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Opportunities for Adding Recycled Content to Primary Aluminum Products †

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Abstract: Rio Tinto is a leading producer of low-carbon primary aluminum due to its efficient processes and hydroelectricity. It has one of the lowest greenhouse gas (GHG) footprints in the world, which is below four tons of CO_2 per ton of primary aluminum. Nevertheless, integrating end-of-life recycling into primary aluminum products, although challenging, plays an important role in further reducing GHG emissions during aluminum production. This is why much effort has been made in recent years throughout Rio Tinto plants to find innovative solutions to overcome this challenge. In 2022, the first circular economy initiative was deployed at Laterrière Works with the addition of a remelt furnace with an initial production capacity of 22,000 tons per year. This project has contributed to adding capacity to remelt both internal process scrap and external industrial scrap. A second initiative is the operation of a new recycling center at Arvida Works to commence in 2025 that will process 30,000 tons per year of end-of-life scrap. As a primary alloy producer, the main challenge for Rio Tinto is to integrate these materials into current and new products without affecting their quality and performance. This paper will present preliminary studies on the chemical compatibility of scrap with current alloys, and the approach used for managing their organic content.

Keywords: primary aluminum; end-of-life recycling; GHG emissions reduction

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1. Introduction

Primary aluminum production from bauxite ores in Canada is approximately 2.9 million tons per year [1]. As a main primary aluminum producer, Rio Tinto produces more than 50 percent of Canadian aluminum production. Its Canadian smelter works are in Québec (Saguenay Lac Saint Jean) and British Columbia (Kitimat). In these regions, Rio Tinto Aluminum (RTA) also produces its own electricity through five hydropower plants. This contributes to Rio Tinto having one of the lowest aluminum carbon footprints in the world, below 4 tons of CO_2 per ton of aluminum.

Apart from its hydroelectricity, other sustainability initiatives are also driven by RTA to valorize residues and avoid waste accumulation. As an example, since 1990, aluminum dross from casting furnaces has been treated without salt addition using plasma furnaces in a partnership with Scepter. The residue from this treatment, called "Noval", is used as feedstock in cement and steel works. A second initiative was to recycle lime used in coke calcinatory scrubbers. In a collaborative effort with Laval University, its by-product, called anhydrite, was found to be a useful fertilizer for agriculture [2]. With the support of a local agriculture cooperative (Albanel COOP), the fertilizer has been used successfully in blueberry fields. A third example of by-product valorization is an asphalt containing a mixture of 5wt% of bauxite and carbon by-products. The pavement test was performed last year on an RT smelter road near RTA's Arvida Research and Development Center (ARDC). This initiative was developed and carried out in collaboration with the

Université du Québec at Chicoutimi (UQAC), Inter-Cité Construction, and the Transport Ministry of Quebec.

All these initiatives are in line with Rio Tinto's ambition to reduce emissions by 50 percent by 2030, to achieve net-zero emissions by 2050, and to reduce global environmental impacts. They also support RTA's customers in meeting their objectives to decarbonize their value chain.

One of the high-profile decarbonization projects is the development and deployment of ELYSIS technology in partnership with Alcoa, Apple, and the Government of Canada. This breakthrough technology, using inert anodes in the smelting process, will eliminate direct greenhouse gas emissions and produce pure oxygen as a by-product.

Although the majority of GHG emissions from aluminum production occurs between bauxite mining and reduction, improvements can also be made in casting centers. Typical emissions come from production equipment used for batching and casting ingots as well as auxiliary and preheating equipment for scraps, launders, filters, etc. RTA has been working to optimize energy consumption at the casting furnaces since 2005. To perform these improvements, automated furnace control parameters such as burner power, furnace pressure, and temperature targets were implemented. This has reduced the consumption of natural gas in Rio Tinto's North American plants by more than 20 percent compared to 2005 consumption [3] while maintaining an average scrap remelt ratio at around 10–15%. To further reduce natural gas consumption, a change in the burner technology is required. Some technology options are regenerative burners, oxyfuel, and plasma or hydrogen. The maturity and risk of these technologies vary considerably. Currently, the two most advanced technologies for a casting furnace are regenerative and oxyfuel burners [4]. RTA has selected the use of regenerative burners for new casting furnaces and will implement them at the new Alma billet casting facility.

Rio Tinto has taken steps to reduce its carbon footprint, but this is not the only area of focus. For aluminum to be truly green, it must be circular. Aluminum is 100% recyclable so long as the metal is collected, sorted, and introduced back into saleable ingots. Aluminum is key to meeting global decarbonization targets, especially in the automotive, renewable energy, and packaging sectors. As secondary supply will grow at about double the pace of primary for the next decade, demand for recycled content will continue to increase. Post-consumer scrap has a near-zero carbon value and requires about 5% of the energy needed to produce primary metal [5,6]. Customers are expecting sustainable solutions and, therefore, combining low-carbon primary aluminum from hydro-powered operations with recycled content is a highly desirable market offering.

Scrap is classified into three categories that have different market availability and attractiveness.

- First is internal process scrap. This is scrap that is generated in the production of ingots. Examples of internal process scrap are top and bottom butts, draining pans, and process dross.
- Second is industrial scrap that is generated during the fabrication process. Examples of industrial scrap are tail ends of extruded billets and stamping cut-offs.

The third category is post-consumer scrap, which is scrap recovered at the end of a product's life. This material is generally found in collectors' yards after items such as cars and windows have been disassembled and sorted into alloy types.

To support the transition to a circular economy, investments are required to manage the extra scrap intake without impacting the production rate. The first closed-loop recycling solution was introduced in 2020 in partnership with Shawinigan Aluminium Inc (SAI). This melting facility has an annual production capacity of 30 kt and was built to cater to the automotive, packaging, and construction sectors. It provides our customers an option to reprocess their industrial scrap. To supplement the closed-looped solution, another aluminum remelt furnace at the Laterriere plant was commissioned in 2022. The remelt furnace is equipped with regenerative burners and expanded capabilities to remelt both internal and industrial scrap from the automotive and packaging industries.

To incorporate recycled post-consumer aluminum, the construction of a specialized facility at Arvida Works was announced and will be operational in 2025. The facility will have an initial capacity of 30,000 tons per year and will be equipped with the latest environmental technologies to deliver best-in-class performance for the environment, safety, and metal quality. However, integrating this remelted scrap into primary production with the desired chemistry is challenging. Feed material needs to be well sorted upfront at the processor's yard to remove plastics and sort out the aluminum from ferrous and other non-ferrous metals. Scrap grades have varying expected chemistries and finding the right grade mix to fit the final desired chemistry is required to produce a saleable ingot.

The challenges of post-consumer scrap integration into primary production are described in this article.

2. Remelt Materials Selection

To develop a circularity offering, important considerations need to be recognized when selecting post-consumer scrap.

2.1. Sorting

The first step to recycle end-of-life (EOL) materials is to have access to different sources of well-sorted aluminum scrap. These materials should be classified into subcategories of aluminum scrap as defined by the Institute of Scrap Recycling Industries (IRSI) [7]. Each subcategory has a specific expected chemistry and a maximum level of contaminants such as ferrous materials, organics (such as plastic, paint, and rubber), or other trace elements. Scrap-sorting companies are also expected to remove the risk of radioactivity contamination that can come from, for example, recycling medical equipment. The quality and the reproducibility of the sorting are key points to optimize the processability of the remelt center.

To sort material, scrap dealers have access to different sorting techniques. For example, form assemblies are first crushed to free components, the proper sizing distribution required for the next sorting steps is obtained, and the bulk density is increased [8]. Magnetic separation is then used to remove iron followed by an air separation method for non-ferrous materials. Thereafter, a sink/float technique can be used to separate aluminum from unwanted non-ferrous materials such as zinc, magnesium, copper, high-density plastics, rubber, etc. That technique is based on the difference in density of all impurities compared to aluminum. This separation is performed with a liquid bath containing water and magnetite. Other scrap sorting techniques, such as spectroscopy, are used to separate impurities from aluminum. These techniques are based on the identification of the composition of the metal elements in the scrap mixture. The most used spectroscopy techniques are laser-induced breakdown spectroscopy (LIBS), X-ray fluorescence (XRF), and gamma fluorescence [9]. Figure 1 presents an example of different types of scrap bundles after sorting.

Figure 1. Different types of remelt material bundles after sorting.

2.2. Environmental and Safety Impact

Post-consumer scrap is typically contaminated by organics such as paint, coating, rubber, plastic, or oil. The amount and type of organics to be treated during a batch varies with the scrap types used, and an adequate gas treatment system is required to deal with burn offs. Organic characterizations on various scrap types to estimate weight percentage and the nature of gas produced are currently in progress at ARDC. This information will be used to define the adequate technical requirement of the gas treatment system to be used.

An inherent risk in dealing with molten metal is the risk of metal explosion. Bundles exposed to weather conditions such as rain or snowfalls may contain water, which is easily dealt with through preheating the bundle before submersion into the melt. Water entrapment, for example, in a closed tube, cannot be dried out using the same preheating cycle as for a regular bundle. Furnace design and other processing methods must be assessed to identify the system providing the best risk management solution.

2.3. Inventory Management

Each scrap sub-category has a different market value and alloy compatibility. To optimize value creation from scrap, the right mix aligned with process constraints and inventory availability is necessary. This requires a sufficient inventory level of various scrap sub-categories. An optimizer tool is already in use at the Laterriere plant to optimize scrap mix compatibility with the targeted chemistry. The tool is being upgraded to consider organic content balance and profitability. Similar tools are also available commercially [10].

3. Chemical Compatibility of Scraps with 6xxx Billets Alloys

At first, the new recycling center will mainly supply Rio Tinto Arvida's billet casting center. The alloys produced are mainly from the 6xxx alloy family, such as 6060, 6063, and 6061. To illustrate the chemistry challenge at hand, the chemical compatibility of 6063 and 6061 alloys with EOL remelt materials is discussed.

The chemistry difference between 6061 and 6063 on elements typically found in scrap is highlighted in Table 1. The first two lines are the maximum specification according to the Aluminum Association (AA), whereas the last two lines are hypothetical alloy specifications defined as 70% of the AA maximum or 70% of the AA average (if there is no max) for both alloys. Another exception is made for 6063 copper and zinc, whose values are often much lower than the maximum values mentioned in AA chemistry; these upper limits being typically around 0.02 wt.% for primary-based alloys as mentioned by Tjoetta et al. [11].

Table 1. Considered chemistry of 6063/6061 extrusion billets (wt.%).

Recipes	Si	Fe	Cu	Mn	Mg	Cr	Zn
AA6063 [12]	0.2–0.6	0.35	0.1	0.1	0.45–0.9	0.1	0.1
AA6061 [12]	0.4–0.8	0.7	0.15–0.4	0.15	0.8–1.2	0.04–0.35	0.25
6063	0.28	0.25	0.02	0.07	0.49	0.07	0.02
6061	0.42	0.49	0.23	0.11	0.9	0.14	0.18

As shown, the specification of 6061 has higher concentration tolerances on both alloying and trace elements compared to the 6063 alloy and therefore makes it a better candidate for scrap reintegration.

To evaluate chemistry compatibility, five scrap grades were utilized: Toto (6063 extrusions with up to 10 wt.% of painted 6063 and 10 wt.% of 6061), 6061 extrusion, 3xxx extrusion, aluminum used beverage can scrap (UBC), and cast aluminum [12,13]. It should be noted that the following analysis was based on the scrap chemistry assumption in Table 2. Since actual chemistries will vary based on material sourcing and the quality of scrap sorting, this variation will impact the capability to be recycled in the final product.

Table 2. Chemistry of the remelt materials.

Recipes [1]	Si	Fe	Cu	Mn	Mg	Cr	Zn
Toto [12]	0.42	0.385	0.118	0.105	0.712	0.110	0.115
AA6061 [12]	0.6	0.7	0.28	0.15	1	0.2	0.25
AA3003 [12]	0.6	0.7	0.12	1.2	0	0.03	0.1
Cast aluminum [2]	7	0.6	0.5	0.4	0.5	0.1	0.5
UBC scrap [13]	0.26	0.4	0.2	0.86	1.22	0.1	0.25

[1] The remaining element is Al. [2] The values presented are a mix of typical cast alloys based on all AA cast alloys.

3.1. Impacts of Trace Elements on 6xxx Billets

Mg and Si contents in 6xxx alloys are typically set to achieve a target strength and extrudability. These alloying elements are typically added to primary metal but when using recycled scrap, they are considered "pre-alloyed" and only minor additions are required. Other trace elements such as iron, copper, and zinc can be carried over when recycling post-consumer scrap; therefore, the concentration will be typically higher than a billet made from primary metal only.

Higher Cu, Zn, and Fe concentrations can have an impact on surface finish depending on the customer's requirements; some applications have a higher trace element tolerance than others. Architectural applications (such as building cladding) are one of the major sectors where surface finish is critical. In these applications, a surface coating is required to hide production-induced imperfections and defects. Anodizing and painting are also generally used to protect extrusion products from atmospheric corrosion over their service life, which can be longer than 10–20 years.

Concerns have been expressed about the impact of higher copper concentration on filiform corrosion (FFC) propensity, which lowers painted extrusion quality. The current consensus in the industry [11,14] is that copper levels up to 0.05% have no effect on FFC when a correct pretreatment is applied prior to painting.

Anodizing is generally more sensitive to impurity levels depending on the etching pre-treatment applied. The two etching chemical processes used are sodium hydroxide and acid.

1. Sodium hydroxide etching is a common process used to remove die lines, which decreases the gloss level of the substrate by removing up to 100 g/m^2 of aluminum prior to anodizing. The consistency of the surface finish is critical to allow an adequate color matching for the product. The appearance, color, and gloss of the anodized finish after such a pre-treatment will be affected by Fe, Cu, and Zn contents as follows:
    - A higher Fe level has a positive impact as it tends to promote a matte finish, so the target concentration is about 0.2 wt.% Fe [15].
    - Copper tends to increase anodized brightness even at a low concentration, around 0.03%. Ramanan et al. also showed that copper may increase the metal removed during etching, which generates more effluent [15]. This effect continues up to the upper limit allowed for this element in AA6063.
    - Zinc, present in the metal at relatively low levels, is well known to promote the "spangle" defect, which involves preferential grain attack [16,17]. Although this can be controlled to some extent by sodium sulfide additions to the etch bath or even by controlling the Cu/Zn ratio [18], in practice, this is difficult to implement with a feedstock with varying zinc content. An upper limit of 0.03 wt.% is widely recognized as an upper limit for anodizing quality billet.
2. Acid etch is the other anodizing pretreatment that is growing in popularity in North America. The pre-treatment is not as sensitive to metal composition [19] but does not always provide the type of matt finish required for large commercial projects.

3.2. Recycling Potential

Four potential remelt scenarios were simulated to investigate the maximum remelt content based on the material being recycled. For each scenario, both a 6063 and a 6061 final chemistry were targeted.

Case I—Maximizing total remelt constraining Toto and 6061 at 5 t each simulating market constraint on scrap purchasing.

Case II—Maximizing total remelt constraining Toto and 6061 at 15 t each simulating low market constraint on scrap purchasing.

Case III—Maximizing total cast aluminum remelt.

Case IV—Maximizing total UBC remelt.

In all cases, the maximum remelt addition for each scrap was calculated using a mass balance analysis. A 100 t furnace capacity with a 5 t heel was used. The chemistry of the primary metal used in the dilution was set at 0.05 wt.% Si and 0.1 wt.% Fe.

Table 3 details the results obtained from the four cases, first for a 6063 alloy and second for a 6061 alloy. The limiting element is specified under Critical element. A GHG reduction impact was also calculated to demonstrate the alignment with our sustainability objective.

Table 3. Maximum remelt content for each EOL scrap.

6063	**Case I**	**Case II**	**Case III**	**Case IV**
Scraps	**Mass (tons)**	**Mass (tons)**	**Mass (tons)**	**Mass (tons)**
Toto	5	9.3	0	0
AA6061	2.4	0	0	0
AA3003	4.8	4.7	0	0
Cast Aluminum	0	0	3.1	0
UBC scrap	0	0	0	7.6
Recycled content (wt.%)	**12.2%**	**14%**	**3.1%**	**7.6%**
Critical element	Cu, Mn, Zn	Cu, Mn, Zn	Si	Zn
GHG reduction	**−10.4%**	**−11.9%**	**−2.6%**	**−6.5%**
6061				
Toto	5	15	0	0
AA6061	5	15	0	0
AA3003	0	0	0	0
Cast Aluminum	4.1	2.9	5.1	0
UBC scrap	8.2	5.8	0	11.6
Recycled content (wt.%)	**22.3%**	**38.7%**	**5.1%**	**11.6%**
Critical element	Mn, Si	Mn, Si	Si	Mn
GHG reduction	**−19%**	**−32.9%**	**−4.3%**	**−9.9%**

As expected, maximizing alloy compatibility in Case I and II offers the greatest GHG reduction opportunity. The higher trace element tolerance of alloy 6061 eliminates copper constraints. The results in Case II show an opportunity to add up to three times more recycling content for 6061 alloys: limited to 14 tons for 6063 alloys and reaching 38.7 tons for 6061 alloys. This results in a lower carbon footprint potential (around 33% GHG reduction) on the customer product offering. 6061 alloys are less limited on the scrap type and offer the flexibility of adding a larger range of remelt material types such as cast aluminum or UBC. The limitation then becomes application-based, which needs to be aligned with corrosion resistance, surface quality, and mechanical property requirements. It should be noted that for many extruders, there is no inventory differentiation made between anodizing and non-anodizing billet quality feedstock; hence, most limiting AA6063/AA6061 chemistries are purchased from producers.

3.3. Friendly Recycling 6063 Alloys

Among the potential solutions that can be exploited to increase the recycling addition capability of 6063 alloys, the development of new friendly alloys could be a good alternative. The objective would be to work in collaboration with customers to find a chemistry with slightly higher limits than those currently used for applications that would not be affected by these modifications. These proposed chemistries would be based on accumulated knowledge of alloy development and validated when required by mechanical/surface characterizations at ARDC facilities.

Table 4 illustrates the impact of increasing Cu and Zn alloy limits on recycling content capacity using Case I assumptions in Section 3.2. Modifying the final targeted chemistry increases the recycled content potential by five tons when increasing Cu and Zn limits by 0.02 wt.% (Case V). An additional 0.02 wt.% increase (Case VI) would have a very limited impact as the limiting element becomes Mn. This further demonstrates that diversification of scrap types in the inventory will be also a key factor of success in maximizing recycled contents as previously discussed.

Table 4. Maximum remelt for 6063 with an increase in Cu and Zn targets.

6063	Case V: 0.04 Cu/0.04 Zn	Case VI: 0.06 Cu/0.06 Zn
Scraps	**Mass (tons)**	**Mass (tons)**
Toto	5	5
AA6061	5	5
AA3003	0	0
Cast Aluminum	1.3	2.3
UBC scrap	5.6	5.2
Recycled content (wt.%)	**16.9%**	**17.5%**
Critical element	Mn, Zn, Cu	Mn
GHG reduction	**−14.4%**	**−14.9%**

4. Conclusions

The announcement and commissioning of the Arvida recycling center are aligned with the sustainability goals advocated by Rio Tinto. The initiative will not only address the challenges of reducing GHGs, but also reduce the amount of EOL scrap to be exported as the quantity of these materials will continue to increase. However, there are environmental and HSE considerations as well as scrap chemistry challenges to consider:

- Two prerequisites from the remelt material recyclers need to be considered. First, they need to propose materials from an adequate and reproducible sorting process. Second, the mix of materials available should be adequate to optimize remelt for each batch performed.
- To ensure proper gas emission management from organics, characterization of organic compounds and content per type of remelt material is required. The ongoing study performed at Arvida Research and Development Center will define the gas treatment and collection required. Other safety hazards such as molten metal explosions due to water trapping, and radioactivity issues, must also be managed through equipment design or process.
- For critical anodized end-use applications, the availability of remelt materials with relatively low copper and zinc contents will dictate the amount of added recycled content, which could be limited.
- For applications less sensitive to anodized surface finish, collaborative work with customers to slightly increase Cu and Zn limits should be performed. This would enable the optimization of recycling content and GHG emission reductions to be maximized.

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