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Process of aluminum dross recycling and life cycle assessment for Al-Si alloys and brown fused alumina

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Abstract: In 2008, around 596 000 t of aluminum dross was generated from secondary aluminum industry in China; however, it was not sufficiently recycled yet. Approximately 95% of the Al dross was land filled without innocent treatment. The purpose of this work is to investigate Al dross recycling by environmentally efficient and friendly methods. Two methods of Al dross recycling which could utilize Al dross efficiently were presented. High-quality aluminum-silicon alloys and brown fused alumina (BFA) were produced successfully by recycling Al dross. Then, life cycle assessment (LCA) was performed to evaluate environmental impact of two methods of Al dross recycling process. The results show that the two methods are reasonable and the average recovery rate of Al dross is up to 98%. As the LCA results indicate, they have some advantages such as less natural resource consumption and pollutant emissions, which efficiently relieves the burden on the environment in electrolytic aluminum and secondary aluminum industry.
Key words: aluminum dross; life cycle assessment; Al-Si alloys; brown fused alumina

1 Introduction

Recently, China has become one of the biggest electrolytic aluminum production countries. The consumption of aluminum also increases rapidly and ranks second globally, only to the United States. According to the prediction from CRU (an independent business analysis and consultancy group focused on the mining, metals, power, cables, fertilizer and chemical sectors), the global electrolytic Al production in 2008 reached 4.254×10^7 t, and the main increase is from China. Report from National Bureau of Statistics (NBS) shows that the electrolytic Al production in China in 2008 was 1.32×10^7 t, which was one-third of the world's total amount[1−2]. Fig.1 shows the electrolytic Al production and increase rate of the world and China from 2000 to 2008.

During the process of producing electrolytic Al, more than 40 kg of Al dross is generated per ton of primary Al. Al dross from Hall-Héroult process usually contains approximately 60%−80% (mass fraction) of metallic Al[3]. Metallic Al has the best recoverability among the structural metallic materials which are frequently used in industry. At a couple of years after Hall-Héroult process was invented, the earliest secondary aluminum process came out actually. Secondary aluminum process has excellent environmental benefits. It not only decreases the production costs, but also reduces the emissions of pollutants[4]. In recent decades, because of environmental protection and continuous growth of consumption demand, the global secondary aluminum production grows rapidly. It is estimated by CRU and Hydro Group that the growth rate of secondary aluminum would be 5.8% per year and the production will reach 2.60×10^7 t in 2015[5−7].

Fig.2 shows the production of Al dross from secondary aluminum industry of China in recent years. The recovery of aluminum scraps is 75%−85%, and 200 kg of Al dross is generated per ton of secondary aluminum in aluminum scraps recycling process[3]. As shown in Fig.2, about 2.98×10^6 t secondary aluminum was produced in 2008. It could be calculated that about 5.96×10^5 t of Al dross was generated from secondary aluminum industry. Because of the shortage of mineral resources, the output of Al dross will be increased in the

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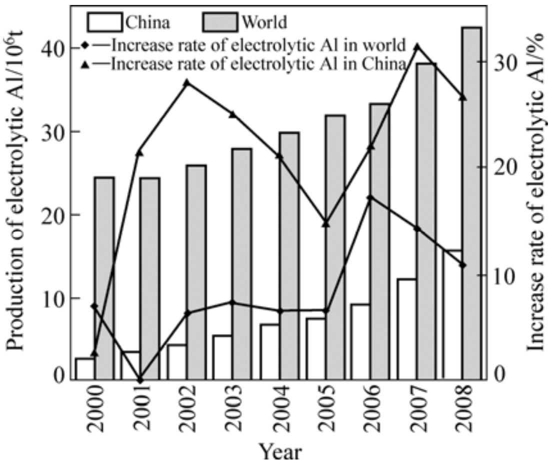

Fig.1 Production and increase rate of electrolytic aluminum[1−2, 5−7]

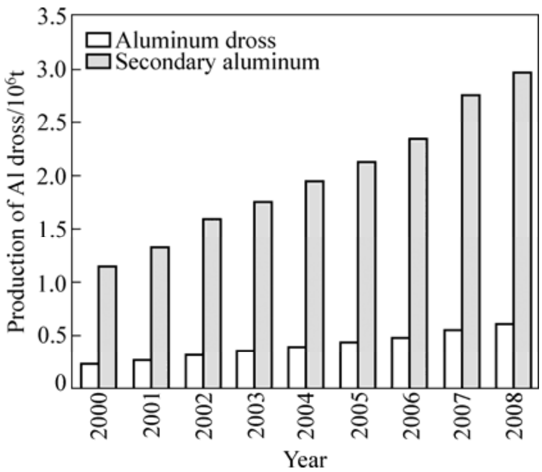

Fig.2 Production of Al dross from secondary aluminum industry in China[1−3]

future. Unfortunately, Al dross, which has high concentration of metallic Al, has not been fully utilized. Reports show the average cost of treatment is 1 680−2 300 RMB/t[8], and about 95% of Al dross is land filled[9]. It is not only a waste of current resources but also causes secondary pollutants which would affect surface and groundwater if Al dross is land filled without innocent treatment[10].

Al dross recycling is always a hard issue in the world and becomes a research focus in these years. For example, some investigations were made on waste aluminum recycling with generation of hydrogen[11−13], YOSHIMURA et al[14] believed that Al dross had the potential use of non-metallic product in the production of concrete blocks and raw materials for refractoriness. $AlPO_4$-5, η-Al_2O_3[15], CrAlPO-5[16] and calcium aluminate cement mixes[17−18] could be obtained from Al dross in the current researches.

Recycling is claimed to save resources, decrease the need for landfill space and enhance environmental awareness among the public[19]. Researchers believe that Al dross recycling is an economical and environmentally friendly process of waste utilization[20]. it is also the only way to realize sustainable development, energy saving and emissions reduction. In order to minimize the environmental impact by Al dross from secondary aluminum, two methods of recycling Al dross as a new raw material were investigated in this work. Al-Si alloys and brown fused alumina were manufactured by Al dross recycling. The effects of the process on the energy requirement, natural resources and carbon dioxide emission were evaluated and then life cycle assessment (LCA) of Al dross recycling was performed.

2 Experimental

2.1 Raw materials

Al dross was provided by SIMGA (one of the largest secondly aluminium manufactories in Asia). Table 1 shows the X-ray Fluorescence Analysis (XRF) results of Al dross. The cationic components of raw Al dross is given in Table 2.

Table 1 Chemical composition of Al dross (mass fraction, %)

Al_2O_3	SiO_2	MgO	Na_2O	Cl
64.4	7.4	6.4	6.2	5.8

CaO	Fe_2O_3	TiO_2	Others
2.7	2.5	1.5	3.1

Table 2 Cationic constitution of raw Al dross (molar fraction, %)

Al^{3+}	Si^{4+}	Mg^{2+}	Na^+	Ca^{2+}	Fe^{3+}	Ti^{4+}
73.05	7.13	9.26	5.78	2.79	0.91	1.08

2.2 Method

Al dross recycling process of Al-Si alloys and brown fused alumina manufacture is illustrated in Fig.3.

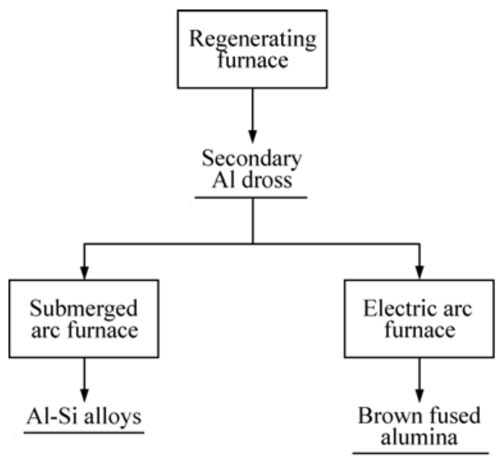

Fig.3 Flow chart of Al dross recycling

It shows a new flow chart of comprehensive utilization of Al dross in secondary aluminium industry.

2.2.1 Al-Si alloys

Al-Si alloys are widely used in industry. They are aslo used as intermediate products of Al-Si alloys and other alloys, such as deoxidizers in steel industry, machinery industry, building materials and auto industry. The rapid growth of global aluminium consumption creates a great demand for aluminite; however, aluminite resource on the earth will be exhausted. Raw materials of conventionally processed Al-Si alloys are: carbon (C), alumina (Al_2O_3) and silicon dioxide (SiO_2). Al_2O_3 and SiO_2 contained in aluminite are reduced by carbon and the final product is Al-Si alloys.

Electrothermal reduction method was applied in this work. Al dross was used instead of aluminite; gangue, petroleum coke and sulphite liquor were prepared for Al-Si alloys manufacturing. Based on the results of high temperature thermodynamic calculation, the reaction principle of reduction process is divided into three steps.

When the temperature is above 1 777 K, silicon dioxide first reacts with carbon by the following equation:

$$SiO_2+3C{=\!=}SiC+2CO \quad (1)$$

Carbon reacts with alumina to form Al_4O_4C at a higher temperature[21−22]:

$$2Al_2O_3+3C{=\!=}Al_4O_4C+2CO \quad (2)$$

Finally, at 2 526 K, SiC reacts with Al_4O_4C and carbon to form Al-Si alloys by the following equation[23]:

$$3SiC+3C+2Al_4O_4C{=\!=}8Al+3Si+8CO \quad (3)$$

In this process, an appropriate heating rate should be held until the third step is finished.

2.2.2 Brown fused alumina (BFA)

According to the relation diagram between Gibbs function and temperature, the order the elements will be reduced from their oxides in the system which carbon exists is[24]: Cu, S, Pb, Ni, Co, Fe, P, K, Zn, Na, Cr, Mn, V, Si, Ti, M, Al and Ca, and the oxides are reduced before alumina by proper manufacturing. Some impurities are removed and the other low-melting compounds evaporate during this reductive process. Then alumina forms high temperature phase and is melted to BFA finally. The main mineral phase of BFA which would be produced from Al dross is α-Al_2O_3, which can improve fire-resistant and mechanical properties of BFA. A series phase transitions of alumina are shown in Fig.4.

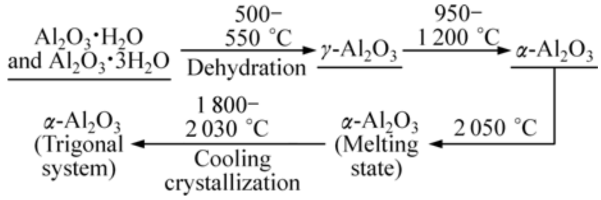

Fig.4 Phase transition process of alumina[25]

Two BFAs with 40% and 60% (mass fraction) Al dross were designed as BFA-40 and BFA-60, respectively. Al dross, bauxite and coke powder were well mixed in different ratios as listed in Table 3. Then, they were melted at high temperature in an electric ARC furnace. The products of BFA were naturally cooled, ground, water washed, magnetically separated and screened.

Table 3 Different raw materials proportion of BFA process (kg)

Process	Bauxite	Al dross	Coke powder	Scrap iron
BFA-40	600	400	15	50
BFA-60	400	600	20	50

3 Results and discussion

3.1 Material preparation

Fig.5 shows the products of Al-Si alloys by Al dross recycling. The chemical composition of Si-Al alloys is shown in Table 4.

Table 5 shows the physical and chemical properties

Fig.5 Photo of Si-Al alloys

Table 4 Chemical composition of Al-Si alloys (mass fraction, %)

Al	Si	Fe	Ti	Ca
55	43.9	0.7	<0.2	<0.2

Table 5 Physical properties and chemical composition of BFA products

Product	Composition(mass fraction)/%						Density/ $(g \cdot cm^{-3})$	Mohs' scale of hardness	Refractory temperature/K
	Al_2O_3	SiO_2	TiO_2	MgO	CaO	Fe_2O_3			
BFA-40	93.30	0.42	1.58	0.41	0.47	0.36	3.91	9	>2 073
BFA-60	94.70	0.38	1.33	0.36	0.98	0.27	3.94	>9	>2 073

of BFA products. They both exhibit chocolate brown, which are very close to traditional BFA produced with 100% bauxite. The refractory temperature is higher than 2 073 K, and the bulk density is higher than 3.90 g/cm^3. BFA-40 products measure up to GB1478−81.

SEM images of BFA are shown in Figs.6(a)−(d). As seen in Fig.6, the surfaces of BFA-40 and BFA-60 have compact microstructures. Fig.7 shows X-ray diffraction patterns of BFA products by Al dross recycling and traditional process. It can be seen that the peak positions are similar. So, the three samples have the same crystal structure and the main mineral phase is corundum. However, the sharp diffraction peaks of curve (c) indicate that BFA-40 contains some well-crystallized spinel but no other mineral phases. X-ray quantitative analysis shows that BFA-60 also contains some calcium-hexaluminum phase.

3.2 LCA of Al dross recycling

LCA is gaining wider acceptance as a method that enables the quantification of environmental interventions and evaluation of the improved options throughout the life cycle of a process, product or activity[26−28]. In 1990s, LCA developed rapidly and reached a certain level of harmonization and standardization, such as ISO standard and established guidelines. Fig.8 shows the LCA framework, which is also a four-step process[29−30]. LCA is a tool or a methodological framework for comparing goods and services (products) and for identifying opportunities for reducing the impacts attributed to associated wastes, emissions, climate change and resource consumption[31−32].

LCA of the two methods of Al dross recycling deals with inventory analysis of Al dross recycling and evaluation of environmental impact assessment.

3.2.1 Inventory analysis

The system boundary of this LCA study is the process of Al dross recycling, including resource and energy import, production process and the output of products and contaminations. Recycling of products is not included because the applications are multiplicate and complex. The functional unit of Al dross recycling system is defined as 1 t product.

Table 6 shows the resources consumption of 1 t products for traditional electrolytic Al, Al-Si alloys and BFA products.

Figs.9(a) and (b) show system boundary of recycling Al dross for Al-Si alloys and BFA products, respectively. Table 7 shows life cycle inventory of 1 t products for traditional electrolytic Al, Al-Si alloys and BFA products.

Table 6 Resources consumption of 1 t products (kg)

Product	Bauxite	Cryolite	Fluoride salt	Carbon anode
Electrolytic Al[4, 33]	4 272	15.0	18.9	500
Product	Gangue	Al dross	Petroleum coke	Sulphite liquor
Al-Si alloys	3 750	750	500	300
Product	Bauxite	Al dross	Coke powder	Scrap iron
BFA-40	600	400	15	50
BFA-60	400	600	20	50

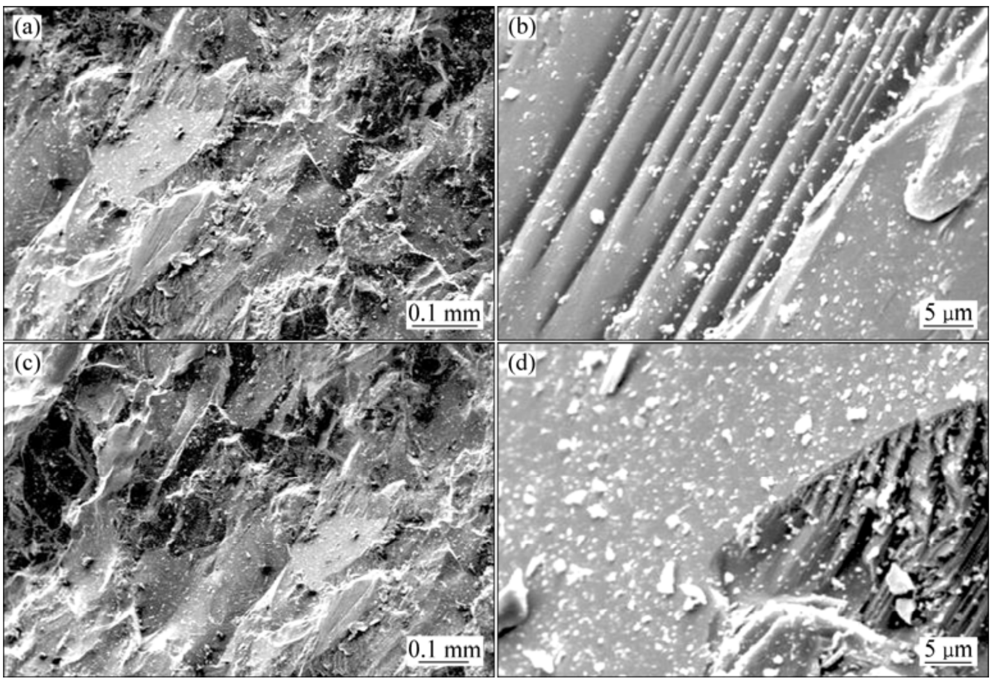

Fig.6 SEM images of BFA-40 (a, b) and BFA−60 (c, d)

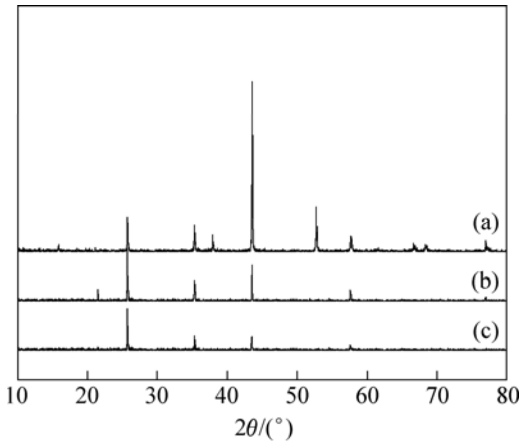

Fig.7 XRD patterns of BFA products: (a) Traditional process; (b) BFA-40; (c) BFA-60

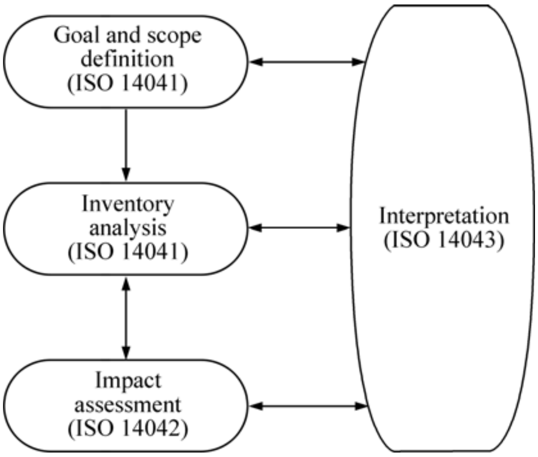

Fig.8 Life cycle assessment framework[26−27, 29−30]

As shown in Fig.9(a), in input term, the raw materials of this process include 750 kg of Al dross, 3 750 kg of gangue, 500 kg of petroleum coke and 300 kg of sulphite liquor. 4.86×10^4 MJ of electricity are consumed during this process. And in output term, 4744 kg of carbon dioxide, 2 300 kg of wastewater and 12 kg of solid waste are emitted. The recovery rate of Al dross during the process for Al-Si alloys is 98.4%.

As shown in Fig.9(b), in input term, the raw materials of BFA-60 process are: 600 kg of Al dross, 400 kg of bauxite, 50 kg of scrap iron and 20 kg of coke power. 0.72×10^4 MJ of electricity is consumed. And in output term, 2 965 kg of carbon dioxide, 2 000 kg of wastewater and 5 kg of solid waste are emitted. The recovery rate of Al dross during the process for BFA-60 is as high as 99.17%. In input term, the raw materials of BFA-40 process are: 400 kg of Al dross, 600 kg of bauxite, 50 kg scrap iron and 15 kg of coke power. 0.71×10^4 MJ of electricity is consumed. 2 687 kg of carbon dioxide, 2 274 kg of wastewater and 4.7 kg of solid waste are emitted. The recovery rate of Al dross during the process for BFA-40 is as high as 98.83%.

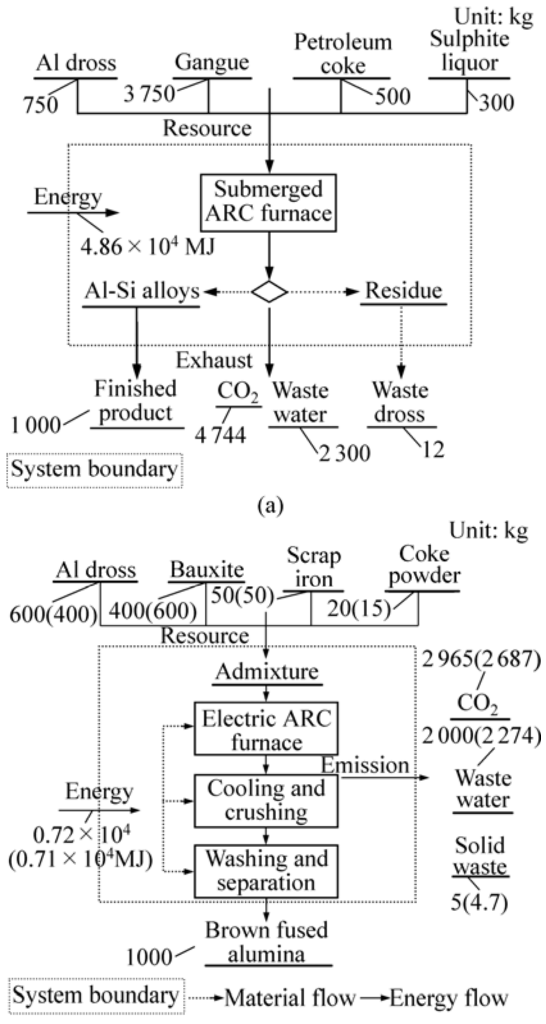

Fig.9 System boundary of recycling Al dross for Al-Si alloys (a) and BFA products (b)

Table 7 Life cycle inventory of 1t products

Product	Input		Output		
	Resources/kg	Electricity/MJ	CO_2/kg	Wastewater/kg	Solid waste/kg
Electrolytic Al[4, 33]	4 806	17.47×10^4	8 566	6 610	86.8
Al-Si alloys	5 300	4.86×10^4	4 744	2 300	12.0
BFA-40	1 065	0.71×10^4	2 687	2 274	4.7
BFA-60	1 070	0.72×10^4	2 965	2 000	5.0

3.2.2 Environmental impact

Table 8 shows the comparison of proposed processes and traditional process in main indexes. The main indexes including resources consumptions, electricity consumption, carbon dioxide emission, wastewater emission and solid waste emission were compared with those in electrolytic Al process. The results show that the quantities of resources, energy sources consumptions and pollutants emissions in proposed processes are less than the quantity of electrolytic Al process, especially during the process of Al dross recycling for BFA products. In the process of BFA-40, only 22.2% of the resources are consumed, 4.06% of electricity is consumed, 31.37% of carbon dioxide is emitted, 34.40% of wastewater is discharged and 5.41% of solid waste is discharged (compared with electrolytic Al process). In the process of BFA-60, only 22.3% of resources were consumed, 4.12% of electricity is consumed, 34.61% of carbon dioxide is emitted, 30.26% of wastewater is discharged and 5.76% of solid waste is discharged (compared with electrolytic Al process).

Table 8 Comparison of proposed processes and traditional process in main indexes (%)

Product	Resource	Electricity	CO_2	Waste water	Solid waste
Electrolytic Al	100	100	100	100	100
Al-Si alloys	110	27.8	55.38	34.80	13.82
BFA-40	22.2	4.06	31.37	34.40	5.41
BFA-60	22.3	4.12	34.61	30.26	5.76

The resources consumption of Al-Si alloys are as high as that of electrolytic Al process; however, it consumes 750 kg of Al dross per ton of Al-Si alloys. It is effective for the reduction of Al dross discharging from aluminum industry.

Environmental effects of proposed processes of Al dross system compared with electrolytic Al process are shown in Fig.10. The results indicate that the utilization of Al dross as Al-Si alloys and BFA resource is effective for the reduction of carbon dioxide and waste emissions. The environmental effect in terms of carbon dioxide, wastewater and solid waste for Al-Si alloys are −44.62%, −65.2% and −86.18%, respectively, compared with those of electrolytic Al. The environmental effect in terms of carbon dioxide, wastewater and solid waste for BFA-40 are −31.37%, −65.6% and −94.59%, respectively, compared with those of electrolytic Al. The environmental effect in terms of carbon dioxide, wastewater and solid waste for BFA-60 are −68.63%, −69.74% and −94.3%, respectively, compared with those of electrolytic Al.

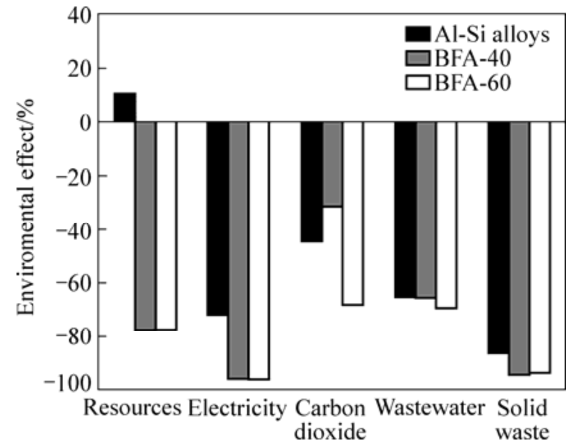

Fig.10 Environmental effect of proposed processes of Al dross system compared with electrolytic Al

4 Conclusions

1) Processes of Al-Si alloys and BFA were investigated in order to reduce the pollution caused by Al dross in aluminum industry.

2) The results indicate that the two methods can reclaim a large amount of Al dross and produce eligible productions, such as Al-Si alloys and BFA.

3) Al dross recycling can efficiently relieve the burden on the environment in aluminum and secondary aluminum industries. Meanwhile, it also brings economic benefits.

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References

[1] The global electrolytic aluminum production in 2008 will reach to 42.54 million tons [EB/OL]. [2008−2−2]. http://paper.cnmn.com.cn/Content.aspx?id=9238&q= 2608&v=2. (in Chinese)

[2] The statistic bulletin of economic and social development of China in 2008 [EB/OL]. [2009−2−26]. http://www.stats.gov.cn/tjgb/ndtjgb/qgndtjgb/ t20090226_402540710.htm. (in Chinese)

[3] YANG Seng, WU Zhu-cheng, YANG Guan-qun. Treatment of the aluminum waste residus and waster ashes [J]. Non-ferrous Metals Recycling and Utilization, 2006.10: 22−24. (In Chinese)

[4] LI Pei-ying. The productions and applications of secondary aluminum [M]. Beijing: Chemical Industry Press, 2007: 6−7. (in Chinese)

[5] WENG Li-min, KANG Jun-wei. Secondary aluminum-bright-spot of recycle economy [J]. Nonferrous Metals Processing, 2009, 38(4): 66−69. (in Chinese)

[6] The global aluminum recycle [J]. Resource Recycling, 2008, 6: 8. (in Chinese)

[7] ZHANG Lun-he. Status of secondary aluminium industry and its countermeasures in China [J]. Light Metals, 2009, 6: 3−5. (in Chinese)

[8] NAKAJIMA K, OSUGA H, YOKOYAMA K, NAGASAKA T. Material flow analysis of aluminum dross and environmental

assessment for its recycling process [J]. Materials Transactions, 2007, 48(8): 2219−2224.

[9] OAKDENE H. Aluminium industry could dramatically reduce landfilling of furnace waste [EB/OL]. [2007−11−11]. http://www.ohlsti.co.uk/ohl/newsletter/ohl_wmr312.pdf.

[10] WANG Yan. Production flow and evaluation of brown fused alumina by recycling aluminum dross [R]. Shanghai: Shanghai Jiao Tong University, 2008. (in Chinese)

[11] HIRAKI T, TAKEUCHI M, HISA M, AKIYAMA T. Hydrogen production from waste aluminum at different temperatures, with LCA [J]. Materials Transactions, 2005, 46(5): 1052−1057.

[12] HIRAKI T, YAMAUCHI S, IIDA M, UESUGI H, AKIYAMA T. Process for recycling waste aluminum with generaton of high-pressure hydrogen [J]. Environ Sci Technol, 2007, 41(12): 4454−4457.

[13] NAKAJIMA K, OSUGA H, YOKOYAMA K, NAGASAKA T. Material flow analysis of aluminum dross and environmental assessmentfor its recycling process [J]. Materials Transactions, 2007, 48(8): 2219−2224.

[14] YOSHIMURA H N, ABREU A P, MOLISANI A L, DE CAMARGO A C, PORTELA J C S, NARITA N E. Evaluation of aluminum dross waste as raw material for refractories [J]. Ceramics International, 2008, 34(3): 581−591.

[15] DAS B R, DASH B, TRIPATHY B C, BHATTACHARYA I N, DAS S C. Production of η-alumina from waste aluminium dross [J]. Minerals Engineering, 2007, 20(3): 252−258.

[16] KIM J, BISWAS K, JHON K W, JEONG S Y, AHN W S. Synthesis of $AlPO_4$-5 and CrAPO-5 using aluminum dross [J]. Journal of Hazardous Materials, 2009, 169(1/2/3): 919−925.

[17] EWAIS E M M, KHALIL N M, AMIN M S, AHMED Y M Z, BARAKAT M A .Utilization of aluminum sludge and aluminum slag (dross) for the manufacture of calcium aluminate cement [J]. Ceramics International, 2009, 35(8): 3381−3388.

[18] PICKENS J W, MORRIS E L. Process for preparing calcium aluminate from aluminum dross: USA Patent No: 6238633 [P]. 2001−05−29.

[19] BLOMBERG J, SODERHOLM P. The economics of secondary aluminium supply: An econometric analysis based on European data [J]. Resources Conservation and Recycling, 2009, 53(8): 455−463.

[20] SHINZATO M C, HYPOLITO R. Solid waste from aluminum recycling process: Characterization and reuse of its economically valuable constituents [J]. Waste Management, 2005, 25(1): 37−46.

[21] QIU Zhu-xian. Si-Al-Fe alloys manufacture by electric reduction process [J]. Light Metals, 1991, 1: 31−34. (in Chinese)

[22] LIHRMANN J M. Thermodynamics of the Al_2O_3-Al_4C_3 system: I. Thermochemical functions of Al oxide, carbide and oxycarbides between 298 and 2100 K [J]. J Eur Ceram Soc, 2008, 28(3): 633−642.

[23] DI Hong-li. Si-Al alloys manufacture by carbon hot-reduction [J]. Light Metals, 1982, 11: 38−47. (in Chinese)

[24] LI Xiao-na. Synthesis $MgMl_2O_4$ spinel from aluminum dross and the application in Al_2O_3 -$MgAl_2O_4$ refractory [D]. Shanghai: Shanghai Jiao Tong University, School of Materials Science and Engineering, 2008: 14−22. (in Chinese)

[25] LIU Da-qiang, LIU Yuan-gui. New technology of making brown adamite from aluminium ash [J]. Journal Harbin Univ Sci ＆Tech, 1996, 1(2): 48−50. (in Chinese)

[26] Inter-national standard ISO 14040. Environmental management—Life-cycle assessment—Principles and framework [S].

[27] FINKBEINER M , INABA A, TAN R, CHRISTIANSEN K, KLÜPPEL H J. The new international standards for life cycle assessment: ISO 14040 and ISO 14044 [J]. The International Journal of Life Cycle Assessment, 2006, 11(2): 80−85.

[28] AZAPAGIC A. Life cycle assessment and its application to process selection, design and optimisation [J]. Chemical Engineering Journal, 1999, 73(1): 1−2.

[29] HEIJUNGS R, GUINE ´E J B, HUPPES G, LANKREIJER R M, UDO DE HAES HA, WEGENER SLEESWIJK A, ANSEMS A M M, EGGELS P G, van DUIN R, de GOEDE H P. Environmental Life-cycle assessment of products: guide and backgrounds [C]//Leiden University, Leiden: Centre of Environmental Science, 1992: 17−21.

[30] LINDFORS L G, CHRISTIANSEN K, HOFFMAN L, VIRTANEN Y, JUNTILLA V, HANSSEN O J, RÖNNING A, EKWALL T, FINNVEDEN G. Nordic guidelines on life-cycle assessment [C]//Nordic Council of Ministers Copenhagen: The Nordic Council, 1995: 20.

[31] REBITZER G, EKVALL T, FRISCHKNECHT R, HUNKELER D, NORRIS G, RYDBERG T, SCHMIDT W P, SUH S, WEIDEMA B P , PENNINGTON D W. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications [J]. Environment International, 2004, 30(5): 701−720.

[32] PENNINGTON D W, POTTING J, FINNVEDEN G, LINDEIJER E, JOLLIET O, RYDBERG T, REBITZER G. Life cycle assessment Part 2: Current impact assessment practice [J]. Environment International, 2004, 30(5): 721−739.

[33] EAA. Environmental Profile Report for the European Aluminium Industry: Life Cycle Inventory Data for Aluminium Production and Transformation Processes in Europe [EB/OL]. [2008-10-10]. http://www.eaa.net/upl/4/en/doc/EAA-Environmental-profile-report-May08.pdf

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