute to a significant weight reduction as they replace traditionally used heavier materials. There is a tendency to use more polymers, aluminium, magnesium and various composite materials. Other attempts to reduce vehicle weight include considering the use of newly developed ultra-strong steel alloys in a different body design, as is the case of the ULSAB [1].

Lightweight metals are recyclable and have relatively high prices in the scrap markets, but other lightweight materials such as polymers and composites represent a challenge for the recycling industry. Their recycling is economically unattractive, as a satisfactory recycling technology has not yet been developed [3]. When a mixture of all these materials is present in the End-of-Life Vehicle (ELV), recycling becomes even more complex and costly. During shredding, the joints between the different materials are not completely liberated, resulting in contamination of the recovered streams [4]. In

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many cases, such contaminations cause the recycled material to lose its properties or to be downgraded and therefore cannot be used for the original applications. As a consequence large quantities of materials are buried in landfills. The EU target of recycling is 85% on a mass basis. However, the quality decrease of the material is not taken into account. This has been addressed by Reuter et al. [5], where they investigated the fundamental limits of recycling by developing recycling models for ELV. Furthermore, these models are being applied to argue recycling legislation that is reflected in an EU stakeholder report to the EU commission [6]. In general, the materials lose quality with each step of recycling. A common remedy is to add high purity primary resources during recycling to dilute the undesired contaminations and thereby to bring the material back to a higher quality. This is necessary because the contaminants cannot be removed because of thermodynamic constraints of the current process routes. These quality losses are not taken into account in the weight-based recovery targets established by the European ELV legislation, because the quality degradation cannot be translated by mass measures alone. Additionally, the recovery targets do not include the downstream recycling processes required to bring the materials back to the resource cycles. In the present work, the quality of recycling streams is quantified by exergy, which also demonstrates the efficiency of resource use, in the case of a concept light car. Various scenarios for dilution of recycled streams are assessed by this thermodynamic life cycle methodology.

2. How good is LCA?

Based on the cradle to grave principle, Life Cycle Assessment (LCA) may currently be used in assessing the sustainability of different technological options. Nevertheless, there is one major bottleneck in the current methodologies. The quality losses during recycling cannot be properly described by current LCAs. These methodologies model the resource flows as parallel to each other and account for recovery of materials during recycling as equivalent with the same quality. But in reality, the resources do not flow parallel, but are in fact mixed during the production phase (joined into one bulk product) and are later separated again, to some extent, during recycling [4]. The interconnectivity of metal flows, alloys and End-of-Life products makes the evaluation very difficult, which is addressed by Reuter et al. [7].

There is another problem in LCA methodologies, resulting in a subjective rather than objective assessment [8]. Once the goal and scope have been defined in LCA, an inventory analysis, an impact assessment and an interpretation are performed. The critical point is situated at the impact assessment stage. Here, effects on resource depletion, human toxicity and ecotoxicity have to be quantified. All effects, however, are measured on a particular scale, with typical units. Global assessment, they have, must be balanced against each other quantitatively in order to obtain a final assessment result. The balance is a rather subjective and arbitrary step in current LCA methodologies [9]. The depletion of natural resources is not well assessed by the LCA methods. In the LCA method of Heijungs et al. [10] depletion of natural resources is determined by the use of the different materials divided by their proven reserves. Due to the problems of calculating depletion of natural resources and the idea that depletion is not a severe environmental problem anymore, depletion is not determined in some methods. However, new ideas are introduced to determine depletion based on the decline of the concentration of ores. A more fundamental problem of the calculation method just described is that depletion of minerals cannot take place [9]. The atoms of the metals, like Fe, Cu and Zn, cannot be lost. The only thing that is lost is rich ores of the different minerals. However, the question can be raised how large the environmental problem is of the depletion of rich copper ore. Of course, it will take more effort to explore low grade copper ore. But even when this is depleted copper can, in principle, be extracted out of seawater, however, this will require more effort in terms of a greater use of natural resources, which are needed to perform the required transformations. So, the measure for depletion of copper ore becomes the loss of natural resources to perform the required transformations. To measure this ‘‘loss’’ the concept of exergy is applied.

3. Exergetic Life Cycle Assessment

A more recent approach in order to assess the sustainability of technological options is thermodynamic life-cycle approach. Whereas, the first law states that energy can neither disappear nor be generated, the second law says that real processes result in a loss of energy which can be transformed into work due to generation of entropy. This available energy is called exergy or availability. The thermodynamic analysis of a life cycle shows a cumulative loss of exergy due to the generation of entropy. Resources extracted out of the ecosphere are quantified in terms of exergy. The conversion of the resources into products, wastes and irreversibility can be analysed in exergy terms, showing the role of process efficiency in sustainability [9].

The Exergetic Life Cycle Assessment (ELCA) uses the same framework as the LCA, but the only criterion is now the life cycle irreversibility, the exergy loss during the complete life cycle. In the ELCA, it is shown in which component the losses of natural resources take place. With this information better proposals for reducing the loss of natural resources can be obtained. The ELCA can be used together with the LCA. In this case, the ELCA determines the depletion of natural resources, while the other environmental effects are calculated with the LCA. When the ELCA is used separately, it is often used to reduce the use of natural resources or the costs associated with their use.

3.1. Exergy definitions

Exergy is a thermodynamic potential; it is a general measure of work, ‘‘difference’’ or contrast. The ability of an energy carrier to do work expresses the general ability to be converted into other kinds of energy, and therefore exergy can be used to investigate technological processes. Opposite to energy, exergy is exempt from the law of conservation. Every irreversible phenomenon/process causes exergy losses leading to the