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Analysis of anthropogenic aluminum cycle in China

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Abstract: Anthropogenic aluminum cycle in China was analyzed by the aluminum flow diagram based on the life cycle of aluminum products. The whole anthropogenic aluminum cycle consists of four stages: alumina and aluminum production, fabrication and manufacture, use and reclamation. Based on the investigation on the 2003−2007 aluminum cycles in China, a number of changes can be found. For instance, resources self-support ratio (RSR) in alumina production dropped from 95.42% to 55.50%, while RSR in the aluminum production increased from 52.45% to 79.25%. However, RSR in the Chinese aluminum industry leveled off at 50% in the period of 2003−2007. The respective use ratios of domestic and imported aluminum scrap in the aluminum industry of 2007 were 5.38% and 9.40%. In contrast, both the net imported Al-containing resources and the lost quantity of Al-containing materials in aluminum cycle increased during the same period, as well as the net increased quantity of Al-containing materials in social stock and recycled Al-scrap. Proposals for promoting aluminum cycle were put forward. The import/export policy and reducing the loss of Al-containing materials for the aluminum industry in China in the future were discussed.

Key words: anthropogenic; aluminum cycle in China; SFA; weighted average method; average use life

1 Introduction

Element flow is composed of anthropogenic flow and natural flow. Anthropogenic flow contains three forms, including fossil fuels combustion, minerals mining and processing and biomass fuels combustion, while the natural flow contains the soil erosion, seawater splash and net primary production [1,2].

In this work, the aim is mainly focused on bauxite mining and processing, which can be called anthropogenic aluminum cycle [1]. That is because it is a human intensively industrial activity, in which primary aluminum production is an energy-intensive process. The recovery and reuse of aluminum scrap has the potential to provide an additional source for aluminum production, and the use of scrap in aluminum production can not only reduce the consumption of bauxite, but also reduce the energy input and emission output. As China's energy consumption and CO_2 emissions have increased quickly in recent years and its energy gap has been in the expansion, the recovery and reuse of aluminum scrap should be paid more attention.

From 1991 to 2007, aluminum production and consumption in China have grown sharply with the rapid development of Chinese economy by 17.25% and 16.90% respectively, which are much higher than those of the global level by 4.22% and 4.39%, as shown in Table 1 [3−5]. Aluminum production mainly depends on two kinds of resources: bauxite and scrap. As a developing country, China has been lack of scrap in recent years [6,7] so that the bauxite consumption increases more quickly than that in developed countries. Compared with the demand, bauxite is severely in shortage and can only be used for several years in the future [8]. Analysis of anthropogenic aluminum cycle is very useful in finding the recycling status of aluminum scrap in Chinese aluminum industry so that it is able to attain saving of Al-containing resources, energy consumption and reducing of waste emissions.

The studies of aluminum cycle or a certain stage in the process of aluminum cycle have already been carried out in recent years. MELO [9] used three different kinds of models to predict the amount of aluminum old scrap

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Table 1 Variation of aluminum production and consumption amount in China and globe in 1991−2007

Year	Production amount/kt		Consumption amount/kt	
	China	Globe	China	Globe
1991	962.5	19652.6	985.0	18743.4
1992	1096.0	19459.2	1328.0	18557.6
1993	1254.5	19714.6	1350.0	18133.6
1994	1498.4	19111.8	1537.0	19715.3
1995	1869.7	19663.6	1685.0	20551.7
1996	1900.7	20846.3	1750.0	20683.8
1997	2178.6	21798.1	2115.0	21869.8
1998	2435.3	22653.9	2425.4	21889.3
1999	2808.9	23707.1	2925.9	23355.5
2000	2989.2	24418.1	3532.7	25059.1
2001	3575.8	24436.0	3545.4	23721.5
2002	4511.1	26076.0	4152.0	25372.3
2003	5962.0	28000.6	5177.6	27606.5
2004	6688.8	29921.7	6190.9	29960.6
2005	7806.0	32020.8	7118.6	31709.3
2006	9264.0	33965.1	8380.0	33994.6
2007	12284.0	38087.3	11979.0	37246.4
Increasing rate	17.25%	4.22%	16.90%	4.39%

in the waste management stage in Germany. BOIN and BERTRAM [10] carried out mass balance analysis in the aluminum recycling industry for the EU-15 in 2002. MARTCHEK [11] used a simplified model to analyze the global aluminum cycle in 2003. PLUNKERT [12] adopted aluminum flow framework to analyze the aluminum cycle in the United States in 2000. HATAYAMA et al [13] calculated the output of aluminum old scrap produced from different sectors. DAHLSTRÖM and EKINS [14] analyzed aluminum flow in the United Kingdom in 2001 combining substance flow analysis and value chain analysis together. In China, CHEN et al [15] used aluminum flow diagram to analyze aluminum cycle of China in 2005 and they explored the production, consumption, import and export, losses and changes of stocks of aluminum in China for 2001, 2004 and 2007 [16]. However, most of these studies were snapshots of bauxite mining and processing in one year period. They did not consider how long the use life of aluminum products is and primarily care about aluminum flows in one year period. In fact, it is better to combine the analysis of anthropogenic aluminum cycle with the average life span of aluminum products life cycle. Then, it can show us the whole picture of anthropogenic aluminum cycle, which is useful in knowing the fundamental characteristics of aluminum flow, e.g. the influence of aluminum products output on the availability of secondary resources for aluminum industry.

This work is based on the theory of metal's industrial metabolism [17,18], and combined the analysis of aluminum cycle with the average use life span of aluminum products. Firstly, we give the anthropogenic aluminum flow diagram based on the aluminum products life cycle; secondly, the average use life of aluminum products life cycle was analyzed by the weighted average method; then substance flow analysis with time factor of the products life cycle [7,19,20] was adopted to analyze anthropogenic aluminum cycle in China in 2007; next, aluminum flow indices of Chinese aluminum industry during the period of 2003−2007 were calculated; last, but certainly not least, proposals for future development of Chinese aluminum industry were discussed.

2 Methodology

2.1 Anthropogenic aluminum flow diagram based on life cycle of aluminum products

The entire anthropogenic aluminum cycle comprises four stages, as shown in Fig. 1 [7,19−23].

Some explanations for the four stages are as follows [13−15].

1) Production: Bauxite mining/milling, the production of alumina and aluminum, has been treated as a separate process, and is shown at stage I. The dissipating amount of Al-containing materials during this stage contains tailing, red sludge and slag.

2) Fabrication & manufacture: The stage II is the fabrication and manufacture stage of the aluminum products. Aluminum flows at this stage include the fabrication of aluminum semis and aluminum alloy semis, and the manufacture of intermediate commodities and finished products.

3) Use: Aluminum products leave the manufacture stage in the form of finished products or being embedded into assembled products (e.g. automobiles). When the aluminum products are produced, they are widely used in national economy, such as constructions and vehicles.

4) Waste management: The retrieve of obsolete aluminum products is the fourth stage in aluminum cycle. Some of obsolete aluminum products are retrieved after their life cycle $\Delta\tau$, while some are permanently stored in terrestrial establishments and constructions; otherwise, they will be dissipated into environment during their life cycle. Aluminum products usually enter their use period after being produced, while the scraps are often recycled in the same year as they are retrieved from obsolete aluminum products. Therefore, the average life span of aluminum products life cycle usually depends on both the distribution of different use

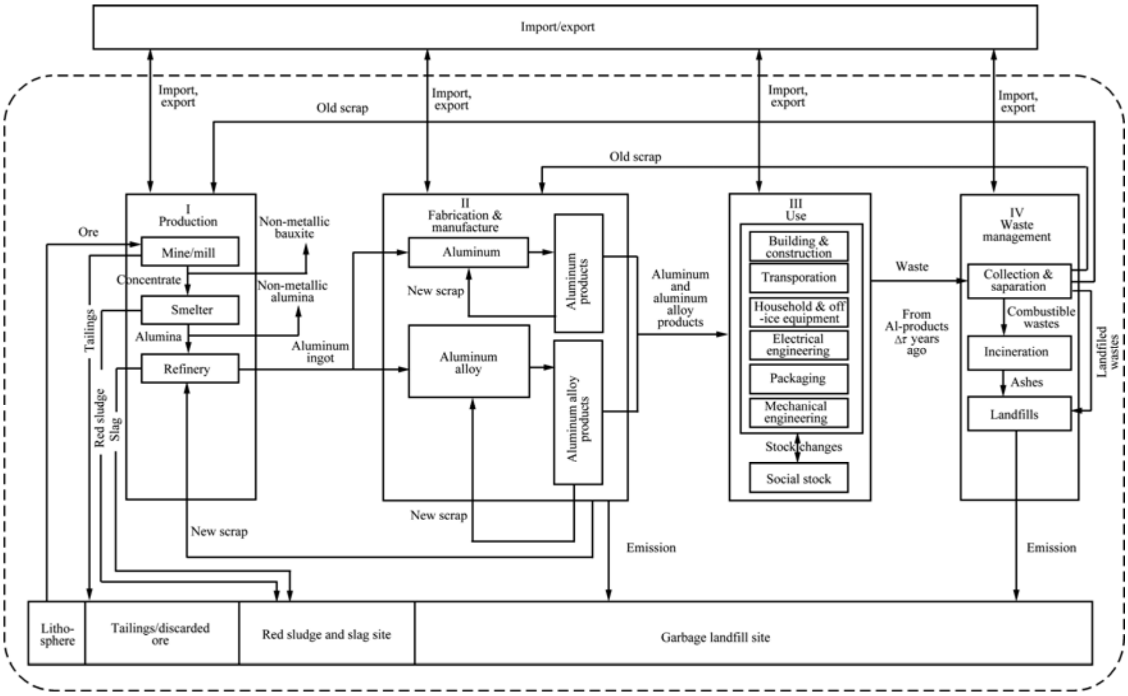

Fig. 1 Anthropogenic aluminum flow diagram

categories of Al–containing products and their use lives.

Two notes for Fig. 1 are stated below.

1) All the flow rates indicated in Fig. 1 are not in materials kind, actually, but they are the flow rates of Al contained in flowing materials, which represents an Al-flow diagram for a life cycle of aluminum products.

2) The time concept is clearly shown in Fig. 1; $\Delta\tau$ is the average use life of aluminum products.

2.2 Implementation of aluminum flow analysis based on life cycle of aluminum products

2.2.1 Data preparation

According to the method described in Fig. 1, data collected for this study could be grouped into four categories: 1) Data on production of bauxite, alumina and aluminum, fabrication and manufacture of aluminum products; 2) Data on the use categories and amount of aluminum final products; 3) Data on the import and export of Al-containing materials; 4) Data on the use lives of the different use categories of aluminum final products.

Data on production of bauxite, alumina and aluminum, fabrication of aluminum were well compiled annually by China Nonferrous Metals Industry Yearbook and other references [3,24] and therefore easily can be collected. Manufacture of aluminum final products and loss rate of aluminum during the aluminum products life cycle were calculated according to the major technical economic targets in Refs. [3,11,15]. Data on the consumption structure and quantities of aluminum by end-uses can be acquired from CEInet Statistics Database and CICC Research Department. Data on the import and export are available from China Nonferrous Metals Industry Yearbook and SMM Statistics Database distributed by the General Administration of Customs of China. The use lives of the different use categories of final aluminum products were drawn lessons from Ref. [9].

2.2.2 Average use life of aluminum products

The crucial element in modeling aluminum products in use and end life of aluminum products depends on the analysis of the average use life of aluminum products, which can be calculated by the weighted average method.

Average use life of aluminum products $\Delta\tau$ can be calculated by [19]

$$\Delta\tau = \sum_{i=1}^{n} f(x_i) \times \Delta\tau_i \tag{1}$$

where i is the use category of aluminum products (i=1, 2, 3, ⋯, n); $f(x_i)$ is the percentage of the use category i of aluminum products; $\Delta\tau_i$ is the life span of the use category i of aluminum products.

Consumption structure of Chinese aluminum products in 2003−2007 by end uses is shown in Table 2. Aluminum products were widely used in the following fields: transportation, mechanical engineering, electrical engineering, building and construction, packaging, household and office equipment and others. The main consumption areas are building and construction, transportation and electrical engineering.

Based on the calculation by Eq. (1) using distribution patterns of the average life span of aluminum products [9] and consumption structure of Chinese aluminum products (Table 2), the average life span of aluminum products can be derived, as described in Table 3.

3 Results and discussion

3.1 Anthropogenic aluminum cycle in China in 2007

According to the four stages in anthropogenic aluminum cycle (Fig. 1) and some references, such as China Nonferrous Metals Industry Yearbook and other references [3,9,11,24], the aluminum flow diagram for the anthropogenic aluminum cycle in China in 2007 is given in Fig. 2. Corresponding data of aluminum flow described in Fig. 2 are shown in Table 4. We set the average life cycle of aluminum products in 2007 in China as 16 years according to Table 3.

Table 2 Consumption structure of aluminum products in China in 2003−2007 by end uses

Use category	Consumption/%				
	2003	2004	2005	2006	2007*
Transportation	16.2	15.0	15.0	17.0	24.0
Mechanical engineering	7.4	11.6	9.4	5.8	10.0
Electrical engineering	18.0	15.0	15.0	18.0	15.0
Building and construction	37.2	30.0	36.0	33.0	33.0
Packaging	8.3	8.1	8.1	16.0	8.0
Household and office equipment	5.4	8.5	6.9	4.3	5.0
Others	7.5	11.8	9.6	5.9	5.0

Source: CEInet Statistics Database. * CICC Research Department, http://www.okokok.com.cn/Htmls/GenCharts/081029/12793.html

Table 3 Average use life of aluminum products in 2003−2007 in China

Probability distribution	Use life/a				
	2003	2004	2005	2006	2007
Normality	19.38	17.80	18.98	17.65	18.64
Weibull(Average life expectancy)	17.78	16.27	17.40	16.20	17.14
Beta(Average life expectancy)	17.80	16.18	17.39	16.21	17.13
Weibull(Most likely life expectancy)	16.89	15.43	16.53	15.39	16.31
Beta(Most likely life expectancy)	17.29	15.59	16.86	15.73	16.59

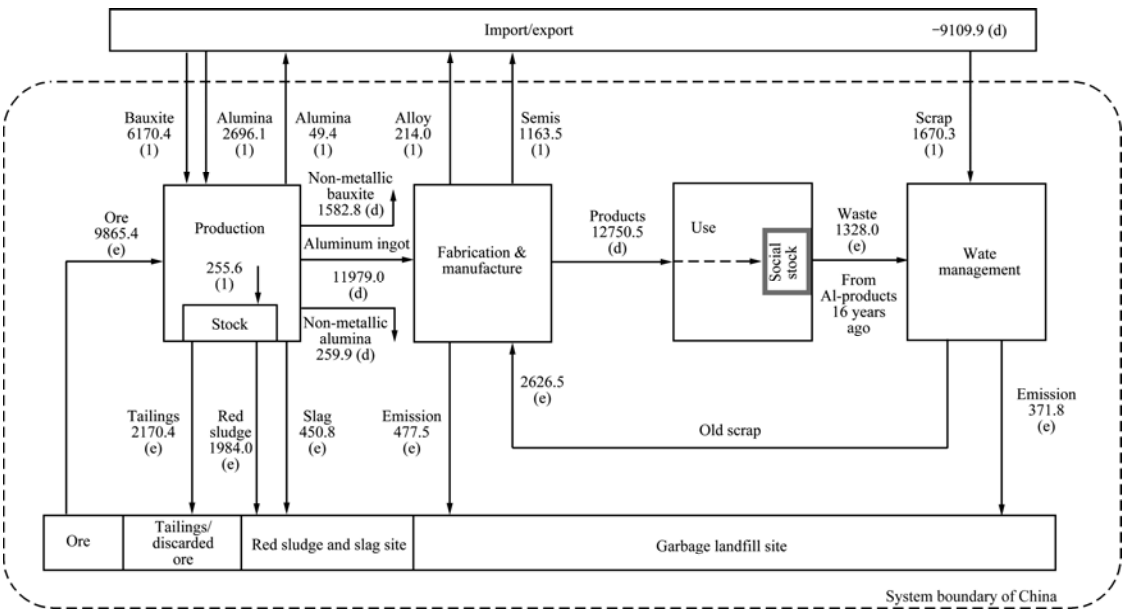

Fig. 2 Aluminum flow diagram in China in 2007 (unit: kt/a) (Letter in bracket follow data shows origin of data: (1) Reference; (d) Calculation; (e) Estimate)

Table 4 Explanations on data described in Fig. 2

Item	Symbol	Value[1]/kt	Quantitative relation	Data source
Ore mined	O_k	9865.4		O_k was estimated based on the major technical economic targets in Refs. [3] and [15]
Tailing	O_w	2170.4		O_w was estimated based on the major technical economic targets in Refs. [3] and [15]
Self-produced bauxite	O_z	7695.0	$O_z=O_k-O_w$	
Net imported bauxite	I_1	6170.4	I_1=imported bauxite−exported bauxite	Ref. [3]
Bauxite used in alumina production	O_A	12282.6		O_A was calculated based on the major technical economic targets in Ref. [3]
Non-metallic bauxite	K_f	1582.8	$K_f=O_z+I_1-O_A$	
Red sludge	R_w	1984.0		R_w was estimated based on the major technical economic targets in Refs. [3] and [15]
Self-produced alumina	Y_z	10298.6		Ref. [3]
Net imported alumina	I_2	2696.1	I_2=imported alumina−exported alumina	Ref. [3]
Alumina used in aluminum production	Y_A	12734.8		Y_A was calculated based on the major technical economic targets in Ref. [3]
Non-metallic alumina	Y_f	259.9	$Y_f=Y_z+I_2-Y_A$	
Slag	T_w	450.8		T_w was estimated based on the major technical economic targets in Refs. [3] and [15]
Self-produced aluminum	P_τ	12284.0		Ref. [3]
Net imported aluminum	I_3	−49.4[2]	I_3=imported aluminum−exported aluminum	Ref. [3]
Net increase of Al-stock	S_n	255.6		Ref. [3]
Al-loss during production	D_1	4605.2	$D_1=O_w+R_w+T_w$	
Aluminum used in aluminum products fabrication and manufacture	P_A	11979.0	$P_A=P_\tau+I_3\text{-}S_n$	
Net imported alloy	I_4	−214.0[2]	I_4=imported alloy−exported alloy	Ref. [3]
Net imported semis	I_5	−1163.5[2]	I_5=imported semis−exported semis	Ref. [3]
Al-loss during fabrication and manufacture	D_2	477.5		D_2 was estimated based on the major technical economic targets in Refs. [3] and [15]
Obsolete aluminum product produced in 2007	$M_{\tau-\Delta\tau}$	1328.0		Ref. [3]
Self-produced old scrap recycled in 2007	F_z	956.2	$F_z=\alpha M_{\tau-\Delta\tau}$	α is the recycling rate[3] of obsolete aluminum products, $\alpha\approx0.72$ [25]
Net imported scrap	I_6	1670.3	I_6=imported scrap−exported scrap	Ref. [3]
Aluminum products output	M_τ	12750.5	$M_\tau=P_A+I_4+I_5+F_z+I_6-D_2$	
Al-loss during obsolete aluminum products recycling in 2007	F_s	371.8	$F_s=M_{\tau-\Delta\tau}-F_z$	
Old scrap recycled in 2023	A_2	9180.4	$A_2=\alpha M_\tau$	α is the recycling rate of obsolete aluminum products, $\alpha\approx0.72$ [25]
Al-loss during obsolete aluminum products recycling in 2023	D_4	3570.1	$D_4=M_\tau-A_2$	
Al-loss during aluminum products life cycle of 2007	D	8652.8	$D=D_1+D_2+D_4$	

1 represents that all the values are Al-contained; 2 represents net exported; 3 can be seen in glossary.

3.2 Materials flow indices of aluminum industry in China in 2007

Several important materials flow indices of Chinese aluminum industry in 2007 were calculated based on Fig. 2. The interpretations and calculations of Chinese aluminum flow indices in 2007 are shown in Table 5.

3.3 Materials flow indices of aluminum industry in China in 2003−2007

Aluminum cycles in China from 2003 to 2006 were also analyzed [3,24] (not listed here), which is similar to the analysis of aluminum flow in 2007 shown in Fig. 2. Consequently, materials flow indices of aluminum industry in China in the period of 2003−2006 are presented in Table 6.

Resources self-support ratios (RSR) in China have different changes. For example, RSR in alumina production (Z_1) was dropped, but RSR in aluminum production (Z_2) was increased, and RSR of the aluminum industry (Z_3) in China was leveled off in the period of 2003−2007, respectively. With the increase of the output of alumina, resources for alumina production gradually depend on the imported bauxite more and more heavily. Resources self-support ratio in the aluminum industry dropped a lot in 2007 because of the rapid increase of the output of the alumina and aluminum at the same time.

In recent years, the overall aluminum scrap use ratio (A_S) has been in the range of 13%−17%, and the amount of self-produced aluminum scrap has been less than that of the imported one. The aluminum scrap used today was originated from the aluminum products produced about 16 years ago, but the output of aluminum products in China in the 1990s was only 1/11−1/9 of Chinese contemporary aluminum products. However, even all the aluminum products are changed into aluminum scrap, they will merely provide a small amount of the total materials required. There are some Al-containing substances dissipated or buried in the underground establishments during the use stage of their life cycle, which are impossible to gather them and turn them into aluminum scrap. Therefore, Chinese contemporary self-produced old aluminum scrap use ratio (Z_S) in aluminum production is smaller, which is about 1/19−1/14. What we can do is to try our best to retrieve the obsolete aluminum products and regenerate them, for

Table 5 Aluminum flow indices in China in 2007

Aluminum flow index		Symbol	Definition	Calculating formula	Ratio/%
Resources self-support ratio(RSR) and resources imported ratio(RIR)	RSR in alumina production	Z_1	Self-produced bauxite accounted for the overall bauxite consumption in the alumina production	$Z_1=\frac{O_z}{O_z+I_1}\times 100\%$	55.50
	RIR in alumina production	J_1	Imported bauxite accounted for the overall bauxite consumption in the alumina production	$J_1=\frac{I_1}{O_z+I_1}\times 100\%$	44.50
	RSR in aluminum production	Z_2	Self-produced alumina accounted for the overall alumina consumption in the aluminum production	$Z_2=\frac{Y_z}{Y_z+I_2}\times 100\%$	79.25
	RIR in aluminum production	J_2	Imported alumina accounted for the overall alumina consumption in the aluminum production	$J_2=\frac{I_2}{Y_z+I_2}\times 100\%$	20.75
	RSR of aluminum industry	Z_3	Self-produced resources accounted for the overall resources consumption in the aluminum industry	$Z_3=\frac{O_z+F_z}{O_z+F_z+I_1+I_2+I_3+I_4+I_5+I_6}\times 100\%$	48.71
	RIR of aluminum industry	J_3	Imported resources accounted for the overall resources consumption in the aluminum industry	$J_3=\frac{I_1+I_2+I_3+I_4+I_5+I_6}{O_z+F_z+I_1+I_2+I_3+I_4+I_5+I_6}\times 100\%$	51.29
Aluminum scrap use ratio of aluminum industry	Self-produced aluminum scrap use ratio	Z_S	Self-produced aluminum scrap accounted for the overall resources consumption in the aluminum industry	$Z_S=\frac{F_z}{O_z+F_z+I_1+I_2+I_3+I_4+I_5+I_6}\times 100\%$	5.38
	Imported aluminum scrap use ratio	J_S	Imported aluminum scrap accounted for the overall resources consumption in the aluminum industry	$J_S=\frac{I_6}{O_z+F_z+I_1+I_2+I_3+I_4+I_5+I_6}\times 100\%$	9.40
	Overall aluminum scrap use ratio	A_S	Aluminum scrap accounted for the overall resources consumption in the aluminum industry	$A_S=\frac{F_z+I_6}{O_z+F_z+I_1+I_2+I_3+I_4+I_5+I_6}\times 100\%$	14.78

Table 6 Material flow indices of aluminum industry in China in period of 2003−2007

Year	Z_1/%	J_1/%	Z_2/%	J_2/%	Z_3/%	J_3/%	Z_S/%	J_S/%	A_S/%
2003	95.42	4.58	52.45	47.55	52.41	47.59	7.04	6.61	13.65
2004	94.58	5.42	55.32	44.68	56.14	43.86	6.25	10.76	17.01
2005	90.78	9.22	54.97	45.03	56.20	43.80	5.52	12.14	17.66
2006	72.82	27.18	65.82	34.18	55.37	44.63	5.17	10.13	15.30
2007	55.50	44.50	79.25	20.75	48.71	51.29	5.38	9.40	14.78

solving the shortage of aluminum scrap in a certain extent. The situation of lack of aluminum scrap is hard to change in the case of fast increment of aluminum production.

3.4 Net imported, lost quantities, net increase in social stock, Al scrap recycled and loss in aluminum products life cycle of Al-containing resources

3.4.1 Net imported Al-containing resources

Amount of net imported bauxite and scrap increased annually in the period of 2003−2007. Aluminum was net exported in this period. Alloy and semis were net exported in 2006 and 2007. Net imported Al-containing resources have been increased during this period (see Fig. 3).

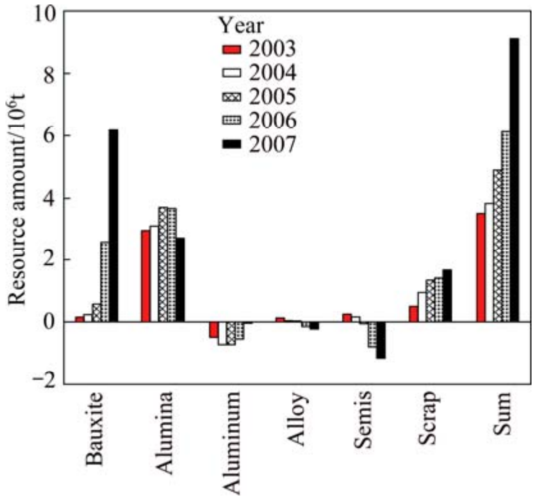

Fig. 3 Net imported Al-containing resources in China in period of 2003−2007

3.4.2 Lost amount of Al-containing materials

Aluminum emissions in tailing, red sludge and slag, etc, increased annually, especially for the aluminum emissions in red sludge, as Bayer process was taken more and more widely in recent years in China. The lost amount of Al content increased in the period of 2003−2007 (see Fig. 4).

3.4.3 Net increase of Al content in social stock

The amount of Al products into social stock and obsolete Al products from social stock increased and maintained almost constant in China in the period of 2003−2007, respectively. Hence, the net increase of Al content in social stock was enhanced in this period (see Fig. 5).

3.4.4 Al scrap recycled in 2003−2007 and loss in aluminum products life cycle

Al scrap recycled in China was increased in the period of 2003−2007, and the loss of aluminum in the life cycle will be expanded, especially the life cycle of aluminum products produced in 2007 (see Fig. 6).

3.5 Strategy to promote aluminum cycle

3.5.1 Policies status of regenerated aluminum industry in developed countries

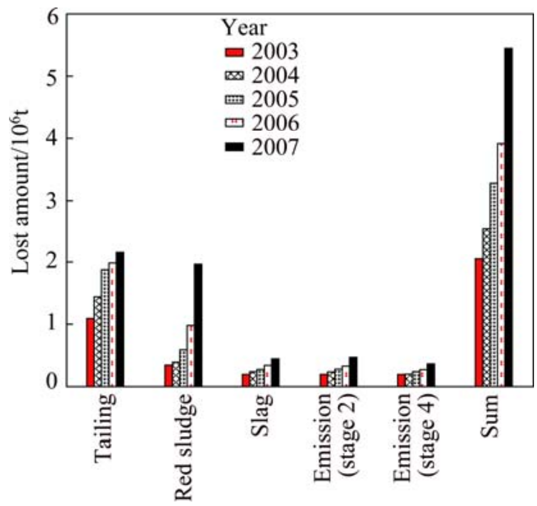

Fig. 4 Lost amount of Al-containing materials in China in 2003−2007

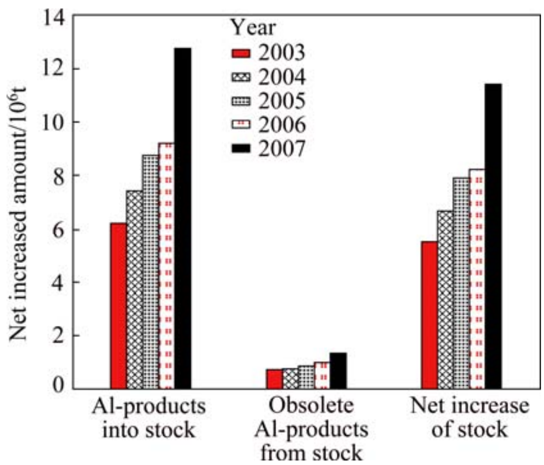

Fig. 5 Net increased amount of Al-containing materials in social stock of China in 2003−2007

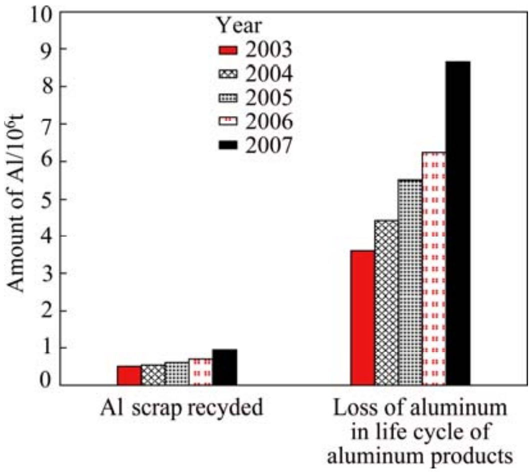

Fig. 6 Amount of Al scrap recycled and loss of aluminum in life cycle of aluminum products in 2003−2007

1) Comprehensive laws and regulations

The whole process, containing callback, collection, identification, transportation, imbursement and smelting for regenerated nonferrous metal, has been made detailed regulations in developed countries. For example, callback and regeneration of metal scrap in USA must adhere to the National Environmental Policy Act, Clean Water Act, Clean Air Act, Pollutant Prevent Act, Resource Conservation and Recycling Act, etc. Related laws and regulations in European countries also have played important roles in the callback and recycling for regenerated nonferrous industries.

2) Sound management and operation mechanism

Regenerated aluminum industry has sound management and operation mechanism in developed countries. Industrial license admittance system has been set up for regenerated aluminum industrial enterprises, which must meet the requirements of large-scale recycling factories, advanced recovery and recycling technologies and completed environmental protect facilities.

3) Strict inspection system

In European countries, there are strict regulations for the production environment of regenerated aluminum recycling factories. Government would punish those factories for against environmental protection law. They could even be forced to close down.

4) Positive policy for development of regenerated aluminum industry

Industrial policy mainly includes compulsory recycling policy that aluminum final products manufacture should consider reclaiming the obsolete products at the design stage, and mortgage policy that aluminum final products manufacture should pay a deposit for perceiving recovery the obsolete products when selling any new products.

Economic policy mainly includes financial subsidies, soft loan and special tax, etc. For instance, USA and Japan both implement financial subsidies for projects of regenerated nonferrous metal, while Iceland implements capital supply policy and Korea provides a long-term loan [26].

3.5.2 Main problems of industrial policy for promoting aluminum cycle in China

1) Unsustainable policy system of Chinese aluminum industry

Nowadays, many mineral processing enterprises only have interests to expand the scale of production and drive sudden huge profits. They do not want to improve the recovery rate of ore milling or save aluminum bauxite resource. In fact, Chinese bauxite production has been far from meeting the demand of the raw materials required for smelting.

In aluminum smelting process, current policies direct to new smelting technologies and large-scale of smelting, which is able to improve aluminum-smelting technology and enhance the efficiency of resource use; on the other hand, the consumption of bauxite increases due to the failure of tackling challenges of structural adjustment of raw materials.

2) Unreasonable value added tax for regeneration enterprises

The current policies are that metal scrap retrieving enterprises exempt from value added tax, but recycling enterprises have to pay tax. As a result, it encourages retrieving enterprises, but harms recycling enterprises. In fact, underpaid or unpaid taxes during aluminum scrap purchasing are transferred to the recycling enterprises, which stops normal economic relationships between retrieving enterprises and recycling enterprises [26].

3.5.3 Promoting aluminum cycle in China

The energy use in aluminum production with the second aluminum resources is only about 4% of that with raw materials [27]. Increasing the amount of regenerated aluminum production vigorously could help Chinese aluminum industry to ease the resource and energy constraint to a certain degree, and be beneficial for realizing the sustainable development of Chinese aluminum industry. The insufficiency of bauxite and energy resources is the major bottleneck, which has restricted the development of Chinese aluminum industry for a long period of time. Due to the huge population base, per capita bauxite and power share in China is still low, and the aluminum industry faces the challenges of constant supply of raw materials and power. In addition, a huge amount of red sludge is generated in the process of alumina production which causes ecological damage and restricts the development of Chinese aluminum industry. The utilization of recycled aluminum resources can reduce not only the dependence on raw materials and energy, but also the influence on the environment. Therefore, it is one of the effective ways to solve the resource, energy and environment constraints in the industrialization process.

According to the consultation report distributed by the Chinese Academy of Engineering, the proportion of regenerated aluminum production to the output of electrolytic aluminum is expected to exceed 30% in the year of 2015 in China. As for the year of 2020, this proportion is expected to be 40%. In addition, the amount of CO_2 emissions per unit industrial added value is aimed to decrease above 25% in 2015, compared with the 2005 level, and this decrease rate is aimed to be 40% for the year of 2020. To achieve these objectives, regenerated aluminum production enterprises with the production scale over 300 kt and some large-scale regenerated resources recycling center are planned to be constructed before 2020 [28].

The following policy recommendations are proposed to promote aluminum cycle based on the analyses of aluminum cycles in China:

1) Implementing the strategic adjustment of raw materials utilization structure of aluminum industry, such as encouraging Chinese smelting and mining companies to go abroad and positively purchase foreign bauxite ore resources; providing preferential policies to guide fabrication and manufacture companies to actively use aluminum scrap as raw materials; scientific exploiting and utilizing bauxite ore resources.

2) Accelerating the research, development and popularization of advanced technology to reduce the loss of Al-containing materials and energy consumption in production of primary aluminum and fabrication and manufacture of aluminum products.

3) Making scientific and rational economic policies, such as amending and improving preferential policy of revenue for worn-out products retrieving and recycling, such as still exempting the value added tax for the scrap reclaiming companies and increasing the deducting income tax or exempting the value added tax for the regenerative enterprises; supporting major projects in the field of regenerated nonferrous metal industry by investment or capital grants, discount loans; levying resource tax for using of all bauxite included high-alumina clay, which should play some role in promoting aluminum recycling. Besides, carbon tax also has the same effect, establishing research funds for developing the recycling technologies of aluminum, copper, lead and zinc, etc [26].

4) Encouraging aluminum products manufacture enterprises to carry out product design, so as to facilitate the regeneration of obsolete products after their retirements.

5) Setting up industrial license admittance system and establishing a more focused discarded products and scrap dismantling pretreatment base with a certain scale.

6) Improving public awareness to prolong the use life of aluminum products, classifying the garbage to be convenient for aluminum recycling, and encouraging producers and manufacturers initiatively to callback the products and components which can be recycled or reused many times.

4 Conclusions

1) Resource self-support ratios in alumina production, aluminum production and the aluminum industry of China in 2007 were 55.50%, 79.25% and 48.71%, respectively. Self-produced and imported aluminum scrap use ratios of the aluminum industry were 5.38% and 9.40%, respectively.

2) In China, resources self-support ratios in alumina production, aluminum production and the aluminum industry were dropped, increased and leveled off in the period of 2003−2007 respectively. Resources self-support ratio in the aluminum industry dropped dramatically in the year of 2007. Self-produced aluminum scrap use ratio dropped from about 7% in 2003 to about 5% in 2007. At the same time, imported aluminum scrap use ratio was bigger than self-produced aluminum scrap use ratio due to the large scrap imported. The overall scrap use ratio dropped a little during this period. The situation of scrap lacking is unable to change in the case of fast increment of aluminum production.

3) China is a net importer of Al-containing resources and its net imported quantities increased continually in 2003−2007, especially for bauxite and scrap. Lost quantity of Al-containing materials in aluminum cycle increased annually in this period, in particular for tailings and red sludge. Net increased quantity of Al-containing materials in social stock increased annually in 2003−2007. We can forecast that recoverable aluminum scrap will increase in the future years along with the increment of aluminum social stocks. Al scrap recycled also will be increased in this period, and the loss of aluminum in the life cycle of aluminum products produced in this period will be expanded.

4) Firstly, Chinese future policy on import/export of aluminum industry should focus on encouraging imports of bauxite and aluminum scrap that are in shortage, at the same time, supporting Chinese companies go abroad to buy bauxite mine and establish a global recycling of aluminum scrap and transport networks, etc; secondly, Chinese future work on reducing the loss of Al-containing materials should include firstly restricting the number of private bauxite mining enterprises and strictly prohibiting the dissipating bauxite mining, then

appropriately controlling the capacity of Bayer process in alumina production; thirdly, eliminating lagged electrobath and increasing the managerial and operational level of electrolytic aluminum enterprises; and finally establishing of a more focused discarded products and aluminum scrap dismantling pretreatment base with a certain scale should be done. It is essential for the relevant governments to make scientific and rational decision-making and further to lay a theoretical foundation for realizing the targets of sustainable and low-carbon economic development for Chinese aluminum industry.

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Glossary

1) Anthropogenic aluminum cycle

It refers to bauxite mining and processing, not including fossil fuels combustion and biomass fuels combustion, because Al content in fuels is emitted into the environment and not recovered after combustion. The following four stages, bauxite mining, alumina and aluminum production→ fabrication and manufacture of aluminum products→ use of final aluminum products→ waste management of obsolete aluminum products constitute the anthropogenic aluminum cycle.

2) Average life span of aluminum products life cycle

The average life span (expressed by $\Delta\tau$) for the whole process of aluminum products life cycle is bauxite mining, alumina and aluminum production → fabrication and manufacture of aluminum products→ use of final aluminum products→ waste management of obsolete aluminum products.

3) Recycling rate

It is defined as the ratio of the self-produced old aluminum scrap recycled in aluminum production and manufacture in year τ to the total metal products $\Delta\tau$ years ago.

中国人为主导的铝循环分析

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摘 要：采用铝产品生命周期的铝流程图进行中国人为主导的铝循环分析。人为主导的铝循环主要包括 4 个阶段：氧化铝及电解铝的生产、铝制品的加工和制造、铝制品的使用和报废铝制品的回收。采用加权平均法确定我国铝制品的平均使用寿命。基于中国 2003−2007 年的铝循环分析，发现了铝工业发生的一些变化。氧化铝生产阶段的原料自给率从 95.42%下降到 55.50%，原铝生产阶段的原料自给率从 52.45%上升到 79.25%，但整个铝工业的原料自给率基本维持在 50%左右。在 2007 年铝工业中，国内自产废铝和进口废铝的使用比例分别占总原料的 5.38% 和 9.40%。在此阶段，净进口各类含铝资源和铝产品生命周期中铝的损失量都是上升的，同时，社会蓄积量中铝的存量及铝的循环量都是增加的。提出了改善铝循环的对策、建议以及中国铝工业的进出口政策和降低铝产品生命周期铝损失量的措施。

关键词：人为主导；中国铝循环；物质流分析；加权平均法；平均使用寿命

(Edited by Xiang-qun LI)