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Recycling of metals: Sustainable management of limited resources

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Abstract: Metals exist in limited quantities in nature, and recycling is critical in the face of increasing demand. Recycling ensures that resources are accessible to future generations as well. However, recovering numerous elements, especially in modern complex products, is not easy. Moving beyond traditional material-based approaches, a systematic approach that evaluates the entire product simultaneously can increase the efficiency of metal recycling. Some leading companies have ensured high metal recovery from complex products with multiple metallurgical capabilities. A recycling and life cycle management-oriented approach in product design will also contribute to sustainable metal use. As a result, with technological advancements and a holistic perspective, more efficient use of metal resources and a transition to a circular economy will be possible.

Keywords: Metals, Recycling, Sustainability, Resource efficiency, EoL, Multi-material products, Optimization, Circular economy, Recycling technologies, Stakeholder collaboration.

1. INTRODUCTION

Metals have accumulated in certain regions of the Earth as a result of geological processes. This natural formation has made human access to metal resources possible. However, metal reserves around the world are limited, and current reserve estimates are not always accurate. The concept of metal ore plays a key role here: Ore is a mineralization in which the metals contained can be economically extracted. Thus, metal prices and production technologies play a decisive role in evaluating a mineral as an ore.

The Brundtland Report draws attention to the complex relationships between natural resources and human activities. Resource efficiency is crucial for sustainability. The philosophy of "doing more with less" aims to offer more and better quality products and services by using fewer resources and energy, producing less waste and emissions. But efficiency gains alone are not enough. At the same time, consumption habits need to change and demand needs to be directed. Sustainable production and consumption are only possible by ensuring resource efficiency and sufficiency together.

Metal recycling plays a critical role at this point. Recovering and reusing used metals is an opportunity for future generations to access the same resources. Although ore-based metal production is expected to require less energy in the future, recycling is the most effective way to reduce resource demand and ecological footprint today and in the near future. Metal recycling is an indispensable application for a sustainable future.

2.EXPERIMENTAL DETAIL

Limitations in Metal Recycling: Table 1 shows the global recycling ratios of some important metals.

These ratios are quite low compared to the goal of recycling all metals in products. One of the main reasons for this is the low recycling rates of end-of-life (EoL) products. Consumers' motivation to return valuable EoL products is still not sufficient. Moreover, existing collection systems are not ready to collect all materials that can be recycled. The shortening of product lifetimes makes this problem even more important. At this point, important responsibilities fall on society. First, the disposal of metal-containing products should be prevented. Instead, these products should be collected and integrated into the recycling system. Effective recycling not only ensures the protection of non-renewable resources, but also ensures the supply of critical metals, forming the infrastructure of a sustainable future. Especially when it comes to rare and valuable metals, their recovery is vital.

Otherwise, these metals will be lost in waste sites. In order to increase metal recycling rates, along with consumer awareness, efficient collection systems and appropriate recycling technologies need to be developed. Governments, local governments, the private sector and civil society organizations should work in partnership to build a system that promotes metal recycling. Only in this way can sustainable management of metal resources be ensured.

Material-oriented and product-oriented recycling approaches: Table 1:National recycling rate of some metals [NOR]

Metal	National recycling rate**, %**
Aluminum	40
Copper	38
Iron and steel	47
Lead	47
Nickel	34
Zinc	36

The material-oriented recycling approach calculates recycling ratios on a metal basis, particularly for commodity metals such as steel and aluminum alloys that are widely used in relatively simple applications like construction and packaging. However, this approach falls short in multi-material products where numerous elements are functionally close. This primary resource-based approach represents a metal/material-centric perspective.

A significant limitation of recycling is that the amount of recyclable metal material is much lower than the annual metal consumption. Metal use is rapidly increasing, but this growth is largely based on material use in long-lived construction, durable goods, machinery, and other installations. Thus, the amount of material held in stock is increasing. For example, in 2006, the total aluminum in use (including stocks in municipal solid waste facilities) was 586 million metric tons, with an annual net addition to stock of 24.4 million metric tons. Only 7.8 million metric tons of this were recycled. It is noteworthy that 3.9 million metric tons of aluminum were not recycled. This situation indicates a lack of sufficient material for recycling. The majority of materials entering the stock are in China. A similar situation was experienced in the USA after World War II, with more than 70% of the world's annual copper production entering the stock in this country.

Recycling of Multi-Material Products: The increasing diversity of materials used in consumer products today poses significant challenges for recycling processes, rendering traditional approaches inadequate. The complexity arises from the multitude of elements, alloys, and compounds present in these products, each with its unique properties and interactions. Effective recycling of such multi-material products necessitates an integrated and holistic approach that considers the product as a whole, taking into account the intricate interactions between all constituent elements.

To optimize recycling processes and maximize resource efficiency while minimizing losses, it is crucial to understand the complex interplay between materials. This presents a multidimensional and dynamic problem that requires going beyond the consideration of individual elements in isolation. Instead, a comprehensive analysis of inter-element interactions, alloy formations, compound creation, and the effects of process metallurgy is essential.

The efficiency of recycling processes heavily depends on several key factors, including scrap quality, compatibility between elements, and various thermodynamic and chemical considerations. Energy consumption also plays a vital role, as its reduction offers both cost and environmental benefits. For instance, steel production through recycling significantly reduces energy requirements and greenhouse gas emissions compared to primary production methods. However, as the complexity of scrap increases, so do the energy demands and process difficulties associated with recycling.

Moreover, the carbon footprint associated with logistics in the recycling industry cannot be overlooked. The transportation of materials to and from recycling facilities contributes significantly to the overall environmental impact. Therefore, optimizing logistics and minimizing transportation distances is crucial for reducing the carbon footprint of recycling operations.

In light of these challenges, a holistic and multidimensional approach is a prerequisite for optimizing recycling processes. This approach should encompass the entire lifecycle of the product, from design and manufacturing to end-of-life management. By considering the product as a system rather than a collection of individual components, designers can make informed decisions that facilitate efficient recycling.

This holistic approach should also involve close collaboration between various stakeholders, including product designers, material scientists, recycling experts, and policymakers. By fostering interdisciplinary cooperation and knowledge sharing, innovative solutions can be developed to address the complex challenges posed by multi-material product recycling.

Furthermore, advanced technologies such as artificial intelligence, machine learning, and robotics can play a crucial role in optimizing recycling processes. These technologies can enable the rapid identification and separation of different materials, improve process control, and optimize resource allocation. By leveraging these cutting-edge tools, recycling facilities can enhance their efficiency, reduce costs, and minimize their environmental impact.

3.CONCLUSION

Metals are limited resources, and their recycling is of great importance for sustainable management. However, challenges such as low recycling ratios, increasing metal demand, and the complexity of multi-material products exist.

To increase recycling, product life extension, improvement of collection systems, and development of technologies are necessary. Optimization of material and product-oriented approaches will ensure energy and resource efficiency.

In conclusion, a holistic approach and collaboration of all stakeholders are essential for the sustainable management of metals. Recycling is a crucial part of the circular economy and is vital for future generations.

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