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OVERVIEW OF TECHNOLOGIES AND METHODS FOR SORTING AND CLASSIFYING END-OF-LIFE ALUMINUM

ОГЛЯД ТЕХНОЛОГІЙ ТА МЕТОДІВ ДЛЯ СОРТУВАННЯ ТА КЛАСИФІКАЦІЇ ВІДПРАЦЬОВАНОГО АЛЮМІНІЮ

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Abstract. Today the quality of castings obtained by aluminum recycling is determined by the technology and the culture of collecting, sorting and preparation of the secondary raw materials for the further processing. The aim of the work is to review modern technologies and methods for sorting and classifying aluminum scrap. As a rule, the collected aluminum scrap consists of a mixture of different materials and the alloys of different grades, which leads to a high content of unwanted impurities in the metal structure and, accordingly, low quality of the final material. Special attention was paid to the technological features of scrap sorting, which ensures the minimum content of iron in the final alloys obtained by processing aluminum. Practical cases of secondary aluminum metallurgy enterprises located in Ukraine, Austria, and Belgium were considered. The work was carried out using a system approach, methods of abstraction, system analysis, comparison and synthesis. Sorting of scrap and waste of aluminum by grade is carried out according to characteristic distinguishing features (color, nature of fracture, hardness, fragility), according to specific features of typical parts, spectral analysis, droplet sampling method, and others. If the current practice of collection of aluminum scrap is maintained, the amount of aluminum scrap collected will soon exceed the production capacity of cast aluminum alloys. Reducing the heterogeneity of scrap and waste can be achieved through the use of innovative technologies such as sorting sensors, spectrometric and X-ray studies, the use of infrared, ultraviolet, laser-induced breakdown spectroscopy, etc., which determine the directions for further research. The other challenge is to estimate economic and environmental advantages of implementing advanced sorting and scrap classification methods. The scientific task of theoretical and methodological substantiation of technologies and methods of sorting and classification of scrap aluminum and aluminum alloys was solved. Consolidated information on existing approaches that are effective, meet the requirements of the time and can be realistically implemented in secondary metallurgy enterprises in Europe. Also, scientific provisions, practical cases and work conclusions can be used in the process of teaching material science and aluminum technologies in higher education institutions and during research.
Key words: downcycling; aluminum purification; particle size separation; scrap surplus; aluminum recovery; aluminum flows.

Анотація. Сьогодні якість виливків, отриманих рециклінгом алюмінію, визначається технологією та культурою збору, сортування та підготовки вторинної сировини до подальшої переробки. Метою роботи є огляд сучасних технологій сортування та класифікації алюмінієвого лому. Як правило, зібраний алюмінієвий брухт складається із суміші різних матеріалів і сплавів різних марок, що призводить до високого вмісту небажаних домішок у структурі металу і, відповідно, низької якості кінцевого матеріалу. Особливу увагу було приділено технологічним особливостям сортування брухту, що забезпечує мінімальний вміст заліза в кінцевих сплавах, отриманих шляхом переробки алюмінію. Розглянуто практичні кейси підприємств вторинної металургії алюмінію, розташованих в Україні, Австрії та Бельгії. Робота виконана з використанням системного підходу, методів абстрагування, системного аналізу, порівняння та синтезу. Сортування брухту та відходів алюмінію за марками здійснюється за характерними ознаками (колір, характер руйнування, твердість, крихкість), за особливостями типових деталей, спектральним аналізом, краплинним методом та ін. Якщо поточна практика збору алюмінієвого брухту буде збережена, кількість зібраного алюмінієвого брухту незабаром перевищить потужність виробництва литих алюмінієвих сплавів. Зменшити неоднорідність брухту та відходів можна за рахунок використання інноваційних технологій, таких як датчики для сортування, спектрометричні та рентгенографічні

дослідження, використання інфрачервоної, ультрафіолетової, лазерно-індукованої спектроскопії пробою тощо, які визначають напрями подальших досліджень. Іншим викликом є оцінювання економічних та екологічних переваг впровадження передових методів сортування та класифікації брухту. Вирішено наукове завдання теоретико-методологічного обґрунтування технологій і методів сортування та класифікації брухту алюмінію та алюмінієвих сплавів. Зведена інформація щодо існуючих підходів, які є ефективними, відповідають вимогам часу та можуть бути реально впроваджені на підприємствах вторинної металургії в Європі. Також наукові положення, практичні кейси та висновки роботи можуть бути використані у процесі викладання матеріалознавства та технологій алюмінію у закладах вищої освіти та під час проведення досліджень.
Ключові слова: даунциклінг; очищення алюмінію; розділення частинок за розміром; надлишок брухту; відновлення алюмінію; потоки алюмінію.

TASK STATEMENT

Nowadays secondary aluminum metallurgy is an independent branch of industry. It aims to process aluminum scrap and waste into high-quality alloys. Technical progress and innovations development impose increased requirements for the quality of the alloys, thus simple remelting of secondary raw materials becomes insufficiently effective [1]. The problem of waste utilization should be solved in complexity with the use of knowledge-intensive, energy-efficient and ecologically friendly approaches [2].

The main part of collected aluminum scrap contains a mixture of the alloys of different grades [3] that results in the presence of different alloying elements and impurities in the structure of the metal. Removing these elements metallurgically from final secondary (recycled) alloys is notoriously difficult and economically unprofitable [4, 5]. As a result most alloys are downcycled [6-8] and processed for production of cast alloys which contain a comparatively high rate of impurities [9]. The smaller part of the alloys is used for the production of deformable alloys, which have less tolerance regarding the content intervals of the main components and impurities. To produce recycled aluminum alloys from mixed scrap, there is a need of dilution with a large amount of primary aluminum [10-12], which increases the cost, and also leads to the depletion of natural resources and pollution of the atmosphere with greenhouse gasses [13, 14].

Today the quality of castings is determined by the technology and the culture of collecting, sorting and preparation of the secondary raw materials for the further processing. The technological cycle of aluminum scrap utilization is divided into two related to each other main stages: premetallurgical preparation of raw materials (collection, sorting, classification) and metallurgical processing. Without quality implementation of the first stage, the irreversible losses of metal in the second stage are inevitable.

SELECTING PREVIOUSLY UNSOLVED PART OF THE GENERAL PROBLEM

Studies have shown that if the current practice of collection of aluminum scrap is maintained, the amount of aluminum scrap collected will soon exceed the production capacity of cast aluminum alloys [15-17]. Thus, it is expected a certain amount of aluminum scrap will be collected, for which there will be no corresponding application, named the scrap surplus [18, 19]. The scientists estimate aluminum scrap surplus at the level of 4.2…6.1 million tonnes in 2030 [20, 21] and nearly 14 million tonnes in 2050 [22]. According to estimations the surplus scrap will reach 11.4 % of all the aluminum scrap collected, and up to 90 % of collected and processed scrap can be used for the production of new alloys [15, 23].

One of the main challenges is to estimate economic and environmental advantages of implementing enhanced sorting and scrap classification methods. The formation of scrap is primarily related to the life cycle of vehicles: for example, for a passenger plane, it is about 25…30 years, for a passenger car – 12…15 years [24-26]. The coefficient of collection of scrap products is 85.90 % and 50.85 %; generation of waste during production is 100…122 % and 25…43 %, respectively [27]. The ratio of deformable and cast alloys in aircraft construction is 90/10 and in car construction about 20/80.

Extensive data research on Al production, consumption, trade and waste management was conducted and resulted in a detailed model of national Al resources. Approximately 20 % of old scrap is not recovered because of losses in waste management processes [28]. Most processing enterprises cannot provide high quality parameters of secondary alloys, primarily due to the imperfection of scrap and waste sorting methods.

The **aim of the work** is to review modern approaches for sorting and classifying aluminum scrap. **Research methods**: system approach, methods of abstraction, system analysis, comparison and synthesis. The **object of the research** are technologies and methods for sorting and classifying scrap used in the process of aluminum alloys recycling. The **subject of the research** is aluminum scrap.

MAIN MATERIAL

The aluminum recycling process can be divided into aluminum scrap sorting, aluminum purification and particle size separation [13, 22, 29-31]. Density separation is one of the first procedures in extracting aluminum from the scrap mix and reducing its mass and dimensions to be suitable for the use in smelting furnaces [32-34]. To support improved aluminum recovery, sampling and sorting procedures are used to identify and quantify the shape, sizes and dimensions of the scrap contained in the fraction [35].

The utilization process is complicated due to the fact that it is necessary to disassemble units consisting of various parts and materials. Electromagnetic pulleys and iron separators with mechanical unloading of the extracted materials for the extraction of ferromagnetic objects from scrap are used [36-40]. The purity from contaminants could be increased by shredding collisions that cause the removal of paint layers [41-43].

The separation of light material fractions (plastics, foam, rubber, etc.) typically start with density separation [10, 44, 45]. Due to its comparative low density aluminum floats can be separated from iron, copper, zinc and other more heavy metals. The other possibility is to use eddy current separation [46-49]. Removing of dust, small particles, glass and other is carried out by the use of sieves. The material flow is sorted to different particle sizes based on the sieve sizes used at the different treatment stages [50-52]. Further sorting of undesirable materials in the aluminum flow is carried out by an eddy current separator, optical separator and head pulley magnet.

Special attention is paid to the preparation of chips and other dispersed oxidized waste [53-55]. For these purposes, the necessary equipment, as a rule, is combined into a single complex, where the following operations are performed: separation of chips, their crushing, removal of oil and emulsion, drying of chips, removal of the magnetic component and sorting by alloys. To remove oil and emulsion, chip washing, dry steaming and centrifugation are used.

Particle size and shape separation mechanisms are of the greatest concern. The researchers [42, 56] point out that the latter is a comparatively budget solution to improve removal efficiency in comparison with conventional air-based classifiers. Prior removal of fines and screening separation of particles more than 50 mm by size and shape may increase efficiency of material flows in the national aluminum cycle [57]. The smaller 4…12 mm size fraction had higher levels of impurities than the 12…40 mm fraction due to the type of material and physical characteristics of the impurities [58, 59].

The physical separation methods are typically used for scrap after shredding [60]. The majority of automotive scrub is subjected to shredding operations before remelting [61]. The shredders use large hammer mills to smash scrap into small pieces typically up to 10 cm [62]. Before using foremost physical separation methods general separation by particle size using screening methods is applied.

Air separation methods include windsifting, elutriation air-knives, winnowing, air column and others. Magnetic separation separates the ferrous and non-ferrous scrap parts, but it is insufficient to separate contaminants such as glass, rubber, plastic, etc. Eddy current separation method is based on the fact that metals with different conductivity produce varying eddy currents and are jettisoned to different distances. Color sorting can be done by manual and spectrographic methods, as well as using automated methods (for example, a computer analyzes images of each scrap and directs it to the appropriate feed belt). Spectrographic methods involve passing various pieces of scrap through sensors that trigger X-ray fluorescence, neutron beams, or pulsed laser methods. Laser-induced breakdown spectroscopy uses a pulsed laser and optical emission spectroscopy.

Based on the appearance and type of the product it is possible to determine the quality of the alloy with a fairly high probability and to sort the scrap and waste according to the current standards. The differentiation of aluminum alloy scrap grades in Ukraine is carried out in accordance with DSTU 3211-95 [63] into foundry alloy scrap, rolled aluminum waste, electrotechnical aluminum, mixed aluminum, piston scrap, oversized scrap, and scrap to be cut. The main operations of the primary processing of aluminum scrap and waste included pyrotechnic and radiological control, sorting, cutting, bringing scrap and waste into overall condition.

The research carried out at the recycling facility Galoo in Menen, Belgium [13, 64] had shown that the aluminum in 40…120 mm fraction originates on average for 40 % from construction waste, 40 % from automotive waste and for 20 % from consumer durables. The types of scrap sources were related to depolluted vehicle hulks (nearly 30 %), demolition scrap (30 %), household waste (20 %) and building scrap (20 %). The studies had shown that the aluminum content in the end-of-life vehicles and household waste accounts for up to 5 wt. % [65, 66]. The aluminum content in demolition and building scrap is less than 1 wt. % [13].

The work on the differentiation of the main types and wastes of aluminum of the Zaporozhye region, Ukraine, was carried out [67]. Thus, the main types of transport scrap include bumpers, block-carter of an automobile engine, air-cooled engine heads, cylinder heads of automobile engines, automobile pumps, wire for wires, automobile radiators, pistons of diesel engines. Due to the rapid development of electric cars, a new source of automotive waste is emerging – batteries.

Based on the method of material flow analysis (MFA), a static model of Austrian aluminum flows was developed [16, 28]. Extensive data research on Al production, consumption, trade and waste management in Austria was conducted and resulted in a detailed model of national Al resources. Approximately 20 % of old scrap is not recovered because of losses in waste management processes [28].

Sorting scrap and waste of aluminum by grade was carried out according to characteristic distinguishing features (color, nature of fracture, hardness, fragility), according to specific features of typical parts (electrical conductors, pistons), spectral analysis, droplet sampling method, and others. Further production work with differentiated grades of scrap and waste made it possible to obtain data on the total contamination of scrap, as well as metallurgical losses during remelting for each nomenclature number of sorted scrap.

It is known that the high quality of production is ensured by carefully organized operations of the primary processing of scrap and production waste. Sorting is the most important operation of the primary processing of scrap. In this regard, an additional differentiation of scrap by iron content was carried out within each group and type of scrap [67, 68]. In the developed classifier No. K110-02-TsPAS, the following are indicated: the name of scrap grades, nomenclature number, fouling (general, with iron and other additives), characteristics of typical products, chemical composition of silicon and iron, metallurgical output including fouling, metallurgical losses during remelting.

One of the tasks of remelting of aluminum scrap and waste is the maximum extraction of aluminum with the provision of the necessary technical requirements. In general, the amount of secondary aluminum that can be used for the production of recycled alloys is slightly lower (up to 90 %) than the amount of scrap collected due to losses during remelting itself [69, 70]. Metallurgical recovery assumes the percentage of metal obtained from the metal content of waste percentage [71-73]. More complete extraction of metal is possible by the correct choice of technology of metallurgical processing and the amount and composition of the flux. According to the International Aluminum Institute aluminum scrap recovery rates after melting exceed 97 % for any industry; foil recovery rates reach 85 % [74]. Accordingly, it can be assumed that the recovery rates of chips, offcuts and other production waste will also be lower [75, 76]. The amount of primary aluminum used is equal to the difference between the demand for cast alloys and the amount of secondary aluminum used in the production of cast alloys. If the amount of recycled aluminum exceeds the ability of the alloys to absorb the material, there will be no destination stream for the aluminum surplus [76].

Discussion of received results. Due to the thermodynamic barriers it is difficult to remove unwanted elements from aluminum in comparison with the other metals, so it is essential to mitigate impurity accumulations during production [62]. Among the most common approaches to level the negative impact on recycling is dilution with primary aluminum. Downcycling means recycling of aluminum into lower value products and permits higher usage of recycled materials.

The problematic impurities refer to Mg, Mn, Cu, Si, Ni, Zn, Cr,etc. One of the most unwanted elements in the composition of the alloys is iron as it is present in the structure primarily in the form of iron-based intermetallics [12, 77-80]. The probability of iron impurities due to separation errors decreases for larger particle sizes in the aluminum fraction, and larger iron impurities are more likely to be separated by the magnetic separator after the milling process. Similar to aluminum samples with high ferrum content, the likelihood of iron-based impurities due to separation errors decreases for larger particle sizes in the aluminum fraction since they can be easily sorted through magnetic separation [31, 81]. During remelting, dilution losses occur due to the need for dilution the residual element concentration (e.g. iron) with primary aluminum [14, 82-84]; to avoid quality losses alloying elements are added.

To evaluate the environmental impacts associated with the quality of different aluminum scrap fractions collected, the research [13] was carried out to assess the dilution and quality losses in remelting the scrap used as aluminum AA6061 alloy. The total environmental impact for aluminum with high ferrous scrap fractions of both sizes increased at least 28 times compared to aluminum scrap fractions (4…12 mm, 12…40 mm, 40…120 mm). The use of primary aluminum as a solvent is the main contributor to the environmental impact of high-iron aluminum scrap, with an impact of at least 92 %.

To achieve higher purity of recycled aluminum alloys the alloying elements are added to meet the compositional limits. The use of primary aluminum for dilution can be minimized by using other high purity scrap streams and optimized aluminum scrap blending [20, 21, 85]. The total environmental impact for aluminum with high iron scrap fractions is greatly influenced by the dilution losses; the total environmental impact for aluminum scrap fractions is largely contributed by recycling process and quality losses since no dilution losses occur.

An environmental assessment based on case study data shows that the effects of dilution and quality loss are closely related to the quality and purity level of the recovered aluminum streams. The processing of high-purity materials can be affected by additional processing costs, profit from final products, or the mass or volume of scrap fractions of different quality produced. The iron content level highly influences the recyclability of aluminum scrap. The main type of joining techniques causing impurities in the aluminum streams are mechanical fasteners such as machine screws, socket screws, bolt screws and rivets, which are commonly used for assembling aluminum with other materials. Sorting of aluminum scrap into different fractions is proven to be effective in obtaining high quality aluminum in most European countries.

CONCLUSIONS

One of the main urgent needs for the metallurgy of secondary aluminum is to invest in new methods and technologies to collect, sort and recycle aluminum scrap and waste [83, 86]. Reducing the heterogeneity of scrap and waste can be achieved through the use of innovative technologies such as sorting sensors [87-90], visible and X-ray imaging [91-95], the use of infrared, ultraviolet, laser-induced breakdown spectroscopy [35, 64, 96-100], which determine the directions for further research.

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