The Chemical Composition of Post-Consumer Aluminium Scrap – A Challenge in Aluminium Recycling

Ciprian Bulei[1], Imre Kiss[2], Mihai–Paul Todor[1]

[1] Doctoral School

[2.] Department of Engineering & Management

University Politehnica Timișoara, Faculty of Engineering Hunedoara,

5, Revolutiei, 331128 Hunedoara, Romania

ciprian.bulei@student.upt.ro, imre.kiss@fih.upt.ro, mihai.todor@student.upt.ro

Abstract: Aluminium is one of the most recyclable materials, as it can be recycled over and over again, and is one of few materials that keeps its properties after recycling. It can be re-melted and used again and again in new products, making it an environmentally friendly metal and a sustainable material. This makes aluminium an excellent material to meet the needs and challenges of different products. Also, aluminium recycling offers advantages in terms of environmental and economic benefits. Therefore, more aluminium must be collected, sorted, and returned into the economy as new products. Aluminium recycling is the process by which various scrap aluminium can reuse in products after its initial production and involves simply re-melting these scraps. This work provides an overview of the basic aluminium recycling process, using postconsumer scrap in the melting process in few laboratory experiments. Typically, postconsumer aluminium scrap is a mixture of alloys and sometimes even a mixture of metals, the main sources for aluminium scrap being the packaging, technology, construction, and the transport industry. In our experiments, different aluminium scrap sources were considered: mixed packaging aluminium scrap and used beverage can scrap, aluminium from electric cables and aluminium from collected castings. Having in view that the chemical composition is the main challenge in aluminium recycling, mass balance of main aluminium alloying elements is performed. This research provides an overview of the aluminium recycling process, from the scrap upgrading to the melting process.

Keywords: aluminium recycling; post-consumer aluminium scrap; re-melting; chemical composition

1 Introduction

Aluminium became the most important structural material of the 20th and 21st Centuries, currently, aluminium being the most widely used non-ferrous metal in the world. The use of aluminium and its alloys has begun to experience a continuous development in the various existing industries and represents one of the most important categories of materials used in modern technology [1-4]. Aluminium is used in many industries for the manufacture of millions of different products and is very important for the world economy. Aluminium structural components are vital for the aerospace industry and very important in other areas of transport and construction where ease, durability and strength are required. The largest amount of aluminium is used to obtain its alloys, which is widely used in various techniques. Without going into technical details now, very many modern industries depend on this metal [1-4]. There is no branch of industry that does not use aluminium and its alloys in the form of castings, forgings, moulds, sheet metal, strips, foils, wire, profiles, engine blocks, etc. Basically, aluminium offers smart and practical solutions to modern life. Without this metal, today's society is unimaginable. Thus, it has practically become a symbol of progress.

The considerable expansion, in recent years, of the widespread use of aluminium and its alloys, processed in different forms, in areas such as automobiles, construction, packaging, electricity, household appliances, has led to a significant increase and accumulation of the significant amount of waste [5-13]. As a result, a special branch of metallurgy and industry was created, called the industry of secondary aluminium or recycling of aluminium from waste. The importance of recycling aluminium results from the analysis of the effects that secondary aluminium production has on the economy and the environment. Aluminium offers a lower-weight alternative to steel and it fits greatly into a circular economy since it is highly recovered and reused in new products (Fig. 1) [1, 6-11].

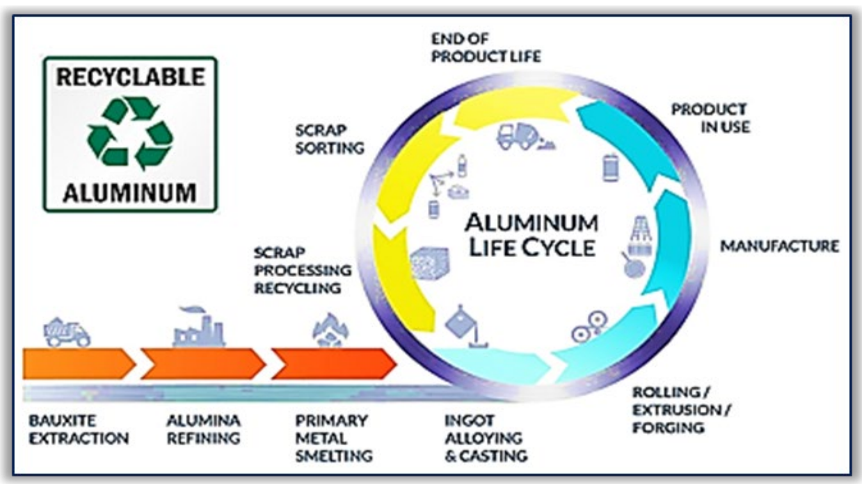

Figure 1
The aluminium life cycle

Among the general objectives of waste management are [1-4]:

- intensifying concerns about reducing the amount of waste generated;
- exploiting all the technical and economic possibilities for the recovery and recycling of waste in order to reduce the amount of waste disposed of.
- awareness of the factors involved regarding the need for separate collection;

When setting the objectives of waste management, the following aspects must be taken into account [1, 4-9]:

- not all used goods are completely reintroduced into the economic circuit;
- the reuse of some waste involves a high energy consumption;
- waste recycling is justified only when profitability and ecological balance are favourable;
- the recycling of some waste is limited by technological barriers;
- the existence of a functional market for the products obtained from waste recycling.

And because the aluminium:

- is light, durable, versatile and, above all, it is very easy to recycle – it can melt easily and quickly turn into a new product;
- is one of the few materials for which recycling costs are exceeded by the selling price of the recycled product – as are steel and copper;
- provides a rare combination of valuable properties: corrosion resistance, high strength and low-density;
- has unique recycling qualities: can be recycled repeatedly without losing quality, is 100% recyclable and can be re-valued indefinitely (in fact, aluminium can be recycled endlessly without loss of material properties);
- recycled, saves energy: aluminium production is a complex process that involves a large amount of energy, recycling aluminium, in turn, needs only 5% of this energy – the re-melting of the used aluminium saving up to 95% of the initial energy needed to produce raw material;
- uses less energy for recycling and recycling is self-sustaining due to the high value of the aluminium used, proving to be economical;
- is still in use, in proportion of 75% of the amount of aluminium produced in time, 60% being still in the first use;
- is extremely versatile and is a material with many uses in a multitude of different products, from cars to window frames and from airplanes to packaging,

aluminium waste is an important resource that is extremely valuable. For this reason, the aluminium used is rarely lost. The aluminium industry has every interest in promoting aluminium recycling as part of its industrial strategy [1-13].

Due to its unique properties (low weight, malleability, conductivity, corrosion resistance and impermeability) and its ability to be recycled infinitely, aluminium is a raw material with multiple options for use [1-13]. Recycled aluminium is part of the solution. Given the current energy problems, the increasing price of oil, the problem of water resources but also the major risks on the environment, it is easy to see how useful the non-ferrous recycling activity is. Compared to other high-volume materials, such as copper, zinc, magnesium, and steel, aluminium production has one of the widest energy differences between the primary and secondary routes.

2 Materials

The material valorisation of aluminium waste includes any operation or succession of dismantling operations, sorting, cutting, shredding, pressing, baling, melting – casting performed on a waste by industrial processes, in order to transform it into secondary raw material. Material valorisation involves the substitution of some raw materials, the waste being used again due to its material characteristics. From the point of view of the recovery possibilities, the waste is classified into [1-4]:

- recirculation waste, if it is recovered on the spot in the foundry of the enterprise that produced it;
- tradable waste, when collected for proper processing and recovery;

Depending on the time after which it returns to the circuit as waste and the area from which it originates, the waste can be classified into [1, 2, 12]:

- pre-consumer waste (manufacturing waste or "new waste"), is typically scrap that comes from the production process and has never been used before it is re–melted again (Fig. 2, left);
- post-consumption waste ("old waste"), is aluminium that has already lived a "life" and has now been collected, sorted and recycled to be turned into something new product (Fig. 2, right).

Thus, the great potential for preventing the generation of aluminium waste is effective in two stages [1-3]:

- in the production phase (Fig. 2, left);
- at the end of a product's life (after consumption – Fig. 2, right).

Figure 2
Aluminium waste in the production phase respectively at the end of a product's life (after consumption) – example for the beverage cans

Aluminium scrap is often categorized as "new scrap" and "old scrap". "New scrap" originates during the manufacturing of semi-fabricated and final products (shavings, off-cuts, casting parts, etc.) where the quality and chemical composition are usually known. Usually, the "new scrap" category is molten without any preliminary treatment. "Old scrap" refers to those products collected after disposal from consumers, thus at the end of their life (cables and electric wires, castings, auto parts, window frame, beverage cans, etc.). This raw material is more contaminated than "new scrap" and preliminary treatments of the scrap are generally necessary [1-3,14-18]. Therefore, the aluminium destined to material valorisation may be separated into two categories, namely:

- new waste: represents the technological waste generated by the processes of casting, thermal or mechanical processing (casting networks, scrap, casting burrs, ends resulting from the cutting of extruded products, edges from cutting sheets, sheet ends, scraps from stamping, spirals, chippings, etc.) and materials with residual aluminium content (such as slags discharged during elaboration operations).
- old waste: are those that come from products or articles put out of service at the end of their life cycle. Such wastes are packaging, those that come from transports, components of vehicles, construction carpentry, old electrical conductors, household appliances, etc. The old waste comes from the collection units, equipped with shredders, magnetic separators, and separation installations in dense environments.

Used aluminium mainly comes from two channels, namely, waste from domestic and industrial consumption. The way in which recycling is carried out is fundamental, its classification plays an important role in obtaining a material that has the same use as before its recovery or is intended for another type of products.

3 Methods

The aluminium recycling circuit can be achieved through two streams, one closed and the other open. In the closed loop, easily recoverable aluminium waste, which has the same provenance and known chemical compositions, can be recycled. They are recycled through smelting operations, being usually used to manufacture the same products (an example being that of car wheels). After the open loop, waste mixtures are most often processed [1-12]. They have variable chemical compositions, require additional refinements and alloys, so that the alloys obtained from their re-melting can be used to make new products, most often by casting.

The streams that process aluminium waste to obtain secondary aluminium or aluminium alloys are composed of two main steps:

— preparation (or pre-treatment) of waste: sorting, dimensional preparation, removal of impurities (purification);

— elaboration with refining of aluminium or aluminium alloys: melting, refining, alloying, casting.

In addition to these stages (Fig. 3), the flow may include other additional stages / operations, depending on the quality of the waste, the sources of waste, the endowment with auxiliary equipment, constructively modified furnaces, the specifications of the products obtained [1-12].

The heart of aluminium recycling is the melting aggregate, in which the waste melting operations are performed in order to obtain new raw materials. Melting is the process by which aluminium scraps can be reused in products after their initial production.

Figure 3
The stream of aluminium waste to recycling into new products

Figure 4
Re-melting the aluminium scrap

The process (Fig. 4) simply involves re-melting metals, which is much less expensive and more energy-intensive than creating a new aluminium by electrolysis of aluminium oxide (Al2O3), which must first be extracted from bauxite ore and then refined using the Bayer process. The selection of the melting furnace is a critical aspect and it depends on the quality and quantity of the scrap.

4 Results & Discussions

The aluminium recycling circuit can be achieved through two streams, one closed and the other open. In the closed loop can be recycled easily recoverable aluminium waste, which has the same provenance and known chemical compositions. They are recycled through melting process (Fig. 5) and are usually used to manufacture the same products (an example being that of car rims or beverage cans). After the open loop, waste mixtures are most often processed. They have variable chemical compositions, require additional refinements and alloying, so that the alloys obtained from their re-melting can be used to make new products, most often by casting.

Figure 5
Aluminium scraps melting process and cast ingots

At the moment the aluminium can (Fig. 6a) is one of the most recycled packaging in the world. Many of the food and beverages that we buy every day are packed in aluminium or steel cans, both materials can be recycled in order to manufacture new containers or other metal products. Sooner or later, each can ends up being thrown in the trash, where it begins its journey to recycling. However, many cans end up in landfills. The melted aluminium cans chemical composition in Table 1 is presented.

Figure 6
Aluminium scraps: beverage cans, castings and electric wires

Aluminium from the car rims (Fig. 6b), engine blocks or membranes, castings, etc. are intended for the manufacture of ingots that present the highest percentage of secondary aluminium production, about 70% of the total production. Therefore, the environmental and economic impact on the use of primary aluminium can be significantly reduced by recycling it. The melted aluminium castings chemical composition in Table 2 is presented.

Table 1
Aluminium cans – Chemical composition (%)

Al	Mg	Fe	Si	Mn	Sn	Pb
97.83	0.402	0.567	0.281	0.284	0.0077	0.337
Ga	Na	Cr	Ni	Cu	Sb	K
0.0112	0.0265	0.0091	0.0053	0.130	0.0107	0.0012
Ca	Zn	La	Zr	Mo	Ti	Ar
0.0391	0.0349	0.0038	0.0021	0.0012	0.0139	0.002

Table 2
Aluminium castings – Chemical composition (%)

Al	Mg	Fe	Si	Mn	Sn	Pb	Zr
95.18	0.739	1.65	0.280	0.725	0.0374	0.980	0.0036
Ga	Na	Cr	Ni	Cu	Sb	K	Ti
0.0119	0.0216	0.0185	0.0107	0.160	0.0575	0.0014	0.0243
Ca	Zn	La	P	Mo	V	As	
0.0425	0.0379	0.0030	0.0031	0.0027	0.0077	0.0022	

Aluminium from electric cables (Fig. 6c) is very pure, and for this fact its applications after recycling are extensive, being used in the manufacture of high purity alloys or as mixtures to reduce the percentage of alloying present in another recovered aluminium alloy. The melted aluminium wires chemical composition in Table 3 is presented.

Table 3
Aluminium wires – Chemical composition (%)

Al	Mg	Fe	Si	Mn
99.55	0.135	0.125	0.0881	0.0291
Ga	Na	Ce	Ni	Cu
0.0175	0.0127	0.0086	0.0071	0.0059
Ca	Zn	La	Hf	Mo
0.0051	0.0036	0.0022	0.0019	0.0014

Different aluminium scrap sources were considered: mixed packaging aluminium scrap and used beverage can scrap, aluminium from electric cables and aluminium from collected castings (Fig. 7). Copper (Cu), silicon (Si), magnesium (Mg), zinc (Zn), manganese (Mn), nickel (Ni) are used for aluminum to set up the main alloys. Along with them are used elements that improve some aspects of the performance of the alloys, known as corrective. Small percentages of titanium (Ti), zirconium (Zr), chromium (Cr), bismuth (Bi), lead (Pb), and also tin (Sn) and iron (Fe) are added for special purposes, the latter of which is always present as an impurity.

Figure 7
Aluminium scraps: melted aluminium and cast aluminium ingots

The quality of the metal is defined by three characteristics, namely:

- control of trace elements;
- eliminating non-metallic inclusions, and
- reduction of dissolved gas emissions.

If these inclusions are not eliminated from the melt before the material solidification, they lead to the worsening of the mechanical properties, such as: tensile strength, fragility, corrosion resistance, thermal and elective conductivity, etc. With all the measures that are taken in the practice of elaboration of aluminium alloys in liquid state, they still contain a certain amount of metallic impurities, non–metallic and gaseous inclusions.

The effects of metallic impurities present in aluminium alloys can be negative or positive, these effects depend on their quantity and combination in the melt. Usually the impurities existing in aluminium alloys after, are: Cu, Fe, Si, Zn, Na, Mg, Ti, V, Cr, Mn, Zr, etc. Impurities in technical aluminium may be classified in the following categories:

- impurities that react chemically, forming various compounds, easily fusible (Fe, Si);
- impurities that form easily fusible eutectics, but which are practically insoluble in the solid state (Sn, Pb, Bi);
- impurities that form chemical compounds that are difficult to fuse, but insoluble in the solid aluminium (As, Sb, Se, Te);
- partially soluble impurities in aluminium in the solid state (Si, Cu, Mg, Zn, etc.);
- impurities from the gas phase (hydrogen, oxygen, nitrogen).

The mechanisms by which these metals act negatively or positively in aluminium and its alloys are those that lead to the formation of chemical and eutectic compounds to the solidification of the material. The most common inclusions in aluminium alloys are the oxide particles that are found on the surface of the load, and then end up in the metal bath. In some cases non-metallic inclusions are formed in the molten alloy, and in others they already pre-exist in it and participate in subsequent processes. As a result of this, we can classify these inclusions into two categories, namely:

- non-metallic inclusions due to metal, which are also called endogenous inclusions, and
- non-metallic solid inclusions coming from the outside (from the shape material, the oven lining, the fondants used, the impurities in the load, etc., which are also called exogenous inclusions.

The need for improved mechanical properties and new applications has led to the continuous development of new kinds of aluminium alloys with specific chemical composition. To remove impure elements from a molten bath is impractical or inconvenient. As a result, the scrap is usually recycled, which avoids the refinement stage. A sustainable solution is the improvement of the efficiency of aluminium recycling in the production chain, which includes the scraps re–melting process, after a correct sorting process.

The chemical composition of the alloys is strictly related to the scrap quality. Therefore, recycled aluminium presents a certain amount of impurities, generally not present in primary alloys, and the alloying elements are more difficult to manage. The melting phase is critically analysed in terms of technological evolution and furnace selection, as it is the most important choice to optimize the melting rate. Fluxing and slag treatments have also been considered to complete the production chain.

During the multiple recycling, more and more alloying elements are introduced into the metal cycle. This effect is put to good use in the production of casting aluminium alloys, which generally need these elements to attain the desired alloy properties.

Conclusions

All aluminium products can be recycled after use. When decommissioned, practically all aluminium products have some value that guarantees that it is possible to create new values by recycling them into products. Since aluminium can be recycled almost without loss of quality, and because it stores a high intrinsic value, there is a strong natural incentive to recover and recycle aluminium products after they are decommissioned. The recycling yield is dependent on the lifetime of products made from aluminium. Average service life-spans range from a few months for the packaging segments, 10-12 years for car castings, to more than 30-40 years for construction and electricity.

Advantages of recycling aluminium waste:

- conservation of natural resources;
- reduction of storage space;
- protecting the environment;

Whether measured in terms of quantity or value, the use of aluminium surpasses that of all other metals except iron, and is important in virtually all segments of the world economy. Pure aluminium is soft and weak, but it can form alloys with small amounts of copper, magnesium, manganese, silicon and other elements that have a wide range of useful properties.

Recovering this metal from waste (through recycling) has become an important part of the aluminium industry. Sources of recycling of aluminium include cars and window frames, appliances, containers and other pr oducts. Recycling is very convenient. The benefits of recycling are undeniable. Each waste selectively collected and recycled/reused helps to save natural resources, reduce pollution and increase the quality of life.

The market exploitation of aluminium waste is worth considering and is economically viable. The use of secondary aluminium provides not only huge resource savings, but also an environmental benefit, with the reduction of emissions compared to the electrolytic process and the guarantee that the material will re-enter a production cycle, therefore, without the risk of an ecological impact. The advantages of this behaviour of this light metal are clear: secondary aluminium is the equivalent of primary aluminium, even after several life cycles. A secondary route for aluminium production is available using aluminium scrap and recycling. It is claimed that recycling saves resources, decreases the need for landfill space and, in the case of non-renewable resources, such as metals, and prolongs the necessary period to deplete them.

Thanks to the immense availability of recycled material (landfilled and collected) and thanks to its mechanical properties the aluminium will be the material of the future. That’s why we must focusing on recycled aluminum from various sources. And the recycled aluminium will be destined mostly for the most important sectors that use this material: automotive and construction (cast and extruded aluminum). But, the excellent recyclability of aluminium, together with its high scrap value and low energy needs during recycling make it highly desirable to all industries, in air, road and sea transport (aircraft, automobiles, bicycles, boats), packaging (beverage cans to food and drinks containers, aerosols, tubes and foil), electronics (phones, computers and its components) and electrical power transmission (wire), kitchen products (aluminium cookware and containers), sports and recreation (skates, instruments, and yacht fittings), and composites industry (as matrix in lightweight composites).

The aluminium industry aims to ensure that all types of waste generated are of high quality and that they are minimised and recycled in the most efficient way. Aluminium is practically a permanent material, a material whose inherent properties do not change during use and following repeated recycling in new products. However, it depends on the recycling method to what extent the re-melted aluminium is reintroduced into the circuit. In fact, recycling is a joint effort and the circular economy is a lifestyle, in which waste is treated as a resource and turned into valuable raw materials that can be reused for new products. Millions of tonnes of recyclable waste are selectively collected annually around the world, with recycling enjoying strong demand from industry and construction companies, as well as constant demand from households. Sources for aluminium scrap include packaging (beverage cans), construction (window frames), energy (electric wires) and the transport industry (auto parts). The greatest opportunity to increase the availability and quality of scrap is in consumer packaging and the automotive sector.

Acknowledgment

These studies was carried out on the basis of extensive research over the last 5 years, undertaken within the Faculty of Engineering Hunedoara. These researches are part of a complex research program, included in a doctoral study plan of University Politehnica Timisoara, which analyzes different possibilities of recycle various landscaped and collected aluminium scraps.

References

[1] D. Raabe, D. Ponge, P. J. Uggowitzer, M. Roscher, M. Paolantonio, C. Liu, H. Antrekowitsch, E. Kozeschnik, D. Seidmann, B. Gault, F. De Geuser, A. Deschamps, C. Hutchinson, C. Liu, Z. Li, P. Prangnell, J. Robson, P. Shanthraj, S. Vakili, C. Sinclair, L. Bourgeois, S. Pogatscher, Making sustainable aluminum by recycling scrap: The science of “dirty” alloys, *Progress in Materials Science*, 128, (2022) https://doi.org/10.1016/j.pmatsci.2022.100947

[2] S. Capuzzi, G. Timelli, Preparation and melting of scrap in aluminum recycling: A review. *Metals (Basel)* (2018) 8:249, https://doi.org/10.3390/met8040249

[3] A. T. Tabereaux, R. D. Peterson, Chapter 2.5 – Aluminum production, treatise on process metallurgy, *Elsevier*, 2014, 839-917, https://doi.org/10.1016/B978–0–08–096988–6.00023–7

[4] P.de Schrynmakers, Life cycle thinking in the aluminium industry. *The International Journal of Life Cycle Assessment*, 14, 2-5 (2009) https://doi.org/10.1007/s11367–009–0072–x

[5] G. Olivieri, A. Romani, P. Neri, Environmental and economic analysis of aluminium recycling through life cycle assessment, *International Journal of Sustainable Development & World Ecology*, 13:4, (2006) 269-276, https://doi:10.1080/13504500609469678

[6] M. Niero, S. I. Olsen, Circular economy: To be or not to be in a closed product loop? A Life Cycle Assessment of aluminium cans with inclusion of alloying elements, *Resources, Conservation and Recycling,* 114, (2016) 18-31, https://doi.org/10.1016/j.resconrec.2016.06.023

[7] G. Gaustad, E. Olivetti, R. Kirchain, Improving aluminum recycling: A survey of sorting and impurity removal technologies. *Resources,*

Conservation and Recycling, 58, (2012) 79-87, https://doi.org/10.1016/j.resconrec.2011.10.010

[8] G. Gaustad, E. Olivetti, R. Kirchain, Improving aluminum recycling: A survey of sorting and impurity removal technologies, *Resources, Conservation and Recycling*, 58, (2012) 79-87, https://doi.org/10.1016/j.resconrec.2011.10.010

[9] S. K. Das, Emerging trends in aluminum recycling: Reasons and responses. *Light Metals*, 4, (2006) 911-916

[10] J. R. Duflou, A. Erman Tekkaya, M. Haase, T. Welo, K. Vanmeensel, K. Kellens, W. Dewulf, D. Paraskevas, Environmental assessment of solid state recycling routes for aluminium alloys: Can solid state processes significantly reduce the environmental impact of aluminium recycling?, *CIRP Annals*, 64(1), (2015) 37-40, https://doi.org/10.1016/j.cirp.2015.04.051

[11] V. K. Soo, J. Peeters, D. Paraskevas, P. Compston, M. Doolan, J. R. Duflou, Sustainable aluminium recycling of end-of-life products: A joining techniques perspective, *Journal of Cleaner Production*, 178 (2018) 119-132, https://doi.org/10.1016/j.jclepro.2017.12.235

[12] S. Eggen, K. Sandaunet, L. Kolbeinsen, A. Kvithyld, Recycling of aluminium from mixed household waste. *Light Metals* (2020) 1091-1100, https://doi.org/10.1007/978–3–030–36408–3_148

[13] S. Shamsudin, M. A. Lajis, Z. W. Zhong, Evolutionary in solid state recycling techniques of aluminium: a review. *Procedia CIRP*, 40, (2016) 256-261, https://doi.org/10.1016/j.procir.2016.01.117

[14] C. Bulei, M. P. Todor, T. Heput, I. Kiss (2018) *Recovering aluminium for recycling in reusable backyard foundry that melts aluminium cans*. In IOP Conference Series: Materials Science and Engineering, 416(1), https://doi:10.1088/1757–899X/416/1/012099

[15] C. Bulei, M. P. Todor, I. Kiss (2018) *Metal matrix composites processing techniques using recycled aluminium alloy*. In IOP Conference Series: Materials Science and Engineering, 393(1), https://doi:10.1088/1757–899X/393/1/012089

[16] C. Bulei, M. P. Todor, I. Kiss, V. Alexa (2019) *Aluminium matrix composites: Processing of matrix from re-melted aluminium wastes in micro-melting station*. In IOP Conference Series: Materials Science and Engineering, 477(1), https://doi:10.1088/1757–899X/477/1/012049

[17] C Bulei, I Kiss, V Alexa, Development of metal matrix composites using recycled secondary raw materials from aluminium wastes, *Materials Today: Proceedings*, 45(5), 2021, pp. 4143-4149, https://doi.org/10.1016/j.matpr.2020.11.926

[18] U. M. J. Boin, M Bertram, Melting standardized aluminum scrap: A mass balance model for Europe. *Jom*, 57(8), (2005) 26-33