UDK 669.715:620.28
Review article/Pregledni članek

ISSN 1580-2949
MTAEC9, 47(1)13(2013)

CHALLENGES AND ADVANTAGES OF RECYCLING WROUGHT ALUMINIUM ALLOYS FROM LOWER GRADES OF METALLURGICALLY CLEAN SCRAP

RECIKLIRANJE GNETNIH ALUMINIJEVIH ZLITIN IZ NIZKOCENOVNIH VRST METALURŠKO ČISTEGA ODPADNEGA ALUMINIJA

Varužan Kevorkijan
Impol R&R, d. o. o., Partizanska 38, 2310 Slovenska Bistrica, Slovenia
varuzan.kevorkijan@impol.si

Prejem rokopisa – received: 2012-09-05; sprejem za objavo – accepted for publication: 2012-09-25

In the recycling of wrought aluminium alloys from lower grades of scrap (metallurgically clean but highly contaminated with non-metallic impurities) the following two tasks were identified as the most demanding: (i) achieving the required final chemical composition of an alloy with a minimal addition of primary aluminium and alloying elements; and (ii) keeping the level of impurities (inclusions, hydrogen, trace elements and alkali metals) in the molten metal below the critical level. Because of the lack of chemically based refining processes for reducing the concentration of alloying and trace elements in the molten aluminium, once the concentrations of these constituents in the melt exceed the corresponding concentration limits, the only practical solution for their reduction would be an appropriate dilution with primary metal. To avoid such a costly correction, carefully predicting and ensuring the chemical composition of the batch in the pre-melting stage of casting should be applied. Fortunately, some of the impurities, like hydrogen and alkali metals, as well as various (mostly exogeneous) inclusions, could be successfully reduced by employing existing refining procedures.

In this work, (i) the state-of-the-art technologies, including some emerging technical topics such as the evolution of wrought alloys toward scrap-intensive compositions, monitoring of the content of organics in the incoming scrap and the quality of molten metal achieved by different smelting and refining technologies, and (ii) the relevant economic advantages of the recycling of wrought aluminium alloys from the lower grades of scrap are reported. By analyzing the market prices of various grades of scrap and the total cost of their recycling, the cost of aluminium ingots made from recycled aluminium was modelled as a function of aluminium and the alloying-element content in the incoming scrap. Furthermore, scrap mixtures for producing aluminium wrought alloys of standard quality from lower grades of scrap and with a significant new added value were illustrated.

Keywords: wrought aluminium alloys, recycling, low grades of aluminium scrap, quality of recycled metal, economic benefits

Pridobivanje recikliranega aluminija standardne kakovosti iz nizkocenovnih virov bo v prihodnje odločilno vplivalo na konkurenčnost in uspešnost evropske aluminijske industrije. Pri recikliranju gnetnih aluminijevih zlitin iz nizkocenovnih vrst odpadnega aluminija (metalurško čistih, vendar onesnaženih z nekovinskimi nečistočami) sta posebej zahtevni naslednji dve tehnološki nalogi: (i) zagotavljanje želene kemijske sestave aluminijeve zlitine ob minimalnem dodatku primarnega aluminija in legirnih elementov in (ii) ohranjanje nivoja nečistoč (vključkov, vodika, elementov v sledovih in alkalijskih kovin) v talini v mejah dovoljenega. Ker koncentracijo legirnih elementov in elementov v sledovih v talini tehnološko ni mogoče spreminjati s kemijskimi postopki rafinacije, je, brž ko njihova koncentracija preseže dovoljeno mejo, edina rešitev redčenje z dodatkom primarnega aluminija. Tovrstnemu dragemu načinu zagotavljanja predpisane kemijske sestave taline se lahko izognemo le z doseganjem želene kemijske sestave pred taljenjem, tj. na stopnji načrtovanja vhodne zmesi. Preostale nečistoče, kot so npr. vodik in alkalijske kovine ter nekateri vključki (predvsem primarni), lahko uspešno obvladujemo že s sedanjimi postopki rafinacije taline, ki jih tu opisujemo.

V tem delu tudi opisujemo (i) sodobne tehnološke postopke načrtovanja recikliranju prijaznih sestav gnetnih aluminijevih zlitin s povečanim deležem odpadnega aluminija, spremljanja koncentracije organskih nečistoč v vhodnem odpadnem aluminiju ter določanja kakovosti taline, pridobljene z različnimi postopki taljenja in rafinacije, in ugotavljamo (ii) ekonomske prednosti proizvodnje gnetnih aluminijevih zlitin z recikliranjem metalurško čistega odpadnega aluminija nižjega cenovnega razreda. Izhajajoč iz sestave in cen različnih vrst odpadnega aluminija ter stroškov njihovega recikliranja nam je uspelo razviti funkcionalni model, ki določa ekonomičnost proizvodnje ingotov iz recikliranega aluminija na osnovi vsebnosti aluminija in legirnih elementov v vhodnem materialu. Model smo aplicirali na različne vrste nizkocenovnega odpadnega aluminija in pokazali, da proizvodnja gnetnih zlitin standardne kakovosti iz tovrstnih virov zagotavlja najvišjo mogočo dodano vrednost.

Ključne besede: gnetne aluminijeve zlitine, recikliranje, nizkocenovne vrste odpadnega aluminija, kakovost recikliranih zlitin, ekonomske prednosti

1 INTRODUCTION

In recent years recycling of low-grade scrap has become an increasingly important issue of the metal supply for both casting and wrought alloys. Looking to the future, the production of recycled aluminium of standard quality from the cheapest sources will play an increasingly significant role in the growth of the European aluminium industry. Despite the economic slowdown, the consumption of primary aluminium in the EU is expected to increase (to 8 Mt by 2012), while the European production of primary aluminium is expected to decrease (gradually down to 2.86 Mt by 2012). The gap between the expected production of primary aluminium and its consumption (of about 5.24 Mt) will be covered by the imports and recycling inside the EU.

At the same time, the continuous increase in the relative proportion of recycled- vs. primary-aluminium sources will be driven by the pressure to improve business results and striving for individual profit maximisation. Additional very important benefits of recycling aluminium from low-grade scrap are: (i) spreading the risk of a potential shortage of raw materials by diversifying the supply sources of aluminium away from exclusively primary metal and clean scrap suppliers; and (ii) an improvement in the logistics – ensuring an appropriate and cost-effective supply from different scrap sources. Other advantages of recycling low grades of aluminium scrap are the additional energy savings and a higher compositional flexibility in combination with clean grades of scrap and dross.

For several decades, a kind of belief existed in the aluminium industry that the standard quality of wrought alloys could be achieved only by combining sufficient amounts of primary aluminium, internal scrap and only clean, well-sorted external scrap. Consequently, ingots made from primary aluminium, internal scrap and clean industrial, or external, old scrap (a single wrought alloy with the mass fraction less than 2 % of non-metallic impurities) were obligatory in the mass production of wrought alloys as the only source of the new and recycled aluminium capable of assuring the standard quality of end products.

Scrap for the production of wrought alloys should be sorted with a strict control of the concentration of alloying elements in order to achieve the prescribed compositional tolerances[1–12]. An additional problem is caused by a very limited ability of wrought alloys to tolerate the elements not normally present in their composition. In other words, well-defined wrought scrap of a proper composition can be effectively remelted into a wrought alloy of the same composition, but it is very demanding to achieve a new wrought composition with direct reuse, without an addition of the primary metal and alloying elements. An addition of primary aluminium is necessary to dilute impurities (the elements not normally present in a wrought alloy) to an acceptable level, while the alloying elements are added, if necessary, for the correction of their concentration. Thus, most of the external scrap inside the EU (above 60 %) is preferably applied in the production of casting alloys and only the remainder is dedicated to remelting.

Although non-metallic impurities can also significantly influence the quality of the molten metal, it is not obligatory that the scrap for wrought alloys should be clean, without any organic and other non-metallic impurities, if these could be effectively removed before or during the recycling procedure. Some of the advanced melting furnaces, such as various rotary or multi-chamber units, allow direct melting of highly contaminated scrap (e.g., painted and lacquered scrap) with the thermal de-coating and the consequent recycling.

Moreover, in the internal technical documentation for the production of wrought alloys, more or less empirical compositions were often established, resulting in the production mixtures with the prescribed amounts of primary aluminium, internal, industrial external and old external scrap. However, it is important to note that such empirical compositions are usually adapted to the common availability of various raw materials and in many cases these are ***below the real potential of a possible replacement*** of primary aluminium with scrap without influencing the standard quality of the final products. The problem is that in many cases these empirical compositions are also approved by the customers, becoming, in that way, a contractual obligation of a producer of the alloys.

On the other hand, it is well known that for aluminium alloys (especially wrought alloys) a practical "compositional-tolerance limit" exists and a fairly complete knowledge of these tolerance limits for all the elements is needed, especially in the recycling operations where unexpected and unusual impurities can creep in inadvertently, and even normal impurities may tend to accumulate and build up to a disastrous degree. In most cases, the influence of these tolerance limits for various elements and various combinations of the elements on the properties (and particularly on the selected properties) of wrought alloys is not well investigated. Because of that, customers often require ***more narrow compositional tolerances*** than necessary, creating unnecessary losses for themselves and the casting house. Customers lose an important part of the competitiveness of their products in downstream business activities by paying more for non-optimal tolerance limits and, at the same time, a casting house loses the added value by producing alloys from more expensive inputs.

As an example, the average new added value created by producing wrought alloys from external contaminated scrap is about 7 % of LME. For the aluminium dross in the form of pressed skulls the new added value is significantly higher and can reach approximately one third of LME (considering pressed skulls as internal scrap).

2 DIFFICULTIES IN RECYCLING THE EXISTING WROUGHT ALUMINIUM ALLOYS

As already mentioned, the main difficulty in the production of wrought aluminium alloys from scrap is to achieve the proper chemical composition of a melt with a minimum addition of primary aluminium and alloying elements. Technically, the problem is in the missing technology (an economically acceptable, chemically based refining process) for reducing the concentration of the critical allying elements, such as copper, iron, manganese, silicon and zinc, in a melt batch produced from various sorts of scrap. Once the concentration of these critical elements in a melt is above the concentration limit for a particular wrought alloy, the only practical solution would be their dilution by primary metal. Another technical solution is to avoid an incorrect melt composition by carefully predicting and assuring the chemical composition of the batch in a pre-melting stage of casting. In principle, there is also the third solution: to convince the customers to accept the so-called "recycling-friendly wrought alloys" – in other words, the alloys with broad compositional-tolerance limits and, consequently, to some extent, a different quality-to-cost ratio. This could be an important future trend in developing new wrought alloys, working hand in hand with customers in the implementation of their requirements for scrap-friendly compositions[1–4], but for the existing alloys and existing customer demands such an approach has definitely quite a limited potential and it is also too risky.

In most of the current plants, the predominant mode of recycling – a more accurate scrap blending or a very strict melt dilution – is decided on the basis of the margin between recycled metal and primary aluminium. However, it is important to note that this margin – the difference between the price of primary aluminium (which is determined globally) and the price of recycled metal (which is calculated locally) – is affected by internal and external circumstances. Among internal factors the most important are: (i) permanent and stable sources of new and old scrap, concentrated sufficiently in one area to justify the cost of collecting; (ii) a scrap-collecting and sorting infrastructure including devices for removing impurities and delivery to a recycling plan; (iii) a method of recycling that is economically competitive with the production of primary aluminium and (iv), a market willing to accept the composition and the quality of wrought alloys made from scrap.

More expensive, clean and sorted scrap (mainly new or industrial scrap) contains a minimum concentration of critical elements, while in the old scrap of a lower cost it becomes more critical.[13] In typical municipal old scrap, which is a cost-effective source of aluminium, the minimal concentration of critical elements (silicon, iron, copper, manganese, zinc, magnesium) is typically too high for direct remelting into wrought compositions without a dilution by primary aluminium (**Table 1**).

Table 1: Typical concentrations of the main alloying elements in the municipal old scrap[13]

Tabela 1: Običajne koncentracije najpogostejših legirnih elementov v komunalnem odpadnem aluminiju[13]

Element	Concentration (%)
Fe	0.60–1.00
Si	0.30–9.00
Cu	0.25–4.00
Mn	0.60–1.50
Zn	0.25–3.00
Mg	0.20–2.00
Cr	0.05–0.30
Ni	0.04–0.30
Pb	0.02–0.25
Sn	0.02–0.30
Bi	0.02–0.30
Ti	0.05–0.25

On the other hand, in the new scrap resulting from collecting and/or treating the metal that forms during the production of aluminium products before these are sold to the final users, the right alloy composition is assured in advance; however, the cost of such scrap is significantly higher and its availability is usually limited to closed production loops.

3 ECONOMICS OF RECYCLING CONTAMINATED WROUGHT ALUMINIUM SCRAP

The economics of recycling wrought aluminium alloys from scrap is specific and differs from the economics of recycling cast alloys, since cast alloys have higher compositional-tolerance limits for impurities and can absorb a wider variety of scrap. During the production of cast alloys from scraps of various compositions, refiners are able to add alloying elements and remove certain unwanted elements after the melting process. Cast alloys tend to have higher alloy content than wrought alloys and because of that they are difficult to recycle into anything other than cast alloys, since the removal of most alloying elements from the molten aluminium would be impractical. On the other hand, wrought scrap cannot be used for the production of new wrought alloys unless separated by alloys or alloy groups and/or diluted with an addition of primary metal.

In this regard, a possible way of improving the recycling of wrought aluminium alloys is the use of new and old scrap with higher amounts of organic impurities. Most aluminium scrap mixtures currently used for the production of wrought aluminium alloys from low-grade scrap have an organic-impurity content in the mass fraction lower than 8 %. The most common organic impurities are oils, polymers such as polyester and epoxy, rubber, lacquers, paints, etc. In some heavily contaminated aluminium scrap, the organic-impurity level exceeds 18–20 %, while in the clean industrial scrap the non-aluminium impurity level is usually less than 2 %. The main reasons to start using contaminated instead of clean scrap for the production of wrought aluminium alloys are the improved added value (a net-profit surplus achieved per weight unit of aluminium or aluminium alloys of the standard quality recycled from the low-quality aluminium scrap) and better logistics (scrap sourcing, availability on the market and improved supply flexibility). The key advantage is the fact that the cost of contaminated scrap is significantly lower than the cost of clean scrap of the same pre-sorting quality (e.g., a single alloy or a single-series grade), in that way providing an opportunity for producing aluminium wrought alloys of the standard quality and with

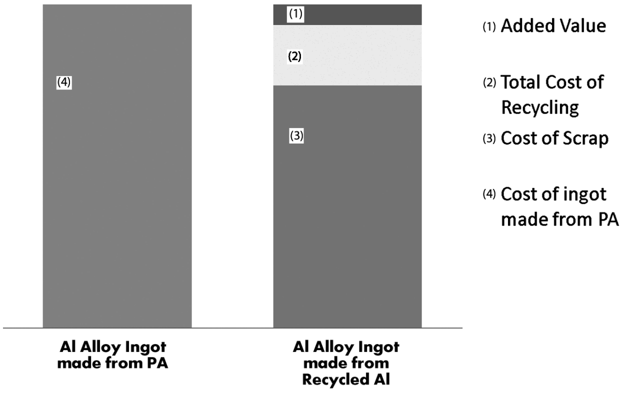

Figure 1: Structure of the cost of Al ingots made from recycled aluminium

Slika 1: Struktura cene Al-ingotov, izdelanih iz recikliranega aluminija

improved competitiveness. The prerequisite for this lies in an appropriate performance of the entire recycling process, from the scrap sourcing and purchasing strategy to the complete recovery of all the by-products, in order to achieve the standard quality of the recycled aluminium and the proper economy. In practice, irrespective of the fact that the recycling of contaminated scrap is more demanding and costly than the remelting of clean scrap, the total cost per weight unit of recycled aluminium or aluminium alloy of the standard quality produced from contaminated scrap is lower than the cost of remelted aluminium or an Al-alloy counterpart produced from clean scrap that is nowadays much in demand for the production of wrought alloys, **Figures 1** and **2**.

As a rule, clean scrap (e.g., the scrap with a minimum of 98 % of Al) represents a costly raw material for the production of wrought alloys. Its market price is close to the one theoretically expected, calculated according to the aluminium content and the cost of recovery. Therefore, the usage of clean scrap in the production of wrought alloys provides only limited possibilities for creating a new added value or, in other words, for lowering of the cost of the input. Typically, the market prices for clean scrap of a single wrought alloy vary slightly below or above the price of the counterpart ingots, depending on their market availability[14,15] (**Table 2**).

On the contrary, the market price of contaminated scrap (the scrap with, e.g., 80 % of Al and 20 % of non-metallic, mostly organic impurities) ranges significantly (10–25 %) below the theoretically expected price based on the aluminium content and the cost of recovery[14,15] (**Table 2**).

Thus, taking into account the cost of recycling and all the related costs, the total cost of producing recycled aluminium alloy fabricated from clean scrap is usually close to the cost of melting the same alloy from primary aluminium (including the cost of the appropriate alloying elements). In contrast to that, by using less-clean scrap (the scrap contaminated with organic impurities) and applying the proper recycling technology, a higher net

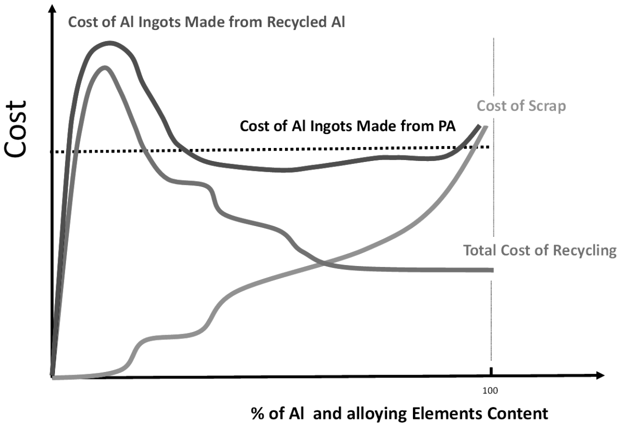

Figure 2: Cost of aluminium ingots made from recycled aluminium as a function of aluminium and alloying-element content in the incoming scrap

Slika 2: Spreminjanje cene aluminijevih ingotov, izdelanih iz recikliranega aluminija, v odvisnosti od vsebnosti aluminija in legirnih elementov v vhodnem odpadnem aluminiju

Table 2: Composition and average price* of selected scrap types[14,15]

Tabela 2: Struktura in povprečna cena* izbranih vrst odpadnega aluminija[14,15]

Scrap description	Aluminium content (%)	Oxides (%)	Foreign material (%)	Average price (% LME)
One single wrought alloy	97.2	1.0	1.8	95–99
Two or more wrought alloys of the same series	97.2	0.8	2.0	80–85
Used beverage cans	94	0.8	5.2	55–60
End of profiles with a thermal bridge (one single wrought alloy)	78	3.8	18.2	55–70
Turnings, one single alloy	95.3	3.7	1.0	80–85
Mixed turnings, two or more alloys	84.0	3.3	12.8	75–80
Packaging (coated)	71.5	3.8	24.7	55–65
Packaging (de-coated)	86.1	12.9	1.0	92–95
Dross (one single wrought alloy)	55.7	44.3	-	15–45

*The reported values are only indicative

*Predstavljene vrednosti cen so le informativnega značaja added value (typically between 5 % and 10 %) can be achieved.

It is important to note that a significant part of the new added value is gained by successful buying of less clean grades of scrap. Hence, it is necessary to understand ***the local*** new and old scrap markets and organize cost-effective buying from the nearest scrap suppliers or though collecting new scrap.

The second part of the new added value is achieved in the process of scrap separation, where the optimum level and method (e.g., hand sorting or automatic screening) of separation should be selected following the compromise between the degree of compositional separation and the cost of achieving it, also taking into consideration that a lower level of compositional separation leads, during the final melting, to a higher consumption of primary aluminium for diluting impurities. Of all the sorting technologies, hand sorting remains the most common method of recovering aluminium. Because a load of mixed scrap (even new, industrial one) often includes a limited number of alloys, hand sorting often makes it possible to produce single-alloy scrap products. Even if this is not possible, hand sorting can help meet specifications for the other scrap grades by removing impurities. A dealer's experience and knowledge of his suppliers is often useful in hand sorting, because the appearance of a piece of new scrap – the shape of punching, the type of a scrapped part – will be sufficient to identify the alloy.

Finally, the remaining part of the new added value depends on the competitiveness of the selected remelting technology, which should be able to provide the highest metal yield, the standard quality of the molten metal and an operation in accordance with the standard environmental regulations.

4 MELTING TECHNOLOGIES FOR CONTAMINATED SCRAP

Generally, regarding the level of organic impurities, two scrap-melting approaches are practiced: with or without melting additives[16]. Without melting additives it is possible to melt clean scrap, preferably containing less than 2–3 % of organic impurities and contaminated scrap (with less than about 10 % of organic impurities) by applying twin or multi-chamber melting furnaces. The scrap with a higher amount of organic impurities should be melted with an addition of melting additives (usually a NaCl and KCl salt mixture) in a drum rotary furnace with a fixed axis, which is the universal furnace for melting all kinds of highly contaminated scrap, including aluminium dross and pressed skulls. However, a more advanced and economic way of recycling aluminium from dross and pressed skulls is with a tilting rotary furnace, in which recycling can be performed with a significantly lower amount of added salts. In addition, tilting rotary furnaces are often used in recycling cast alloys, while only a limited numbers of such devices have been installed until now for the recycling of wrought alloys. It is important to note that salts provide the best quality of a molten metal. The salt mixture covers the aluminium to prevent further oxidation, strips away the oxide layer from the molten metal, promotes the coalescence of metallic droplets and dissolves or suspends other impurities attached to the metal. Therefore, the use of salt is imperative for achieving the maximum quality of recycled aluminium, especially when highly contaminated scrap and scrap with a large specific surface area are melted.

However, salts are costly additives in the production and result in a significant amount of the salt cake by-product, whose processing introduces an extra cost of salt recovery and the deposition of the non-metallic residue on commercial or industrial landfills. The melting strategy for recycling wrought alloys from scrap contaminated with organic impurities depends on several factors, among which the maximum level of organic impurities in the batches prepared for melting is one of the most important. For melting contaminated scrap salt free, various possibilities exist. The most advanced and integrated device for direct melting of contaminated scrap without melting additives is the multi-chamber furnace with a tower. The alternative is to melt contaminated scrap in a twin-chamber furnace. However, in this case the organic impurities should be reduced in advance to some acceptable level. Salt-free remelting devices (e.g., three-chamber melting furnace, twin-chamber furnace with a tower, etc.) are suitable for contaminated scrap having less than 10 % of the total organic impurities. This could be achieved mechanically by shredding or by thermal de-coating. The practical alternative is lowering the amount of organic impurities by mixing the contaminated scrap with a sufficient amount of clean scrap.

In any case, the melting technology chosen will determine the allowed level of organic impurities in the scrap, as well as the eventual necessity for melting additives. Currently, there is no single universal melting device flexible enough for all the grades of scrap (regarding the content of organic and non-metallic impurities, as well as the scrap specific surface area), operating without melting additives. For example, the double-pass rotary drum furnace is the only furnace that is suitable for all kinds of scrap. However, it operates with the highest salt factor. On the other hand, salt-free devices are limited by the amount of organic impurities, which can also reduce productivity. The same problem exists in rotary furnaces, where the highest productivity is achieved with a well controlled amount of organic impurities.

5 EVOLUTION OF WROUGHT ALLOYS TOWARD SCRAP INTENSIVE COMPOSITIONS

First of all, it is important to note that customers do not buy a wrought alloy composition but wrought properties. This fact, which is crucial in a negotiation about the ***optimum*** wrought-alloy composition, should be well recognized by both parties involved in an order negotiation – not only by customers, but also by producers of wrought alloys, and vice-versa.

Unfortunately, in the existing, standardized wrought aluminium alloys the tolerance limits for all the constituents of the alloys were well defined before scrap recycling became the key issue in the added-value engineering along the aluminium production chain. Thus, when ordering these traditional alloys, customers are more or less obliged to request the standard composition and properties.

The common limitation of the existing wrought alloys is that they are not compositionally tolerant enough to be produced by direct mixing and melting of scrap batches without sorting the mixed scraps to the desired level. Therefore, traditional wrought aluminium alloys offer only limited opportunities for a direct reuse of the recycled wrought alloy scrap without tight compositional corrections (the so-called "sweetening") by primary metal and alloying elements.

In the current wrought alloys the real operational dilemma of how well to sort[17] depends on the extent of primary aluminium, which is to be substituted by a recycled grade without influencing the quality of the wrought alloy. It is absolutely clear that the amount of primary aluminium, which can be effectively replaced in a particular wrought alloy by a recycled metal, depends on the level of compositional separation of the scrap. In other words, more precisely compositionally separated scrap has a higher potential for replacing primary aluminium without affecting the quality of the final alloy. Theoretically, by repurposing the completely sorted scrap (one single wrought alloy), a zero consumption of primary aluminium can be achieved in the production of wrought alloys. However, in order to avoid the economic inefficiencies occurring when such high-value scrap is repurposed into compositionally more tolerant wrought alloys, it is always necessary, in practice, to measure the net economic benefits of such a replacement, taking into consideration the cost of separation and the market value of the selected wrought alloy.

On the other hand, compositionally less-separated scrap grades with the alloys inside the same series, two wrought alloys of different series or even a mixture of various wrought alloys, will require, during the melting, an additional consumption of primary aluminium for diluting the impurities influencing the final economic benefit of such a substitution.

In any case, it is important to note that the "de facto" role of primary aluminium is the dilution of the impurity level (not sufficiently reduced through compositional separation of scrap) and not the provision of a sometimes mystic, necessary amount of "virgin metal", which is, according to some opinions, obligatory for achieving the standard quality of wrought alloys.

Finally, the question of economy arises again. By applying the state-of-the-art scrap-separation technology, from a technical point of view, it is possible to achieve compositionally well separated grades of scrap suitable for direct melting to the appropriate wrought alloys. The problem is that this is still not economically reasonable due to the high cost of scrap separation to a level of impurities acceptable for the ***existing*** wrought alloys. For that very reason, the technique of creating a new added value through scrap recycling should lead toward a formulation of new, recycling-friendly wrought alloys if, finally, this would be acceptable for the end product customers.

There are several fundamental questions to be answered concerning future developments of new wrought alloys designed to provide wider compositional tolerances of the existing or other alloying elements and, hence, better opportunities for scrap consumption. The most important one is whether these new alloys can possibly be composed without a critical loss of application properties or, in other words, still provide the valuable and desired combination of wrought properties for customers. Significant efforts, scientifically, technologically and financially, will be necessary for achieving this goal and implementing it in the industrial usage. Another important question concerns a possible long-term reduction in the number of wrought aluminium alloys by establishing a limited number of universal wrought compositions, making the refining of alloys easier. Although a unification of wrought compositions was proposed several times in the past, the actual development is progressing toward a further diversity of the alloys and highly tuned properties.

Irrespective of whether a new generation of recycling-friendly wrought alloys will be developed or the existing ones unified, it is important to note that newly tailored wrought alloys will require a fulfilment of the following two, hardly compatible, demands: (i) compositions with relatively broad specification limits on the major alloying elements and more tolerant limits on impurities; (ii) no significant restrictions on performance characteristics for final applications. A complete development and implementation of such alloys is, obviously, not an easy metallurgical task and will remain, most probably, the challenge for future decades.

6 DETERMINING THE CONTENT OF ORGANICS IN ALUMINIUM SCRAP

The suitability of aluminium scrap with organics as an appropriate source of aluminium in terms of value and quality for the production of wrought aluminium alloys of the standard quality depends on its metallurgical composition and content of organic and other impurities (humidity, non-metals such as oxides, non-oxides, etc.)[1]. The metallurgical composition of incoming scrap, influenced by the mix of the included alloys, is routinely determined in recycling plants by standard optical emission spectroscopy. However, a similarly fast and cost-effective method of analysing the amount of organics and other impurities in the representative samples of incoming scrap is still under development[2,3].

In recycling plants specialising in recycling of low grades of aluminium scrap, timely and accurate information about the amount of organics and other impurities in the incoming scrap is an absolute prerequisite in achieving a higher net added value. The goal is, considering the amount of organics and other impurities, to recycle each grade of scrap with the optimum recycling procedure from both the economic and the metallurgical aspects.

From an economic point of view, the content of organics and other impurities (of non-aluminium phases) defines the cost of scrap and it is thus absolutely indispensable information in commercial issues related to scrap buying, as well as the added-value engineering of the entire process of recycling[1].

From the metallurgical aspect, the amount of organics and other impurities determines the key technological parameters of recycling and the process of refining the molten metal for achieving the standard quality of end products. Firstly, the amount of organics determines the exothermic/endothermic behaviour of the incoming scrap and the volume of gaseous products liberated during the early stages of recycling. In addition, the concentration of organics and other impurities favours the formation of inclusions, influencing the quality of the molten metal[4].

Aluminium scrap, especially the grades with organics, represents a highly exothermic input (e.g., scrap with approximately 6 % of organic impurities is exothermic enough for self-melting). During the melting of such an input, a huge amount of energy and gaseous products are generated simultaneously, influencing the productivity, the cost of recycling, as well as the quality of the molten aluminium obtained – in particular its suitability for the production of wrought aluminium alloys for highly demanding end products.

Inclusions appearing as various solid particles in molten aluminium or aluminium alloy can be classified into two main groups: (i) indigenous or *in-situ* inclusions, and (ii) exogenous inclusions. The growth of indigenous inclusions is caused by chemical reactions taking place in the melt due to the existing chemical composition and the applied processing parameters (temperature, time, atmosphere, etc.). In contrast with that, exogenous inclusions already exist as a separate phase in the system before the melting and are introduced to the melt by raw materials, alloying elements, additives, refractory materials and the furnace atmosphere[4].

Exogenous inclusions can be effectively removed by filtering. On the other hand, the presence of indigenous inclusions may be prevented effectively only by mastering the overall reactivity in the system – by selecting and maintaining the proper chemical composition of the melt and the processing parameters.

Regarding the overall reactivity in a system, it is particularly important to note that the level of impurities, and the resultant chemical reactivity in remelted aluminium scrap with organics (painted scrap), is quite different from that in primary metal or remelted clean scrap. The organic component of paint can be volatilized during decoating and pyrolysis, but paint often contains inorganic compounds (fillers and pigments) that do not respond to thermal processing or become converted to oxides or other (usually binary) compounds, remaining on the surface of pyrolyzed scrap as exogenous inclusions. Many of these exogenous inclusions may also react with molten aluminium and/or alloying elements dissolved in the melt, creating indigenous as well as new exogenous inclusions.

Note that fillers and pigments can react either with molten aluminium or/and in parallel with some of the alloying elements dissolved in the melt. Hence, in real scrap mixtures of a very complex chemical impurity composition originating from organics, it is very important to take into account all the thermodynamically possible chemical reactions enabling the formation of inclusions. The aim of such a consideration is a careful prescription of the tolerance limits for all the recycled alloy constituents (incoming scrap), including impurities originating from organics.

Due to an enormous growth of the secondary aluminium industry, the development of an industrial method of determining the amount of organics and other impurities in incoming scrap has become a highly important issue. This is particularly the case in recycling plants and casting houses where low grades of scrap are also used for the production of wrought aluminium alloys. Thus, the purpose of this paper is to present an industrial method of determining the amount of organics and other impurities in representative samples of incoming scrap.

6.1 Batch and continuous procedures of a TG analysis

Industrial TG/DTA analyses can be run either as a batch or a continuous process, **Figures 3** and **4**.

The batch TG/DTA device is schematically presented in **Figure 5**.

A significantly higher productivity of a scrap analysis can be achieved with the TG/DTA unit presented in **Figure 6**, which operates continuously.

The accuracy of measuring the humidity and the organics content in the batch method (in an inert

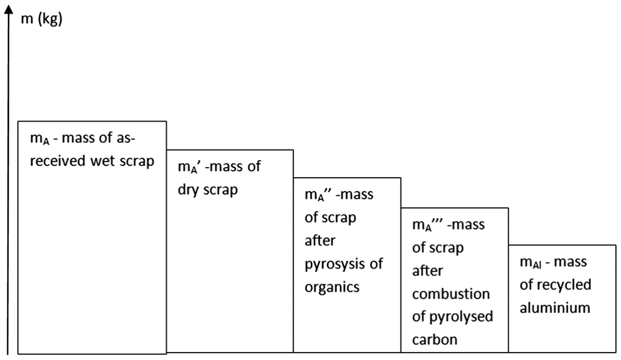

Figure 3: Histogram of mass changes of a representative scrap sample during TG/DTA performed in the batch mode
Slika 3: Histogram spreminjanja mase reprezentativnega vzorca odpadnega aluminija pri šaržni TG/DTA-analizi

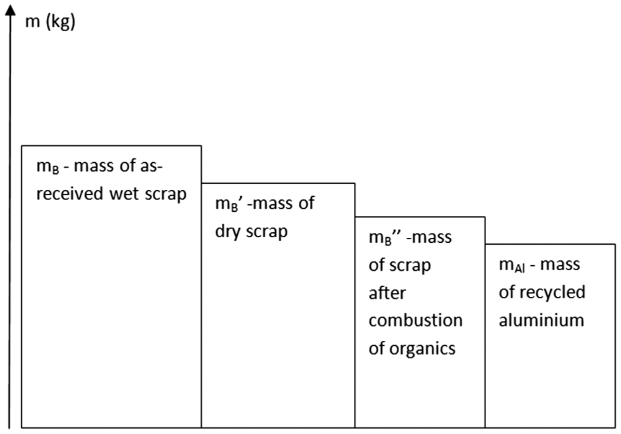

Figure 4: Histogram of mass changes of a representative scrap sample during TG/DTA performed in the continuous mode
Slika 4: Histogram spreminjanja mase reprezentativnega vzorca odpadnega aluminija med zvezno TG/DTA-analizo

atmosphere) depends on the sensitivity of the balance employed. In our case this was ±50 g, corresponding to the maximum relative error of about 1 %. The lowest relative error was obtained in the samples with minimum weight losses (the minimum content of organics). For example, the relative error of measuring the organic content in a sample with an initial mass of 50 kg and

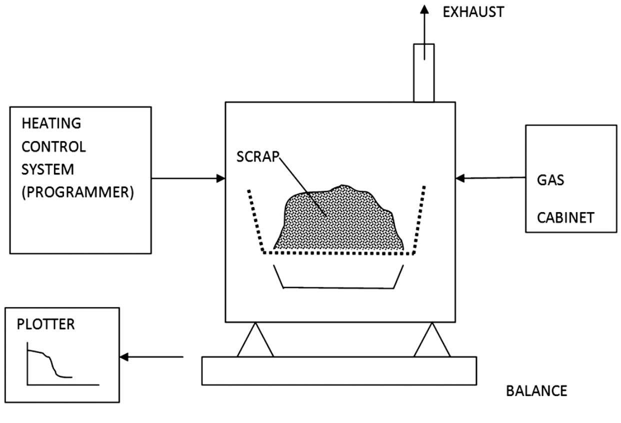

Figure 5: Industrial TG/DTA device operating in the batch mode
Slika 5: Shema industrijske opreme za šaržni postopek TG/DTA-analize

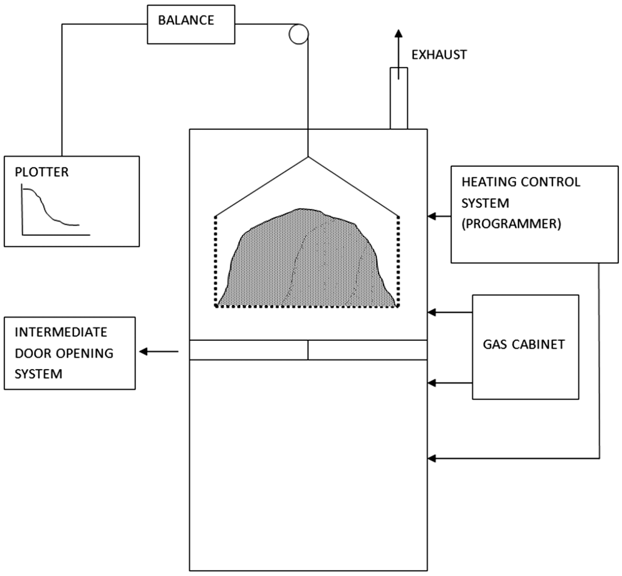

Figure 6: Industrial TG/DTA device capable of operating in both continuous and batch modes
Slika 6: Shema industrijske opreme za TG/DTA-analizo odpadnega aluminija, ki omogoča merjenje po šaržnem ali zveznem postopku

Table 3: Comparison of experimental results of the TG/DTA analysis for aluminium scrap obtained in the batch and continuous modes
Tabela 3: Primerjava eksperimentalnih rezultatov TG/DTA-analize odpadnega aluminija, pridobljenih pri šaržnem in zveznem načinu merjenja

Scrap lot 1	Sample A, batch mode	Sample B, continuous mode
Humidity (%)	0.7 ± 0.02	0.8 ± 0.02
Content of organics (%)	15.6 ± 0.4	14.1 ± 0.4
Content of non-organics including aluminium (%)	84.6 ± 2	85.8 ± 2
Recycled aluminium* (%)	73.6 ± 2	74.7 ± 2

* The estimated recycling efficiency was 0.88

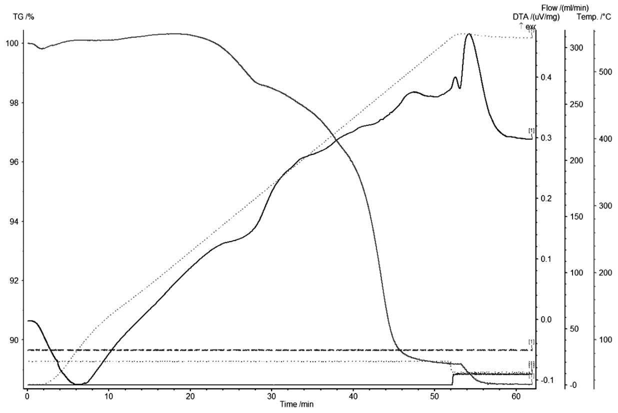

Figure 7: TG/DTA curve obtained in the batch-process mode
Slika 7: TG/DTA-krivulja pri šaržnem postopku merjenja

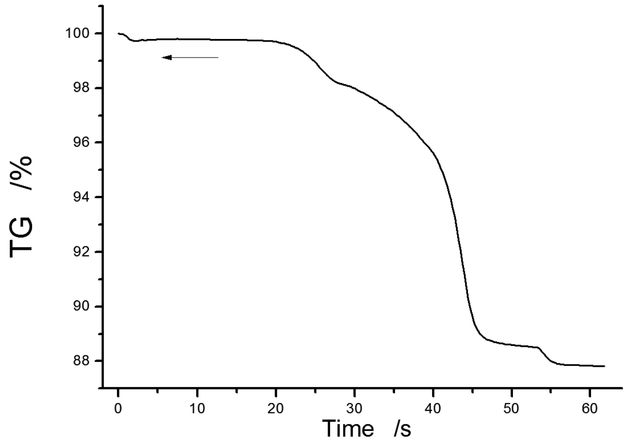

Figure 8: Example of a TG curve generated in the continuous mode
Slika 8: Primer TG-krivulje, pridobljene pri zveznem postopku merjenja

approximately 10 kg of organics was about 0.25 %, while in a sample of the same initial mass but having 80 % of organics, the relative error of measurement was 1 %. However, in both cases the relative error of measurement is within the demands of industrial users.

The accuracy of measuring humidity and organics content with the continuous method (in an oxidizing atmosphere of argon with 1 % of oxygen) in the same way depends on the sensitivity of the balance applied and, in addition, on the time and temperature of the thermal degradation of organics, and is usually lower than in the batch mode. The most important prerequisite in achieving the highest accuracy of measurement in the continuous mode, similar to that achieved in the batch mode, is an efficient minimization of oxidation of aluminium during the thermal degradation of organics in the scrap sample. Due to the fact that the molar mass of aluminium oxide is almost twice as high as the molar mass of the stoichiometrically equivalent amount of aluminium, any oxidation of aluminium during the TG/DTA measurement is detected as an increase in the mass of the remaining scrap sample and, correspondingly, interpreted as a lower content of organics.

Two basic approaches are practiced for minimizing aluminium oxidation during the TG/DTA measurement performed in the continuous mode: (i) prolonged exposure of the scrap sample at a lower temperature (480 °C to 520 °C), or rapid heating of the scrap at a temperature just below the melting point (560 °C to 620 °C). The right combination of the temperature and the time strongly depends on the scrap morphology (a thick or thin gauge), the kind of organics (soluble oil, mineral oil, paint, plastic or lacquer) and the percentage of the organic phase. On that account, for each particular lot of incoming scrap, in which the organics content is to be analysed by an industrial TG/DTA measurement made in the continuous mode, the proper time and temperature of a complete organics removal with a minimum aluminium oxidation should be defined in advance. The best way of selecting the proper temperature and time is based on the results (humidity, content of organics, content of non-organics including aluminium) obtained on a representative sample in the batch mode as the reference values. Accordingly, the parameters of the continuous mode (temperature and time) should be selected to reproduce the results at the same accuracy level as determined in the batch mode.

It is important to note that the industrial TG/DTA device developed for working in the continuous mode (**Figure 5**) can quite easily also operate in the batch mode. This can be done by heating the sample in the bottom chamber starting at room temperature in an atmosphere of pure argon. The decisive advantage of such an industrial TG/DTA device is in its ability to operate in both modes. Thus, the optimisation of the processing parameters (temperature and time) for operating in the continuous mode with the same level of accuracy as in the batch mode gained a reference counterpart and become an end-user-friendly and routine operation, easily applicable to a wide spectrum of incoming aluminium scraps. Following this methodology, the batch measurement should be completed first, irrespective of the scrap morphology, the kind of organics and the percentage of organic phase, thus providing the complete reference values of a scrap analysis. After that, in the second step, the main processing parameters (temperature and time) of the continuous mode should be tuned in order to assure, at the same accuracy level, comparable results for a scrap analysis.

A comparison of the experimental results (**Figures 7** and **8**) obtained with the TG/DTA analysis performed in the batch and continuous mode (**Table 3**) clearly confirms that the parameters of the continuous mode applied in this work (temperature: 560 °C, holding time: 60 s) were correctly selected, resulting in comparable values of humidity, content of organics and content of non-organics including aluminium.

7 QUALITY OF THE MOLTEN METAL

The quality of the molten metal is one of the critical issues, particularly if low-grade scrap becomes the

Table 4: Common impurities in primary and recycled molten aluminium[18]
Tabela 4: Najpogostejše nečistoče v talini na osnovi primarnega in sekundarnega aluminija[18]

Impurity	Concentration in primary aluminium melt	Concentration in recycled aluminium melt
Hydrogen	0.1–0.3 µg/g	0.4–0.6 µg/g
Inclusions (PoDFA scale)	>1 mm^2/kg (Al_4C_3)	0.5–5.0 mm^2/kg (Al_2O_3, MgO, $MgAl_2O_4$, Al_4C_3, TiB_2)
Sodium	30–150 µg/g	<10 µg/g
Calcium	2–5 µg/g	5–40 µg/g
Lithium	0–20 µg/g	<1 µg/g

dominant raw material for the production of wrought alloys of the standard quality.

As already discussed, various scrap-melting technologies influence the quality of the resulting metal through the concentration of the most common impurities in the molten aluminium, such as hydrogen, reactive metals and inclusions.

Throughout almost the whole of the 20th century, the aluminium produced by remelting scrap was treated by customers as less valuable than primary aluminium produced by electrolysis, mostly due to the concerns over the purity of the recycled metal compared to that of primary aluminium[18,19] (**Table 4**). However, the development of the refining technology (in-line degassing and filtration) and analytical methods for measuring the impurity levels in the past 20 years eliminated this ***stigma*** completely, providing the same quality of the ***refined*** molten aluminium, irrespective of its fabrication pre-history.

8 CHALLENGES FOR THE FUTURE

The most important reasons for the increasing demands for lower-grade scrap consumption in wrought-alloy production are in seeking individual profit maximisation, a shortage of clean scrap and both a shortage and the high price of primary aluminium.

The increased consumption of lower grades of scrap (contaminated external scrap) in the production of wrought aluminium alloys makes the achieving of the standard quality of the end products more challenging. Thus, scrap pre-sorting from alloy to alloy, or at least in a series of alloys, proper mixing of various scraps to provide the required chemical composition of the raw material before melting with a minimum consumption of ingots and alloying elements, advanced melting technology for achieving a high yield and the required environmental standards, as well as refining and filtration to assure the standard quality of the alloy, are increasingly necessary.

The development of new alloys with the required properties (e.g., tensile properties, workability, heat treatment, deformation, etc.) could be achievable with more flexible compositional limits. It would be necessary to develop such recycling-friendly wrought compositions and demonstrate to customers the ability to tailor end properties and the economic benefits created by high contents of scrap.

The following advancements in technology will be necessary to achieve the production of any wrought alloys from scrap without ecological problems:

- Develop and design melting furnaces that minimize the melt loss (oxidation and dross formation during remelting) and consumption of melting additives, improve cost effectiveness and productivity, increase safety and reduce emissions.
- Develop a low-cost process for metal purification to enable the production of primary alloys from recycled scrap, including the methods to remove specific impurities such as Mg, Fe, Pb, Li, Si, and Ti.
- Develop new, scrap-tolerant wrought alloys that better match scrap to the specifications for an increased utilization.

However, it is important to note that until now, there have been no effective methods for fulfilling the above requirements technically and economically. Most of the investigations (e.g., metal purification) are still at the stage of fundamental or early applied research, with their progress being uncertain and not foreseeable. Hence, the earliest eventual implementation at the industrial level might be expected in the coming decades.

9 CONCLUSION

Because of high costs and shortages of raw materials (primary aluminium and clean scrap), the main challenge for the producers of wrought aluminium alloys and semis are: (i) running the production with alternative, cost-effective sources of aluminium; and (ii) with the sources of metal that are more easily available.

According to the general estimation that between 3–10 % of LME is the average amount of the new added value achieved by remelting contaminated scrap, the consumption of low-grade scrap, which is already frequently practised by the producers of cast alloys, is also being increasingly introduced by remelters.

However, in contrast to mixed scrap for refiners, scrap batches for remelting should be compositionally well correlated with the chemical composition of the wrought alloy to be produced (preferably consisting of one alloy) and clean enough (not oxidized or contaminated with non-metallic impurities). Traditionally, remelters were defined as the producers of wrought alloys, mainly from clean and sorted wrought-alloy scrap and also distinguished from refiners by a lack of refining capability.

Recent developments in the remelting technology and inside the global recycling industry – together with the actual global economic crisis – started to change this traditional framework toward a new mentality of remelters. Following the opportunities for creating a new added value in their niche business, remelters reconciled the production of wrought alloys from less clean, the so-called ***metallurgically*** clean scrap, which can be contaminated even with high amounts of various non-metallic (e.g., organic) impurities. In addition, they became familiar with achieving the proper composition of scrap batches before loading the scrap into the furnace (through the refining of scrap), avoiding the more expensive dilution of impurities by primary aluminium during the melting. To this end, several ***pre-melting operations*** (scrap sorting and separation, as well as the in-house-scrap batch compositional blending) were integrated into the production chain, together with some ***post-melting operations***, such as the traditional molten-metal refining.

With all these changes contributing essentially to the creation of a new added value, a new mentality of remelters closer to the refining-production practice was established inside the EU, increasing the importance of contaminated scrap as a long-term source of aluminium for wrought alloys. Actually, remelters well understood that the most significant part of the new added value is created through proper scrap buying and sorting, while only the remainder is gained by advanced remelting. Thus, a kind of "scrap refining" practice must be introduced to keep different aluminium alloys separated at some appropriate level, considering both the metallurgical and economic point of view. The key issue is to achieve the right alloy composition of a scrap mixture before melting and not at the end of melting by diluting the impurity content to the required level. The only way to achieve this is by being fully acquainted with the scrap quality through an excellent knowledge of the scrap market, the individual scrap suppliers and an internal knowledge of scrap sampling.

10 REFERENCES

[1] D. G. Altenpohl, P. Paschen, Aluminium, 77 (**2001**) 1–2, 8

[2] S. K. Das, Materials Science Forum, 519–512 (**2006**), 1239

[3] S. K. Das, In Light Metals 2006, Ed. T. J. Galloway, TMS-AIME, Warrendale, PA 2006, 911

[4] S. K. Das, In Aluminium Recycling and Processing for Energy Conservation and Sustainability, Ed. J. A. S. Green, ASM International 2007, 147

[5] R. Hirve, Metalworld, 8 (**2009**) 3, 32

[6] R. E. Sanders, Jr., JOM, 53 (**2001**) 2, 21

[7] J. B. Hess, Metal. Mater. Trans. A, 14 (**1993**), 323

[8] D. G. Altenpohl, Aluminium: Technology, Applications and Environment, 6th ed., TMS-AIME, Warrendale, PA 1998, 15

[9] G. Rombach, In Light Metalas 2002, Ed. W. Schneider, TMS-AIME, Warrendale, PA 2002, 1011

[10] M. E. Schlesinger, Aluminum Recycling, CRC Press, Broken Sound Parkway, NW 2007, 9

[11] M. E. Schlesinger, Aluminum Recycling, CRC Press, Broken Sound Parkway, NW 2007, 171

[12] Aluminium Association, International Ally Designation and Chemical Composition Limits for Wrought Aluminium and Wrought Aluminium Alloys, Aluminium Association, Arlington, VA 2009

[13] M. E. Schlesinger, Aluminum Recycling, CRC Press, Broken Sound Parkway, NW 2007, 101

[14] U. M. J. Boin, M. Bertram, JOM, 57 (**2005**) 8, 26

[15] A&L, The aluminium figures, Edimet (www.edimet.com)

[16] Ch. Schmitz, Handbook of Aluminium Recycling, Vulkan-Verlag, Essen, Germany 2006, 74

[17] P. Li, S. Guldberg, H. O. Riddervold, R. Kirchain, In EPD Congress 2005, Ed. M. E. Schlesinger, TMS, Warrendale 2005, 1159

[18] M. E. Schlesinger, Aluminum Recycling, CRC Press, Broken Sound Parkway, NW 2007, 171

[19] M. E. Schlesinger, Aluminum Recycling, CRC Press, Broken Sound Parkway, NW 2007, 172