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Rotary Recycling of Aluminum Slags in Aluminum Shop Casting

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Abstract
Environmental friendly recycling is the trend toward total recycling of aluminium metal. In the secondary aluminium industry, due to the complexity of compositions and contaminants in the various types of aluminium scraps, an understanding of the behavior of different scraps during melting is crucial in the recycling process. In This Research, aluminum slags produced from melting aluminum alloy AA 8011 in melting and holding reverberatory furnace was collected. After the crushing and sorting, and passing from screen, the slag was heated in gas fired silicon carbide crucible furnace to 750°C, 800°C , 850°C and 900°C respectively and mixed with coverall flux No. 11, and then poured in cast iron mixing ladle with a 3 cm hole in bottom of ladle. This hole was placed to pass of molten metal and pour in preheated ingot molds. After adding 2% coverall no. 11, it was mixing at 100, 200, 250 and 300 RPM for 15 minutes. The recycled molten aluminum passed the hole and cast continuously in to the preheated ingot molds. The results show maximum efficiency of aluminum recycling in 850°C and 250 RPM. Metallographic and SEM microscopy tests, shows metallic and nonmetallic inclusions content and other impurities in each recycling conditions.

1. Introduction
Developments of aluminum alloys and increasing consumption of aluminum for production industrial parts, increase the amount of slags which form during melting or casting process significantly. In addition to economic costs, it has an adverse environmental impact. Therefore, the companies producing aluminum components are looking for ways to solve these problems. One of the most effective ways is recycling aluminum from melting furnaces [1]. In the European Union, about 60 % of the aluminum oxides are under operation and this annual value is on the rise [2]. Figure 1 show the aluminum production as the primary and secondary ingots and total production in period of 1950-2020 [2]. The factors that cause aluminum production growth can be divided as:
-High growth of aluminum demand
-High cost of aluminum production compared to aluminum recycling. According to the literatures, the amount of energy required to produce recycled aluminum is about 5 % of the primary aluminum production. That is, with the recycling of aluminum, 95 % of the energy saving required for the primary aluminum production [3].
- Environmental issues and environmental protection against hazardous materials.
- Technological development in recent years.

- Reducing the emission of toxic substances. Extraction of the bauxite ore and the production processes of primary aluminum cause the emission of toxic gases such as fluorides, sulfur dioxide, carbon dioxide and so. Although the production of recycled aluminum has a biological effect and affect air quality, but its negative effects are negligible. For example, the amount of carbon dioxide produce during recycling of slags is less than 95% of production primary aluminum. For carbon monoxide, it is less than 99% and fluoride gases released completely eliminates [3].

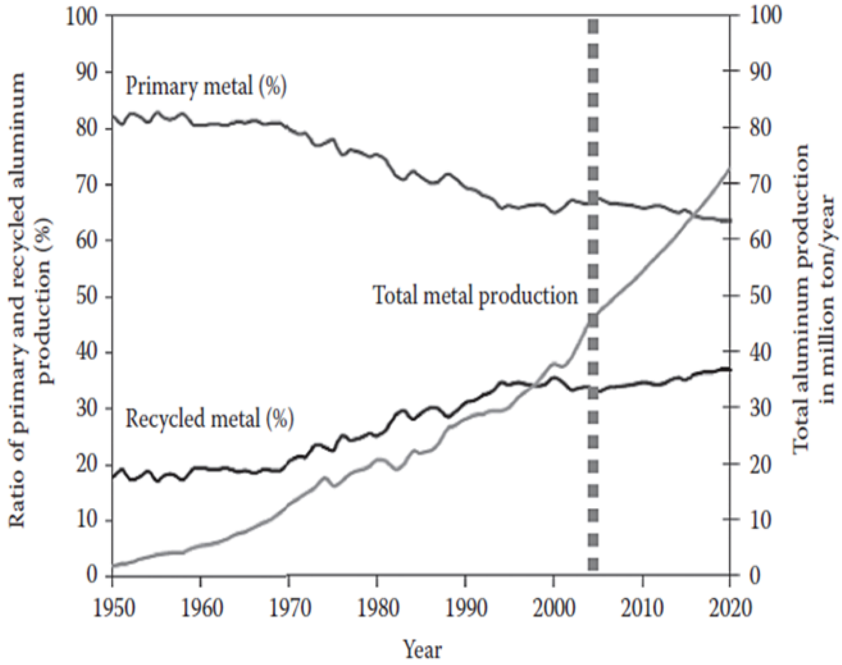

Figure 1: Production of primary and recycled and total aluminum in Europe

-Reduction of Burial Materials: International researches show that the recycling of aluminum has 85% lower burial materials in comparison with extraction of primary aluminum [4-5].

It should be considered that burial of slag in addition to environmental damage has many economic costs. For example only in UK, its cost is 80 million Euros per year [6].

- Reducing initial investment: Aluminum production requires many facilities and equipment. Investments in this sector are extremely difficult and require much financial resources. In some countries, these industries are usually operated by government support. But the equipment and facilities required for recycling are simple and have low cost. It is estimated that the production cost of recycled aluminum is 90% less than production of primary aluminum. The required facilities for recycling aluminum from slags are simple and have 95% lower cost in comparison with extraction facilities of primary aluminum [7].

1.1 Challenges of recycling aluminum from slags

-Problems relating to collection and sorting of slags: Slags have various kinds in comparison with bauxite. Also the slags are located in various factories and workshops and locations and sometimes far apart, which is difficult to collect and handle [8]:

- Air pollution: although the amount of toxic and non - toxic gases in the recycling factories is much lower than primary aluminum production, it can cause air and environmental pollution because many of the recycling centers are located in urban areas. Table 1 compare the type and amount of gases emitted from primary and recycled aluminum production [9].

Table 1: Type and amount of gases emitted from primary and recycled aluminum production

Chemical composition	Emitted gas from Primary aluminum extraction kg / mt	Emitted gas from recycling the slag / mt	Reduction Percentage
CO2	15.3	0.0702	95.4
CO	519	1.21	99.8
SO2	53.5	1.2	97.8
NOX	40.4	1.79	95.6
CH4	34	0.614	98.2
CF4	0.0858	0	100
C2F6	0.0104	0	100
HF	8.01	0	100
PAH	0.0266	0	100

- The problem of the micro - waste materials: recycling of slags, produce solid materials, which are not recycled or have small size which not commercial for recycling. Among Salt cakes which have less than 5 % aluminum [10].

1.2 Types of aluminum slags

Non salty slags

Sometimes this type of slags called white or grey slags. It is obtained from the melting of primary aluminum and according to the type of melting operation and its alloying elements, it can have 15-80 % aluminum. Examples are aluminum oxide, aluminum carbide (Al_4C_3), aluminum nitrides (AlN). In addition, these slags may have small amount of cryolite (Na_3AlF_6) or can have other elements according to melting analysis [11].

Salty slags

Salty slags are derived from remelting or secondary melting of aluminum or aluminum alloys which use fluxing in melting process. These types of slags have less than 20% aluminum and 30-50% aluminum oxide in composition [12]. White slags are more recyclable which produce from primary aluminum ingot melting. Sometimes this type of slags called dark or black slags [13].

1.3 Recycling of aluminum slags and purification of molten metal

Recycling of slags begins with their separation. At this stage, recycling companies will be able to buy these slags from the manufacturers of the foundry companies, the extrusion, or other manufacturers, [14]. Unfortunately one of the most problems of recycling the slag is the lack attentions of the companies and aluminum manufacturing plants in separation and stacking of aluminum slag. Most factories collect the slag without considering the type of alloy and without separation or stacking, which causes the recycling complicate and reduction of aluminum quality obtained from the slags.

One of the most important challenges in recycling industry is remained elements and impurities in aluminum ingots which destroy the mechanical and physical properties and create the defects in production parts. It is necessary that the recycled aluminum have economic benefits, high quality and maximum aluminum recycling. To achieve these goals, it is important to use the advance technologies and facilities [11]. This research considers the effect of temperature and mixing rate of slags in recycling process and their effects on quality and quantity of recycled aluminum and remained impurities in it.

2. Research Methodology

Slags resulted from melting aluminum alloy AA 8011 in reverberatory melting and holding furnace with 20 tons capacity in a large aluminum production company was collected. In this company, a mixture of 50% primary ingot, 30% secondary ingot and 20% scrap were used for melting. The slag used in the experiment was a mixture of white and black slags. In melting of aluminum alloys, coverall flux no. 11 applied for coating, cleaning and recycling of aluminum slags. The recommended flux is 1% wt%. This flux consist of 45% NaCl, 45% KCl, and 10% other additives. Before heating, the slags were checked and the fine content was separated by screen. Large pieces of slag were crushed for better heating and stirring. The weight of each batch of slags was 50 kg for each test. The heating of the slags was carried out in a silicon carbide crucible furnace with 750, 800, 850, and 900 ºC. Then the total content of each ladle was transferred to a preheated cast iron ladle with 3 cm hole at the central bottom and 1 kg (2%) coverall flux no 11 was added to each ladle. Then steel made mixer with 100, 200, 250, and 300 rpm was used to stirring the slags for 15 minutes. The molten aluminum extracted from slags was poured continuously from bottom ladle hole to preheated ingot molds where located under the hole. Figure 2 show the facility for stirring preheated slags. After cooling of ingots, they were weighted and required samples were cut from each one.

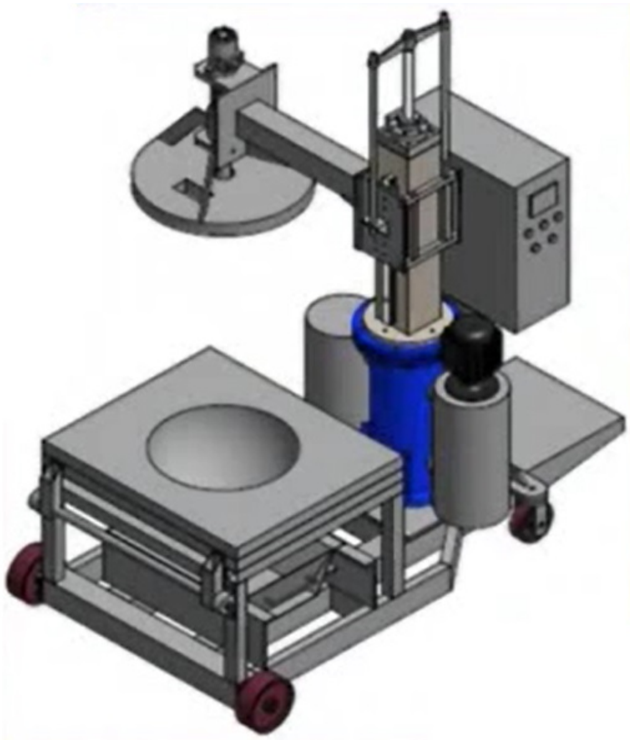

Figure 2: Mixing facility for preheated slags with adjustable rotating speed and time

Table 2 show chemical composition of recycled aluminum ingots from processing aluminum slags resulted of melting Al AA8011 in reverberatory furnace.

Table 2: Chemical Composition of recycled aluminum

Alloy	Mg	Mn	Cu	Fe	Si	Zn	Ti	Al
Wt%	0.1	0,1	0,1	0.85	0,35	0,1	0,03	Balance

3 Results and discussion

Table 3 shows the results of recycling aluminum from melting furnace slags. As can be seen, the maximum recycling is 66.8% which obtain at 850 ºC and 250 rpm. For evaluating the results, it is necessary to consider five factors.

3.1 Effect of heating temperature

Generally, heating affects the recycling of aluminum slags by two ways.

First, direct influence: Increasing the temperature causes melting of oxidized compounds which perform better recycling of aluminum slags. It should be noted, however, that the effect will be reduced if the temperature is too high. It causes the re-oxidation of metal and the loss of recycled aluminum. Low preheating temperature decrease reactivity of flux material and increase viscosity of oxides and decrease the efficiency of recycling process.

Table 3: Weight and percentage of aluminum recovered from 50 kg slag with 2% coverall flux no 11 at various temperatures and rotating rates.

Preheating Temperature (°C)	Rotating rate (rpm)	Aluminum Ingot weight (kg)	Wt% Aluminum Recovery
750	100	27.2	%54.4
	200	27	%54
	250	28.5	%57
	300	27.6	%55.2
800	100	28.3	%56.6
	200	28.7	%57.4
	250	30.5	%61
	300	29.3	%58.6
850	100	29.6	%59.2
	200	32	%64
	250	33.4	%66.8
	300	31.3	%62.6
900	100	29.1	%58.2
	200	30.2	%60.4
	250	31	%62
	300	30.2	%60.4

Second, indirect influence: Generally, the Al slag is a mixture of Al oxide, metals, chloride, fluoride, alloying elements and salts from the fluxing agent, nitride, carbide, sulfides, and other substances, which are the result of molten Al reactions with other elements present in the melting system. Heating can affect the flux function. By increasing the temperature, the flux viscosity decrease and can enter to the oxide layers and increase recycling efficiency. However, it should be note that, at extreme temperatures, the efficiency of flux can reduce and in addition to energy loss and gas formation, cause gas holes in products. It is expected that at optimal temperature, the amount of aluminum recycling is the highest and therefore, the flux has the highest performance. In this research, the optimum temperature for best flux operation is 850 ° C.

3.2 Effect of mixing rate

The main general categories of operations included in the aluminum slag recovery are slags pretreatment and mixing. Increasing the mixing rate, increase the contact surface of slags with flux and cause the better reaction between slags and flux and consequent increase the aluminum recycling. Extreme mixing rate, increase the slag temperature and cause re-oxidation of extracted aluminum or compounds. Concerning the results of table 2, are in agreement with this opinion. It can see from table 2 results, at high mixing rate, wt% aluminum recovery decrease. High mixing rate, increase friction of oxide particles which can increase the heating of bath and re-oxidation of recovered aluminum. Low mixing rate, increase viscosity of slags and flux, and consequently, decrease the mixing efficiency and reduce recycled aluminum. It is also reported by other researchers [15].

3.3 Effect of fluxing

Factory configuration, the type of slag usage, and the output product vary over the secondary aluminum industry. There are many researches which confirm the effect of fluxing on recycling of aluminum from slags and removing of impurities and the inhibition of re-oxidation of it. Most of fluxes have calcium fluoride ($CaF2$) which improve fluidity and increase inclusion removal and degassing of products [16]. Based on the recommendation of the researchers and the flux producers, the optimum weight percent for adding flux to preheating of slags is 1% and for mixing stage is 2%. It should be noted that higher content of flux, increase alkaline and rare earth elements and can increase problems in further melting and processing of products [17-18] .

3.4 Metallography assessment

After preparation of ingots, scanning electron microscopy (FE-SEM) model TeScan – Mira III made in Czechia republic was used for checking the microstructure of ingots. Figure 3a shows SEM microstructure of recycled aluminum which produced by heating at 850 ºC and mixing at 250 rpm, and Figure 3b shows SEM microstructure of recycled aluminum which produced by heating at 800 ºC and mixing at 200 rpm respectively. Nonmetallic compounds appear as angular and acicular shapes in microstructures. Comparing two images show lower inclusion in Figure 3a. Recycling of aluminum at 850 ºC and 250 rpm give better recycling and better quality of ingots. Probably, the added flux has better operation in these conditions.

Aluminum is a reactive metal, readily oxidizing when exposed to the high mixing rate or temperature during recycling process. It forms stable oxides and nonmetallic inclusions during the recycling, mixing melting, or casting processes [19-20]. The term „inclusion" refers to any type of un-dissolved foreign material present in cast metal ingots. Inclusions are well known as a common defect in cast or wrought products and normally are obtained during production processes [21-22]. Residual inclusions in castings, ingots, or slabs cause stress concentration, cracking, pinhole defect and reduce mechanical properties and economic production [23-24].

3.5 Chemical composition

Table 4 shows specification for chemical composition of aluminum AA 8011 according to the aluminum association standards. Comparing tables 2 and 4 shows that the chemical compositions of recycled aluminum and standard composition of AA8011, are more near together. The most difference is attributed to ferrous content of ingots which is higher than specification. Mixing and stirring of slags was done in cast iron crucibles and absorption of Fe from iron crucible may be occurred. The other main difference is related to silicon content. Silicon content of recycled aluminum ingots is lower than specification. Silicon has lower tendency to oxidation in comparison with aluminum and recycled slags has lower content of silicon oxides. So in recycling process, the recycled aluminum has lower content of silicon than molten aluminum in melting furnace.

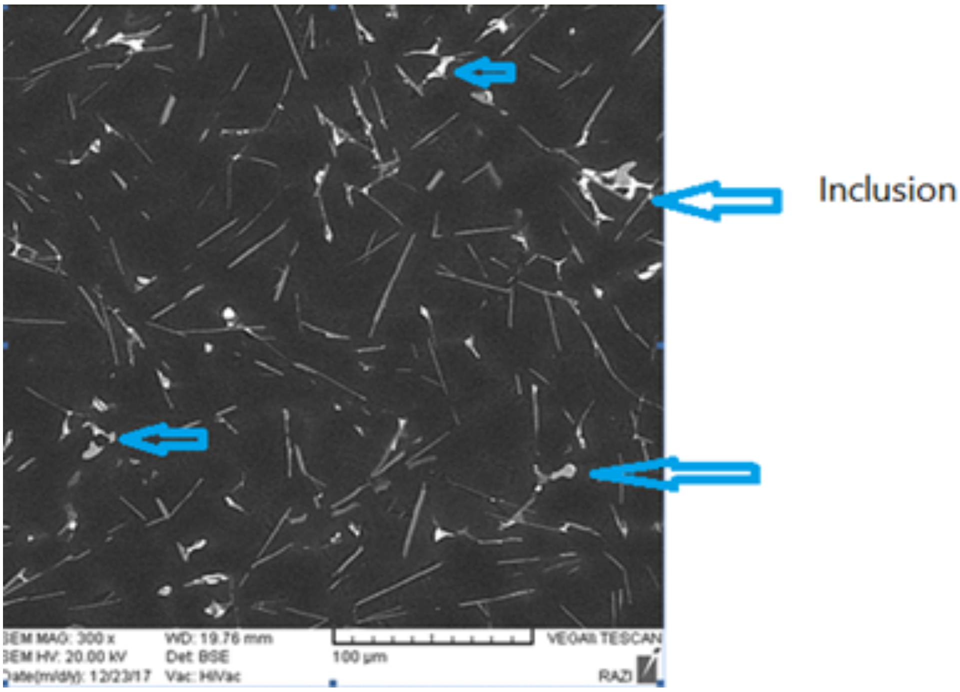

Figure3a: SEM microstructure of recycled aluminum at 850 ºC and 250 rpm

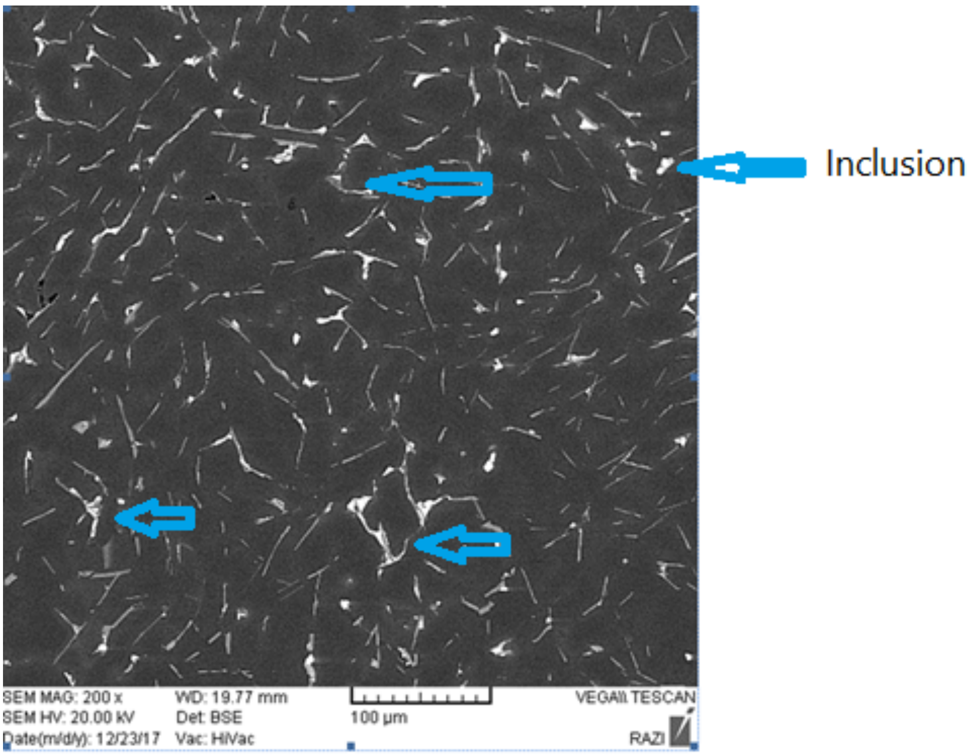

Figure3b: SEM microstructure of recycled aluminum at 800 ºC and 200 rpm

Table 4: Comparing chemical composition of recycled aluminum from slags with standard specification

Alloying Element	Element Percentage in Recycled Ingot	Specification AA8011 (wt%)
%Al	98.32%	97.5-99.1%
%Fe	1.2%	0.6%-1%
%Si	0.38%	0.5%-0.9%
%Cu	0.04%	Max: 0.1%
%Mn	O.03%	Max: 0.1%
%Mg	0.0%%	Max: 0.01%
%Zn	0.0%%	Max: 0.01%
%Cr	0.0%%	Max: 0.1%
%Ti	0.01%	Max: 0.05%
Total Remained	0.01%	Max: 0.015%

Conclusions

- Heating and mixing of the aluminum slags, reduce of slag size and breakage of oxide layers which surround aluminum particles and increase recycling efficiency. This breakage increase contact area between flux and slags and increase aluminum recycling.
- Heating of aluminum slags at 850° C and mixing at 250 rpm give maximum recycling of aluminum.

- Higher temperatures or mixing rate, increase re oxidation of recycled aluminum and decrease efficiency of recycling.

- Lower temperatures or mixing rate, reduce the fluidity of slags and decrease contact area between slag and flux and reduce the efficiency of recycling.

- Suitable fluxing process, not only increase the recycling efficiency but also increase ingots quality.

- The chemical composition of the recycled ingots is not significantly different from the primary alloy, most differences due to absorption of elements from ladle, or different oxidation tendency of alloying elements.

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