RECYCLING OF ALUMINIUM - GENERAL ASPECTS

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Abstract

The object of the present paper is to give a general survey of the recycling of aluminium and especially of the different recycling strategies.
All the strategies, which are significant for the recycling of aluminium products and materials are systematically described taking into consideration the material properties used for the current recycling techniques. Furthermore, the recently evolved rules for a recycling-oriented product design are presented and examples for their application on aluminium products are given.
The various options for the recycling of aluminium products and materials make it possible to characterize three kinds of recycling properties. As a result of this, evidently aluminium is a suitable material for high level recycling.

Introduction

Over the last years the topic of recycling in general and of metals in particular has appearing more and more frequently in discussion. In this context one could get the impression, that something new has been discovered. However, as a matter of fact recycling of metals is well known for a long time. For instance, already in the twenties aluminium scrap from production has been remelted and used again. But nowadays, predominant justifications for recycling are environmental and economic considerations as well.
The materials selection for planning and developing products depends on numerous factors such as costs, availability of raw materials and the material properties, i.e. the mechanical, physical and chemical properties. The combination of these material properties decides about the fabricability, usability and also about the recyclability of materials.
In the last years an increasing environmental awareness based on environmental challenges such as saving of natural resources and reduction of solid waste has caused a lot of ecological parameters which have to be considered in product development. Especially tough European environmental legislation will soon make it more expensive to dispose of automotive and electronics waste. According to German regulations proposed for introduction in 1995 the responsibility for the disposal of electronics and vehicles at the end of their service life will be placed directly back to the original manufacturers. As a result of this the "recy-

clability" has become one of the industries' requirements to materials. But, what does the expression 'recyclability' exactly mean?
Recycling can be defined as "renewed use or utilization of products or parts of products in life-cycles". But, corresponding to this definition, recyclability merely includes any possibility to close the cycle. However, any information about the way of closing the cycle will not be given. This status is insufficient for today's technical standard and demand for a high level recycling[1]. Therefore it may be helpful to describe all the strategies relevant to recycling of aluminium products and materials by investigating the stages of life cycles. According to the thesis of Hornbogen, life cycles of engineering materials consist of the following six stages: primary raw material from deposits, production of engineering materials, fabrication of systems, their use, their failure, and closure of the cycle by recycling (Fig.1).

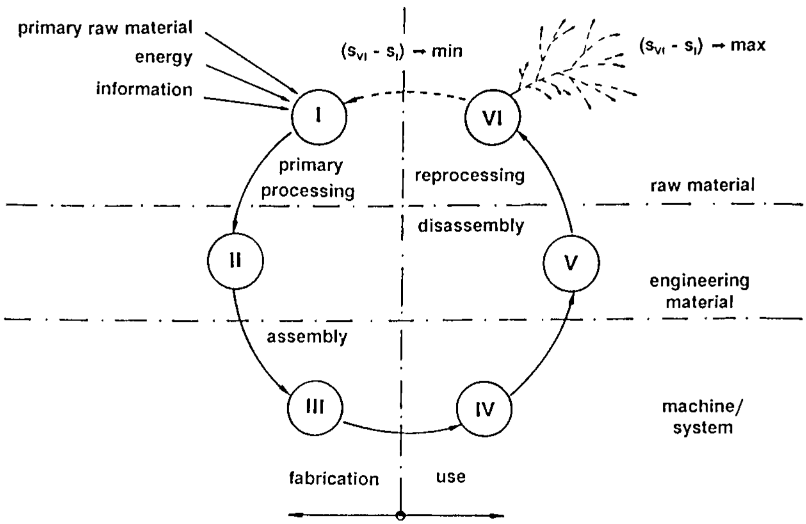

Figure 1. Life cycle of engineering materials consisting of following stages: I) primary raw material from deposits, II) production of engineering materials, III) fabrication of systems, IV) use, V) failure, VI) closure of the cycle by recycling (s = entropy), after [2].

An exact analysis of all the options for the closure of the life cycle regarding the different recycling strategies provides a chance to describe the "recyclability" of materials and especially of aluminium. Besides that, the rules for recycling oriented product design also have to be taken into account.

[1] Especially dismantling and sorting operations are characterized by ineffective and cost-intensive manual work. Thus, the mechanization or rather the automation of individual operation steps will be the requirements for future technical development.

The recycling strategies

The application of the recycling strategies to close the life cycle depends on two different ways for recycling, which have to be considered: *product and material recycling* (Fig.2).

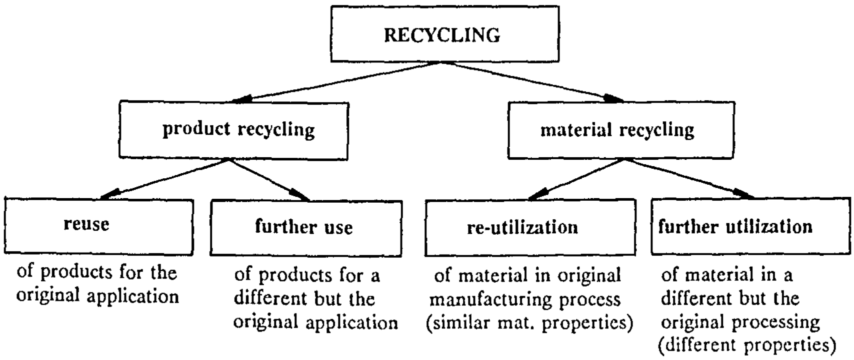

Figure 2. Classification of recycling ways (product and material recycling) and recycling strategies (use/utilization). An additional way is represented by energy recycling, e.g. regaining of stored energy by combustion of plastics.

Product recycling can be characterized by the renewed use of products for the original application and by the use of products for new applications, respectively. If material recycling is desired one has to distinguish between re-utilization and further utilization strategy depending on the properties of the secondary material.
This classification represents an attempt to provide a general characterization of the recycling strategies including a standard terminology [3]. Finally, there are four options for a closure of the life cycle of aluminium products and materials (Fig.3).

Strategy of reuse

The modern environmental legislation favours all activities that contribute to the avoiding of waste. In this context priority is given to the reuse of products or parts of products. The reuse strategy is defined as renewed use of a used product for its original application. However, the reuse of a product can be restricted by damaged parts or by lacks of machining practicability.
The first steps of the reuse strategy are represented by dismantling of the product and subsequent cleaning of the components. For cleaning the aggressive effect of cleaning agents and solvents on the material surface has to be considered. In comparison to thermoplastics aluminium alloys are generally less sensitive especially to solvents.
After the cleaning process the parts have to be checked for usability by measuring methods and nondestructive testing.

The applicability of nondestructive testing methods depends on the physical properties of the materials. Whereas optical, acoustical and penetrant testing methods are suitable for all materials, collector and eddy current testing only can be applied to electroconductive materials. The radiation test represents another method for nondestructive testing of aluminium parts using the effect of weakening of x- and γ-rays. On the other hand all the testing methods operating with ferromagnetic materials properties (e.g. leakage flux testing) are naturally inapplicable to aluminium alloys.
The applicated testing methods decide about whether a part can be directly reused or whether it has to be reconditioned by machining (e.g. turning, milling).
The last operation step of the reuse strategy is represented by reassembly of used and possibly reconditioned parts and components to a remanufactured product to be used for a next life cycle.

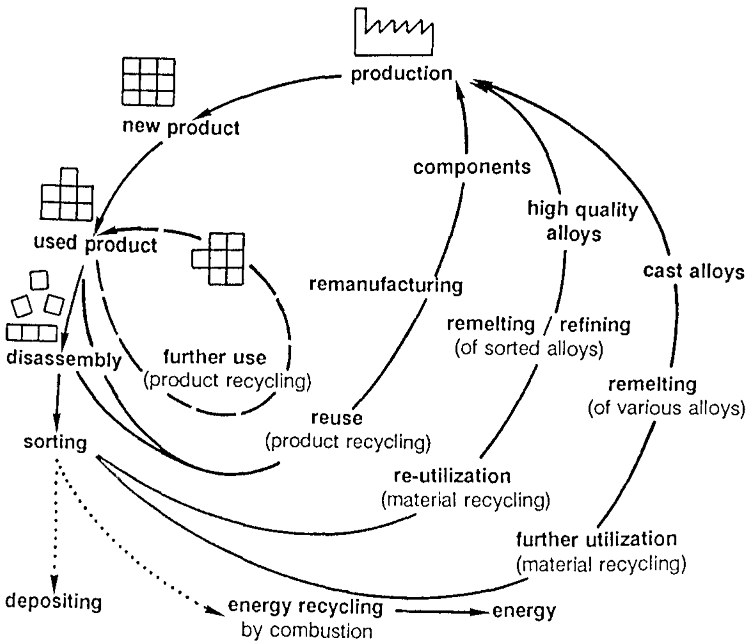

Figure 3. Life cycle of aluminium products and materials.
The further use strategy (broken line) plays an insignificant role for aluminium recycling due to high scrap value. Energy recycling by combustion and depositing (dotted line) should be avoided.

Strategy of further use

The further use strategy, i.e. the usage of a used product for a different but the original application, is well known for many decades. An example for this recycling strategy may be given by a wheel rim made of steel that can be used as base plate for a provisional traffic sign. However, further use strategy will only play an insignificant role for aluminium recycling due to high scrap value. According to economic considerations remelting of aluminium to manufacture new high quality products will be more efficient.

Strategy of re-utilization

The most interesting recycling strategy under both economic and technical aspects is represented by the re-utilization of aluminium. This strategy is characterized by the repeated use of old or new scrap in a process similar to the original manufacturing process [3]. Additionally, refining procedure can be carried out depending on the composition or contamination of the scrap. The result of this processing are remelted aluminium alloys with similar properties compared to original (primary) material.
One of the most remarkable features of the remelting process of aluminium is the energy saving. A scrap remelting operation consumes approximately 5% of the energy required to electrolytically extract aluminium from its oxide (Fig.4).

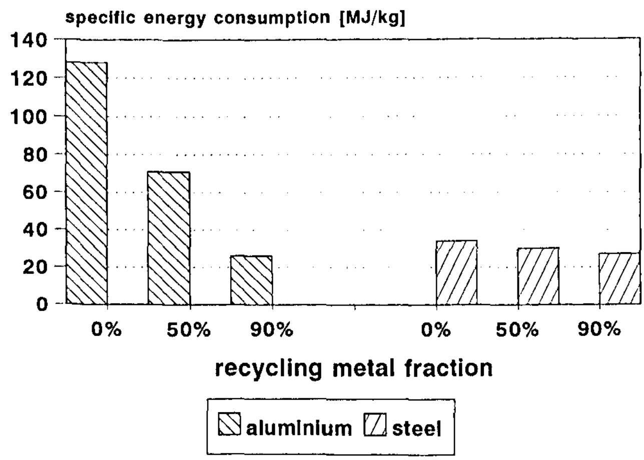

Figure 4. The energy saving of recycling aluminium scrap has been recognized for many years. Due to the high amount of stored energy recycling by remelting reduces the energy demand by up to 95% compared to producing aluminium from ore. The higher the amount of secondary aluminium on total consumption, the lower the required energy for metallurgical production, after [4].

Furthermore the recycling process by remelting can be repeated again and again without any loss of quality due to the atomic structure of metals. In contrast to this, reprocessing even of sorted thermoplastics causes a temperature dependent degradation of molecular

chains resulting in decreasing mechanical properties.
The main characteristic of the re-utilization strategy is the preservation of the quality level of primary alloys, i.e. aluminium wrought alloy scrap will be re-utilized for the manufacturing of similar wrought alloys. If this quality level is obtained secondary alloys[2] can be used for the fabrication of high-quality products, e.g. wrought alloys.
The strategy of re-utilization is very good practicable by remelting of similar alloys using either new scrap from production or carefully sorted old scrap. In this context a permanent identification marking of aluminium parts with alloy designation might help to improve the separation if it is carried out manually by handpicking. But this is an inefficient and expensive procedure. Therefore, the Metallgesellschaft AG has developed an automatic sorting technique using the atomic emission spectroscopy process for analytical identification of aluminium alloys [5]. A pulsed laser beam evaporates an area of the surface of the scrap to plasma, which can be subsequently analysed (Fig.5). This technique makes it possible to separate four different wrought and casting alloy types using material immanent parameters (Fig.6).

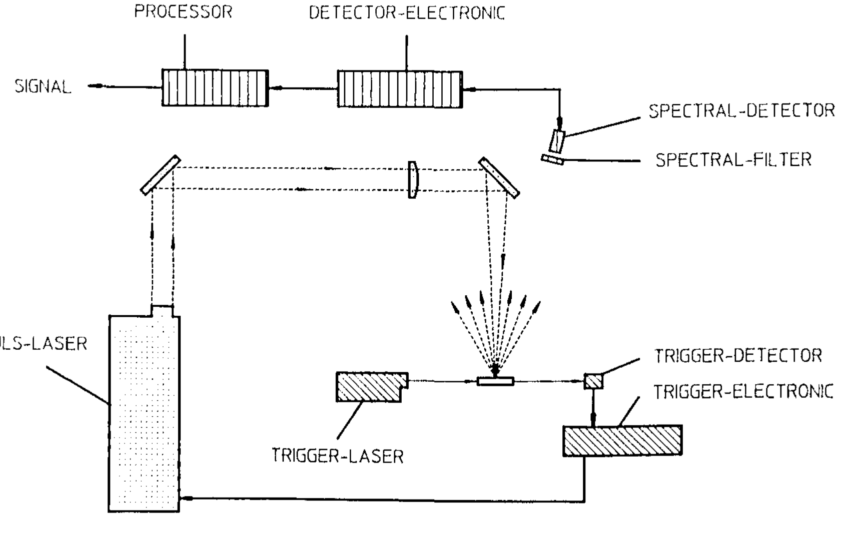

Figure 5. Diagram of the detection process for analytical identification of shredder scrap [3]

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[2] Note: The traditional definition of "secondary aluminium" is limited to aluminium cast alloys and desoxidation aluminium. However, in this report all remelted aluminium alloys are classified as secondary alloys, because -in contrast to copper- aluminium once used cannot be reprocessed to unalloyed primary aluminium.

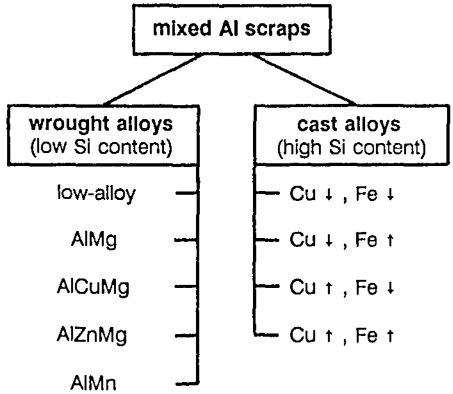

Figure 6. Scheme for sorting of mixed Al-scrap. The separation of five wrought and four casting alloy types is possible by laser aided identification of alloy constituents.

The re-utilization of alloy scrap is restricted by metallic (e.g. Fe, Cu, Zn, Na, Ca), non-metallic (e.g. polymers) and oxidic (e.g. alumina) contaminations causing a decrease in materials properties. For instance, additions of few ppm Na can induce transverse corner cracks in hot-rolled Al-Mg alloys. Thus, refining techniques have been developed to reduce such contaminations based on the principles of sedimentation, flotation and filtration [6]. The sedimentation causes a segregation of the constituents due to difference in density. With spinning nozzle inert flotation it is possible to remove least contaminations by gassing the melt with Argon. Besides that the adsorption of undesired particles on small alumina balls is used by the filtration technique (Alcan bed filter technology).

Strategy of further utilization

The recycling strategy of further utilization is defined as the use of old or new scrap in a different but the original manufacturing process resulting in materials with different properties compared to primary material (input). Consequently, the main characteristic of this strategy is a loss in quality of primary material, e.g. by using of high quality aluminium wrought alloys modified with expensive alloy additions (Mg, Mn) for processing of secondary aluminium casting alloys. This kind of "down-cycling"[3] is due to the variety of mixed Al-

[3] Metals can be remelted without any loss of quality due to their atomic structure. In contrast to this, reprocessing even of sorted thermoplastic polymers causes a degradation of molecular chains resulting in reduction of molecular weight. This implies a decrease of melting temperature and strength, if the cohesion of the chains is only based on molecular interaction. A continuation of this degradation effect occurs during each subsequent reprocessing procedure and results in a loss in strength step-by-step. This so-called 'cascade-recycling' is significantly increased if mixed incompatible polymers containing different additives are reprocessed simultaneously.

scrap containing a wide range of alloying elements and contaminations as well. For example, irreversible contaminations by Fe-additions can induce undesired effects on microstructure resulting in a decrease in ductility (Fig.7).

Figure 7. Al-5wt%Li (model alloy): formation of undesired phases (Al_3Fe and Al_7Cr) due to alloy contamination by Fe and Cr [SEM-micrograph].

To avoid such contaminations suitable separation techniques have to be applied depending on scrap input, that may consist of either mixed metal scrap or mixed scrap (metals and non-metals). In general, the separation is an important activity in implementing any type of recycling scheme, because the ability to obtain "clean" materials determines the applicability for secondary alloys and, thus, the final value of products.

The separation of scrap iron from non-metals (rubber, plastics, glass), nonferrous metals and austenitic steels is possible by magnetic separators. With two-stage heavy media flotation, featuring medium densities of 2,2 and 3,4 gcm^{-3} composed of water and FeSi powder, Al-alloys are separated from remaining heavy metals (e.g. Cu, Zn, Pb), Mg-alloys and polymers (Fig.8). However, the flotation technique only provides a low-grade scrap quality due to undesired extraneous metal contents and carried over FeSi particles.

The separation of nonferrous metals from non-metals can also be achieved by eddy current separation providing recovery rates of up to 98%. In contrast to this, an identification and sorting of non-magnetic metal scrap is possible by the atomic emission spectroscopy providing clean fractions of Al, Cu, CuZn, Mg, Pb, Zn and austenitic steels. Up to 100 identification cycles per second are at present possible by using this system. With this technique 3 to 5 tons per hour non-ferrous metals can be recovered from shredder scrap depending on the feed material. The purity of the sorted material is at least 96% [5].

A systematic survey of all the recycling strategies is given in Fig. 9 summarizing individual process steps and specific properties of aluminium.

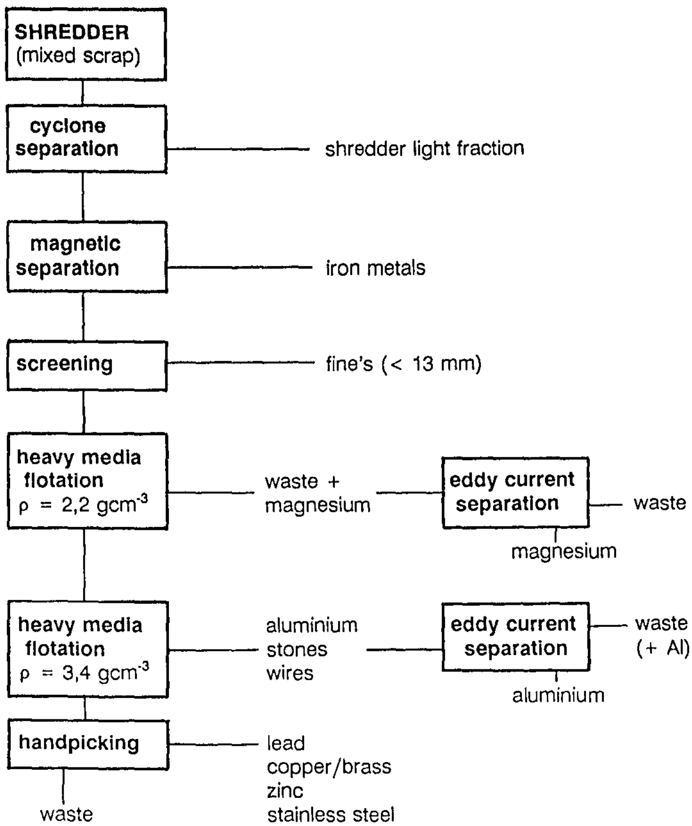

Figure 8. Flow diagram of presently carried out separation for the recycling of metals from automobile shredder.

recycling strategy	procedure steps	required properties
1. reuse (product recycling)	**1.1 disassembly**	**1.1.1 corrosion resistance** **1.1.2 strength** (detaching of joining elements)
	1.2 cleaning	**1.2.1 chemical stability** (applicability of cleaning agents)
	1.3 nondestructive testing/ sorting	**1.3.1 charact. acoustic impedance** (ultrasonic testing) **1.3.2 el. conductivity** (eddy current testing) **1.3.3 absorption coefficient** (x-ray-, γ-ray-testing)
	1.4 reconditioning (machining/finishing)	**1.4.1 machinability** (turning, milling) **1.4.2 joinability** (welding, brazing)
	1.5 re-assembly	**1.5.1 strength** (joining elements)
2. further use (product recycling)	**2.1 none**	**2.1.1 none**
	2.2 modification of product shape	**2.2.1 machinability** (turning, milling) **2.2.2 joinability** (welding, brazing)
3. re-utilization (material recycling)	**3.1 remelting** (sorted and classified alloys)	**3.1.1 energy demand** (ratio of energy required for manufacturing of primary and secondary alloys)
	3.2 remelting and refining (sorted alloys with few contaminations)	**3.2.1 atomic weight** (sedimentation) **3.2.2 oxidation stability** in comparison to companion elements (flotation) (selective oxidation)
	3.3 separation of Al-alloys (mixed Al-scrap)	**3.3.1 atomic structure** (atomic emission spectroscopy)
4. further utilization (material recycling)	**4.1 separation** (mixed Al-scrap resp. mixed metal scrap)	**4.1.1 magnetizability** (magnetic separator) **4.1.2 specific weight** (heavy media flotation) **4.1.3 atomic structure** (atomic emission spectroscopy)
	4.2 separation (mixed scrap/waste)	**4.2.1 magnetizability** **4.2.2 specific weight** **4.2.3 el. conductivity** (eddy current separator) (electrostatic separator)

Figure 9. Survey of relevant procedure steps and required properties depending on recycling strategies.

Additionally to the recycling strategies described above there are developments for reprocessing of the residues from the material recycling process. A for-instance: Melting flux and slag can be reprocessed to new flux and Al-shots (Fig.10).
In future it is intended to use conditioned residues of the reprocessing procedure either as refractory material or as raw material (Al_2O_3) for the Al production (Fig. 10).

MATERIAL RECYCLING OF ALUMINIUM

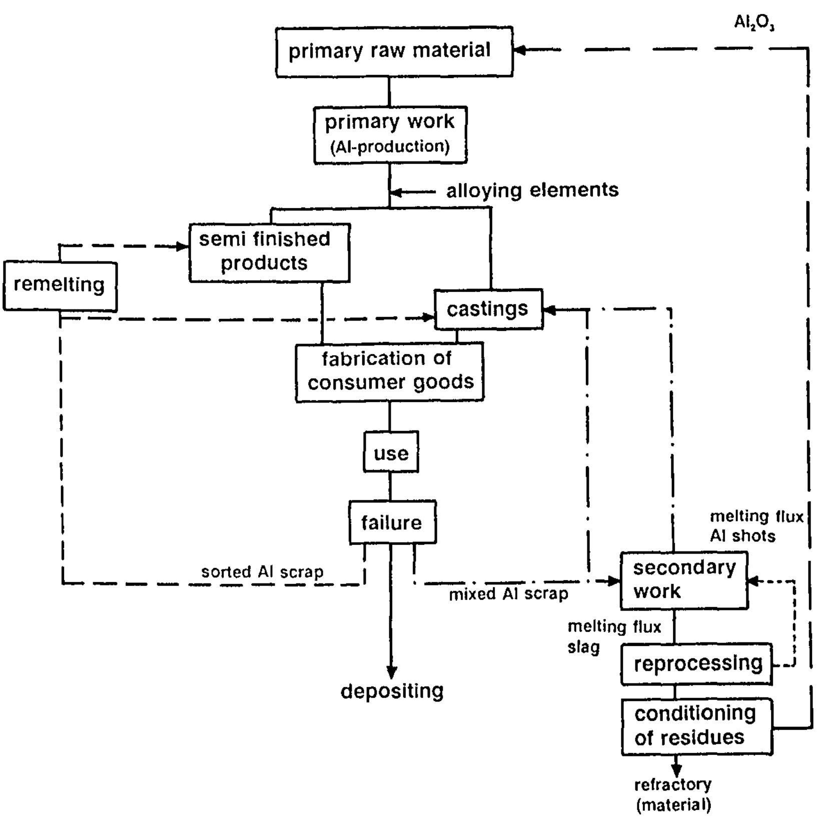

Figure 10. Flow diagram for the material recycling of aluminium: Re-utilization of sorted Al scrap for manufacturing of high quality castings or semi finished products and further utilization of mixed Al scrap for production of castings.

Recycling-oriented product design

The requirements of environmental legislation are directed at environmentally compatible production and products as well. That's the reason why the characteristic features of modern technology have to be defined as follows: saving of raw material resources, decrease of avoidable waste in production, extension of product service life and improvement of product and material recycling. Consequently an intelligent recycling-oriented product design has to be integrated in future product development.

For example, improved material properties make it possible to save raw materials by reduction of material required for a certain useful function. Additionally, extension of product service life can also be obtained by selection of improved materials and by using modular design for quickest replacement of defect components. On the other hand recycling oriented materials selection improves the efficiency of the present recycling techniques (e.g. sorting) and contributes to a reduction of the content of undesired metallic and non-metallic contaminations (Fig. 11).

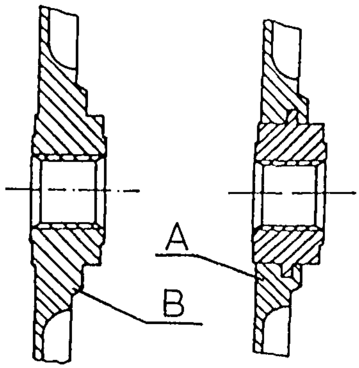

Figure 11. Example for recycling oriented product design of a belt-pulley for washing machines, after [7].

A) Previous construction consisting of Al-casting pulley with embedded iron bearing shell (separation of Al and Fe is required for material recycling).

B) Improved design: pulley consisting of only one material (Al diecasting alloy). No separation is required for material recycling.

If all the aspects of recycling-oriented design are considered it will be possible to avoid waste and to apply techniques for high level recycling. In Figure 12 these aspects, product development steps as well as recycling aspects of aluminium and their interdependence are described.

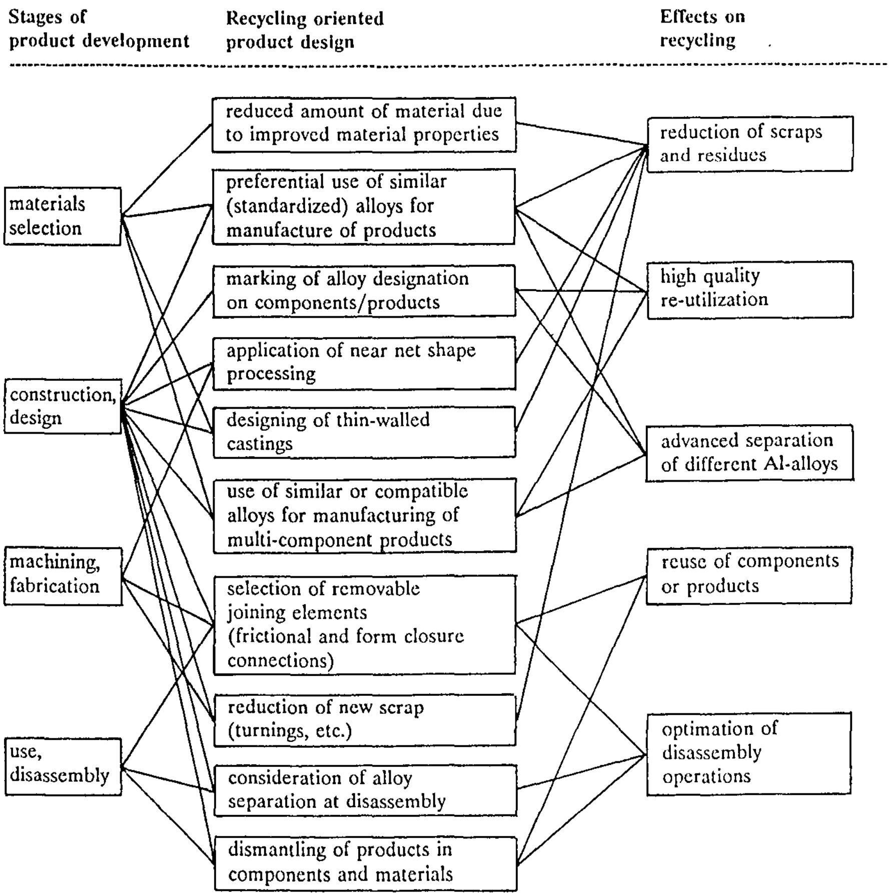

Figure 12. Examples for recycling-oriented design of aluminium products including the consequences for recycling if considered in product development.

Recycling properties

Basing on the examination of all the properties of aluminium relevant to recycling strategies and to recycling-oriented product design it is proposed to set up recycling properties and to subdevide them into three groups [8].

The **reuse properties**[4] characterize the suitability of a product or a component for a renewed use in a life cycle. In this context aspects such as machinability and also the applicability of cleaning agents and nondestructive testing methods have to be considered.

The **utilization properties** sum up all the properties concerning the applicability of materials for recycling techniques, e.g. separation, remelting etc. The main criteria according to both ecological and economic considerations has become the ratio of primary to secondary energy demand. Besides that it is necessary to compare the properties of aluminium with those of other materials, because above all the application of separation techniques is based on different physical properties such as ferromagnetism, density and electrical conductivity.

The **design properties** are given by the rules for recycling oriented product design considering special fabrication properties, e.g. suitability for near net shape processing to reduce avoidable production scrap and residues. Additionally, the range of aluminium alloys used for products and components has to be reduced. For instance, a standardization of alloys for technical applications provides the chance for high-quality re-utilization due to the compatibility of particular aluminium alloy groups.

Conclusions

As a result of the characterization of the recycling properties, which are systematically examined taking into consideration the strategies for product and material recycling, it becomes obvious that aluminium is well suited for existing recycling techniques. The future development of advanced recycling techniques combined with the insertion of the rules for recycling oriented design in product development will lead as well to an increase in the reusability of Al-products as to a raise of the amount of re-utilizable high quality Al-materials. In this context it may be expected that aluminium will become the "green" metal of the future. The reasons for this are:

1. Low energy demand for secondary aluminium production.

2. Easy separation of aluminium from various scrap inputs (due to its favourable combination of physical properties compared to other metals and non-metals).

3. High quality of remelted aluminium alloys.

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[4] The author is of the opinion that the further use strategy should be ignored for classification of recycling properties due to its low significance for aluminium product recycling.

4. High material value of aluminium scrap (representing the economic stimulation for collection, sorting and recycling of scrap).

5. High durability of aluminium products (due to corrosion resistance and favourable mechanical properties).

6. High potential for reduction of emissions and energy required in use (due to weight saving by use of aluminium instead of steel for automotive applications, e.g. body sheets)

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