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Development and Evolution of Aluminum Industry in China Based on Aluminum Flow Analysis

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Abstract The whole process of aluminum cycle consists of four stages: Production of alumina and primary aluminum, fabrication and manufacture of aluminum products, use of aluminum final products, and recycling of obsolete aluminum products. Aluminum cycle in China in 2011 was analyzed using alumium flow diagram, and the following indices were obtained: The resource self-support ratio of alumina, aluminum and the whole aluminum industry were 53.18%, 95.58% and 54.85%, respectively; self-produced and net imported aluminum scrap use ratios of the aluminum industry were 4.68% and 7.98%, respectively. Aluminum cycles and aluminum flow indices in China of the year 1990, 1995, 2000, 2005 and 2008–2010 were also analyzed. It was found that from 1990 to 2011, imported Al-containing resources increased and imported bauxite has increased significantly since 2005. Resources self-support ratio of aluminum industry changed gradually from fully self-support to depencdent on the imports of raw materials. Self-produced auminum scrap use ratio presented downtrend basically and the imported aluminum scrap use ratio was greater than self-produced aluminum scrap use ratio after 1995.

Keywords aluminum cycle; substance flow analysis; resources self-support ratio; scrap use ratio; aluminum industry

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1 Introduction

Chinese aluminum industry was in a rapid development in recent years (see Table 1), aluminum production capacity increased quickly and demand for bauxite etc growed rapidly. Domestic bauxite mining, reserve consumption and imported Al-containing resources continue to grow. Aluminum production and consumption caused a huge gap of supply for bauxite, scrap etc raw materials. Decrease in the grade and short supply of ore resources has become a bottleneck in the development of aluminum industry in China.

Table 1 Variations of aluminum production and consumption in China in the period of 1990–2013 (unti: 10^4t)

Year	Production	Consumption	Year	Production	Consumption
1990	85.43	83.68	2002	451.11	415.20
1991	96.25	98.50	2003	596.20	517.76
1992	109.60	132.80	2004	668.88	619.09
1993	125.15	135.00	2005	780.60	711.86
1994	149.84	153.70	2006	926.40	838.00
1995	186.97	168.50	2007	1228.40	1197.90
1996	190.07	175.00	2008	1317.63	1241.25
1997	217.86	211.50	2009	128861	1315.0
1998	243.53	242.54	2010	157713	15855
1999	280.89	292.59	2011	176789	17629
2000	298.82	353.27	2012	202084	2148.15
2001	357.58	354.54	2013	2205.85	2320.00

Bauxite resources are relatively poor in China, at the same time, the quality of more than 85% of the reserves are also disappointed. Bauxite reserve per person in China is 1/9 of the global average level and current reserve is accounted to lower than 2% of the global reserve. Dynamic reserve to consumption is less than 12 years and reserve to production is less than 20 years in China. In 2020 China's domestic bauxite guarantee degree is only about 38% of the demand, and this is a very serious problem. There are some uncertain factors regarding to a large number of imports, which will be limited to the exporter. Imported bauxite is equal to imported a large number of pollutants at the same time, about 50% for hazardous waste (red sludge)[1].

Therefore, under a so large and rapidly increasing aluminum industry, bauxite resource was severely deficient and depends on a large number of imports at the same time, it is necessary to study on the history of aluminum industry in China. Analysis of Chinese aluminum industry based on substance flow analysis is very useful in finding the development and evolution of aluminum industry in China, which can help to attain the savings of Al-containing resources and achieve a sustainable development in the aluminum industry. It has been carried out some related research on the aluminum industry.

Melo used three different kinds of models to predict the amount of aluminum old scrap in the waste management stage in Germany[2]. Martchek used a simplified model to analyze the global aluminum cycle in 2003[3]. Hatayama and his colleagues calculated the output of aluminum old scrap produced from different sectors[4]. Plunkert adopted aluminum flow framework to analyze the aluminum cycle in the United States in 2000[5]. Liu and Müller described the global journey of anthropogenic aluminum by adopting trade-linked materials flow analysis[6]. Dahlström and Ekins analyzed aluminum flow in the United Kingdom in 2001 combining substance flow analysis and value chain analysis together[7]. Liu and Müller reviewed the problem of addressing the sustainability of aluminum industry by life cycle assessment approach[8]. Chen and his colleagues used aluminum flow diagram to analyze aluminum cycle of China in 2005[9]. Yue and his colleagues used alumnum flow diagram to analyze aluminum cycles in 2003–2007 in China[10]. Chen and his colleagues explored the production, consumption, import and export, losses and changes of stocks of aluminum in China for 2001, 2004 and 2007[11]. Yue and Lu analyzed aluminum social stock in China[12].

This paper is based on the theory of metal's industrial metabolism, aluminum flow diagram was adopted to analyze, aluminum flow for the aluminum product life cycle of 1990, 1995, 2000, 2005 and 2008–2011 in China. Aluminum flow indices of China's aluminum industry during these periods were calculated, and proposals for future development of China's aluminum industry were put forward.

2 Methods and Indices

2.1 Method

Substance flow analysis (SFA) is an effective tool for studying the industrial metabolism of specific substances (e.g., aluminum, copper) on a certain spatial scale, for example, on the scale of a nation, a region or a firm. Industrial metabolism means the whole integrated collection of physical processes that convert raw materials and energy, plus labor, into finished products and wastes. Therefore, the subject of SFA is to identify and quantify the material flows related to those physical processes and the relationship among them[13]. The purpose of SFA is looking for the potentials and measures of resource conservation and environment protection, and encouraging industrial system to meet the requirement of sustainable development. Thus, the proposals offered in SFA can be of assistance to decision makers.

The aluminum flow diagram for the aluminum products life cycle is given in Figure 1.

The entire life cycle of aluminum products comprises four stages. Some explanations for the four stages are as follows[10,14]:

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 within 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. When the aluminum products are produced, they are widely used in national economy, such as constructions and vehicles, and so on.

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.

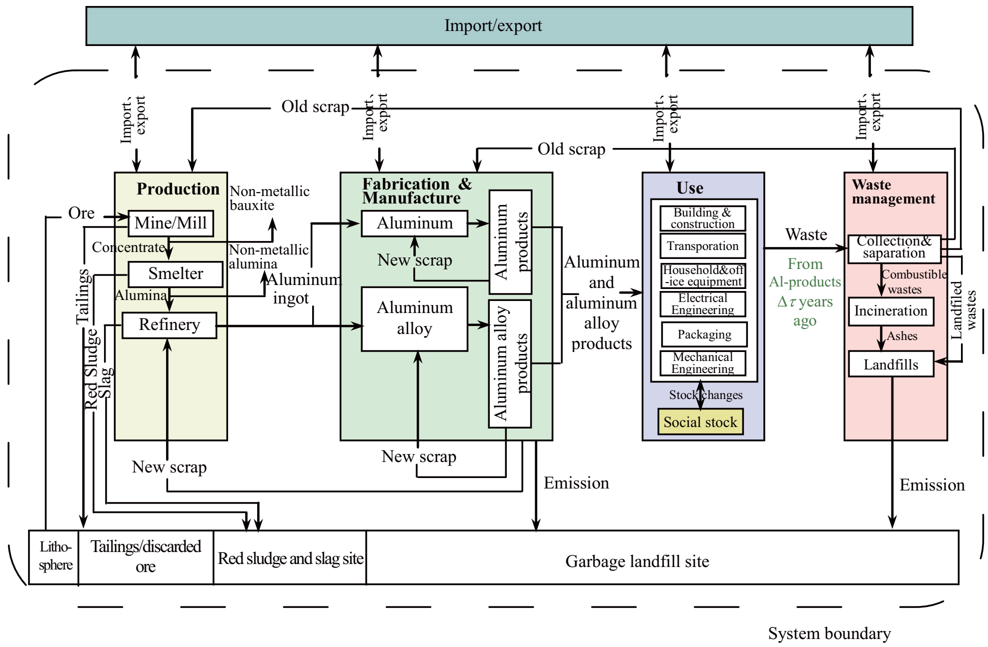

Figure 1 Aluminum flow diagram

2.2 Relevant Indices

The items described in Figure 1 are listed in Table 2, we can obtain some important aluminum flow indices based on these parameters (see Table 2).

The indices can be divided into three categories:

a. Resources self-support ratio and resources imported ratio

Resources self-support ratio is the self-produced resources accounted to total resources input, while resources imported ratio is the imported resources accounted to total materials imput.

b. Aluminum scrap use ratio

Aluminum scrap use ratio is the scrap used accounted to total resources input.

3 Aluminum Flow Analysis in China

3.1 Aluminum Flow Diagram of China in 2011

Based on China Nonferrous Metals Industry Yearbook, etc[15], a aluminum flow diagram for the aluminum products life cycle of 2011 in China can be drawn to reflect the directions of Al-flow and the distribution of aluminum based on the application of the conservation law at every stage with the following-observing method of substance flow analysis (see Figure 2 and Table 3).

Table 2 Items described in Figure 1 and the corresponding aluminum flow indices

Items	Indicated by	Aluminum flow indices	Calculating formulas
Bauxite mined	O_k	Resources Self-support Ratio (RSR) and Resources Imported Ratio (RIR)	
Tailing	O_w		
Bauxite produced	O_z	RSR in alumina production, $Z1$	$Z1 = \frac{O_z}{O_z+I_1} \times 100\%$
Net imported bauxite	I_1		
Net imported alumina	I_2	RIR in alumina production, $J1$	$J1 = \frac{I_1}{O_z+I_1} \times 100\%$
Net imported aluminum	I_3		
Non-metallic bauxite	K_f	RSR in aluminum production, $Z2$	$Z2 = \frac{Y_z}{Y_z+I_2} \times 100\%$
Self-produced alumina	Y_z		
Non-metallic alumina	Y_f	RIR in aluminum production, $J2$	$J2 = \frac{I_2}{Y_z+I_2} \times 100\%$
Net increase of Al-stock	S_n		
Al-loss during production	D_1	RSR of aluminum industry, $Z3$	$Z3 = \frac{O_z+F_z}{O_z+F_z+I_1+I_2+\cdots+I_6} \times 100\%$
Aluminum output	P_τ		
Old scrap recycled in the year τ	F_z	RIR of aluminum industry, $J3$	$J3 = \frac{I_1+I_2+\cdots+I_6}{O_z+F_z+I_1+I_2+\cdots+I_6} \times 100\%$
Al-loss during obsolete aluminum products recycling in the year τ	F_s		
Net imported alloy	I_4	Aluminum scrap use ratio of aluminum industry	
Net imported semis	I_5		
Net imported scrap	I_6	Self-produced aluminum scrap use ratio, ZS	$ZS = \frac{F_z}{O_z+F_z+I_1+I_2+\cdots+I_6} \times 100\%$
Aluminum products output	M_τ		
Al-loss during manufacture	D_2	Imported aluminum scrap use ratio, JS	$JS = \frac{I_6}{O_z+F_z+I_1+I_2+\cdots+I_6} \times 100\%$
Old scrap recycled in the year $\tau+\tau$	A_2		
Al-loss during obsolete aluminum products recycling in the year $\tau+\tau$	D_4	Overall aluminum scrap use ratio, AS	$AS = \frac{F_z+I_6}{O_z+F_z+I_1+I_2+\cdots+I_6} \times 100\%$
Al-loss during the aluminum products life cycle of the year τ	D		

Corresponding data of aluminum flow described in Figure 2 are shown in Table 3.

Table 3 Explanations on the data described in Figure 2

Items	Values(10^4t)[1]	Quantitative relations	Data sources
Ore mined	1755.00		O_k was estimated based on the major technical economic targets in [15] and [9]
Tailing	403.65		O_w was estimated based on the major technical economic targets in [15] and [9]
Self-produced bauxite	1351.35	$O_z = O_k - O_w$	
Net imported bauxite	1189.56	I_1=(imported bauxite− exported bauxite)	[15]
Bauxite used in alumina production	2378.01		O_A was calculated based on the major technical economic targets in [15]
Non-metallic bauxite	162.90	$K_f = O_z + I_1 - O_A$	
Red sludge	313.30		R_w was estimated based on the major technical economic targets in [15] and [9]
Self-produced alumina	2064.71		[15]
Net imported alumina	95.40	I_2=(imported alumina− exported alumina)	[15]
Alumina used in aluminum production	2038.41		Y_A was calculated based on the major technical economic targets in [15]
Non-metallic alumina	121.70	$Y_f = Y_z + I_2 - Y_A$	
Slag	78.40		T_w was estimated based on the major technical economic targets in [15] and [9]
Self-produced aluminum	1960.00		[15]
Net imported aluminum	14.30	I_3=(imported aluminum− exported aluminum)	[15]
Net decrease of Al-stock	30.70		[15]
Al-loss during production	795.35	$D_1 = O_w + R_w + T_w$	
Aluminum used in aluminum products fabrication and manufacture	2005.00	$P_A = P_\tau + I_3 - S_n$	
Net imported alloy	−57.60[2]	I_4=(imported alloy− exported alloy)	[15]
Net imported semis	−240.40[2]	I_5=(imported semis− exported semis)	[15]
Al-loss during fabrication and manufacture	78.45		D_2 was estimated based on the major technical economic targets in [15] and [9]
Obsolete aluminum product produced in 2011	175.00		[15]
Self-produced old scrap recycled in 2011	126.00	$F_z=\alpha\times M_{\tau-\Delta\tau}$	α is the recycling rate of obsolete aluminum products, $\alpha\approx0.72$[16]
Net imported scrap	214.88	I_6=(imported scrap− exported scrap)	[15]
Aluminum products output	2068.55	$M_\tau = P_A + I_4 + I_5 + F_z + I_6 - D_2$	
Al-loss during obsolete aluminum products recycling in 2011	49.00	$F_s = M_{\tau-\Delta\tau} - F_z$	
Old scrap recycled in 2027	1489.36	$A_2=\alpha\times M_\tau$	α is the recycling rate of obsolete aluminum products, $\alpha\approx0.72$[16]
Al-loss during obsolete aluminum products recycling in 2027	579.19	$D_4 = M_\tau - A_2$	
Al-loss during the aluminum products life cycle of 2011	1452.99	$D = D_1 + D_2 + D_4$	

1: All the values are Al-contained; 2: "−"represent net exported.

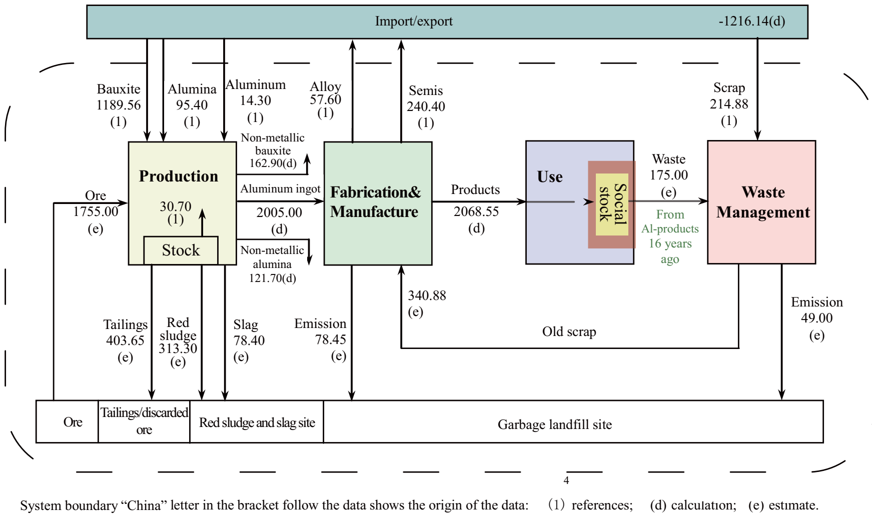

Figure 2 Aluminum flow diagram in China in 2011 (unit: 10^4t-Al/a)

3.2 Al-containing Materials Flow and Corresponding Aluminum Flow Indices in 1990, 1995, 2000, 2005 and 2008–2011

Similar to the diagram described in Figure 3, aluminum cycles in China in 1990, 1995, 2000, 2005 and 2008–2011 were also analyzed. The values of Al-containing materials flow are described in Table 4.

Table 4 Al-containing materials flow of aluminum industry in China (unit: 10^4t)

Year	2011	2010	2009	2008	2005	2000	1995	1990
Alumina production stage								
Self-produced bauxite	1351.35	1091.85	1041.32	824.82	564.3	277.29	216	108.62
Net imported bauxite	1189.56	804.54	524.75	687.07	57.3	19.35	−9.47	−18.03
Aluminum production stage								
Self-produced alumina	2064.71	1531.59	1259.47	1218.71	451.9	228.81	116.44	77.51
Net imported alumina	95.4	227.9	268.71	240.93	370.18	99	63	1.74
Aluminum industry								
Self-produced bauxite	1351.35	1091.85	1041.32	824.82	564.3	277.29	216	108.62
Self-produced scrap	126	121.32	110.66	97.2	59.11	37.78	28.74	15.93
Net imported bauxite	1189.56	804.54	524.75	687.07	57.3	19.35	−9.47	−18.03
Net imported alumina	95.4	227.9	268.71	240.93	370.18	99	63	1.74
Net imported aluminum	14.3	−38.94	142.98	1.15	−70.9	70.51	19.66	0.66
Net imported alloy	−57.6	−38.13	−2.1	−59.25	2.73	17.14	4.78	0.16
Net imported semis	−240.4	−158.94	−80.37	−126.27	−6.39	32.69	16.24	2.6
Net imported scrap	214.88	226.04	210.02	170.32	134.89	63.77	28.8	0.44

Based on the aluminum cycles in China during these years, materials flow indices of aluminum industry were also analyzed (see Table 5).

Table 5 Materials flow indices of aluminum industry in China (unit: %)

Year	2011	2010	2009	2008	2005	2000	1995	1990
Resources self-suport ratio and resources import ratio								
Resources self-support ratio in alumina production	53.18	57.58	66.49	54.55	90.78	93.48	100	100
Resources import ratio in alumina production	46.82	42.42	33.51	45.45	9.22	6.52	0	0
Resources self-support ratio in aluminum production	95.58	87.06	82.42	83.49	54.97	69.83	64.89	97.80
Resources import ratio in aluminum production	4.42	12.94	17.58	16.51	45.03	30.17	35.11	2.20
Resources self-support ratio of aluminum industry	54.85	54.26	51.99	51.57	56.10	51.05	61.48	100
Resources import ratio of aluminum industry	45.15	45.74	48.01	48.43	43.90	48.95	38.52	0
Aluminum scrap use ratio of aluminum industry								
Self-produced aluminum scrap use ratio	4.68	5.43	4.99	5.44	5.32	6.12	7.22	14.21
Net imported aluminum scrap use ratio	7.98	10.11	9.48	9.64	12.14	10.33	7.23	0.39
Overall aluminum scrap use ratio	12.66	15.54	14.47	15.08	17.46	16.45	14.45	14.60

4 Analysis and Discussion

4.1 Indices Analysis for the Year 1990, 1995, 2000, 2005 and 2010

1) Net imported of Al-contained resources (Figure 3)

Bauxite in China during 1990 and 1995 was in a state of net exports, and then the net imports of bauxite increased year by year, especially from 2005 to 2010 net imports of bauxite rose from 575000 tons to 8.0454 million tons, the growth is significant. At the same time, the quantities of China's net imported aluminum scrap increased year by year. Aluminum products consumption increased quickly with the rapid development of Chinese economy, as there is a shortage of bauxite resources in China, make the production of aluminum industry in China depend on foreign imports of bauxite and aluminum scrap to a certain extent.

In the period 1995–2010, China's aluminum, aluminum alloy and aluminum products were changed from net imports gradually to a net export state, the main reason is with the rapid development of China's economic and industrial smelting technology and progress, makes the domestic production of aluminum products at a faster rate than the growth of the domestic aluminum products needed for consumption. But alumina production in China has maintained a net import state, this is mainly due to the production of raw material for aluminum is mainly alumina, and with the increasing of primary aluminum production in China, the production for alumina is sure to increase.

2) RSR of alumina, aluminum and aluminum industry (Figure 4)

In 1990, production of alumina and aluminum had almost completely self-support. Its resource self-support ratio of alumina production dropped from 100% in 1990 and 1995 to 57.58% in 2010. This is mainly because with the rapid increase of alumina production, bauxite appears more and more insufficient, the raw materials for alumina production depended on imports of bauxite.

In 2010, resources self-support ratio of primary aluminum production increased, close to 90%. Except in 1990, the whole aluminum industry has a relatively stable its self-support ratio of raw materials, basically remain unchanged.

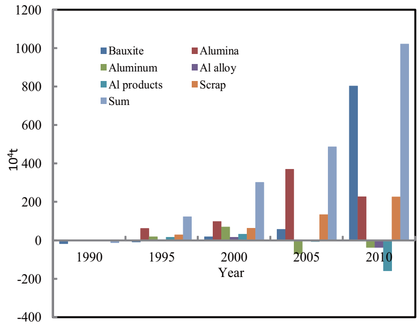

Figure 3 Net imported Al-contained resources in China in 1990, 1995, 2000, 2005 and 2010

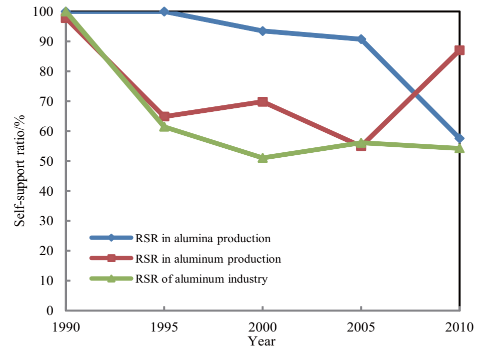

Figure 4 Resources self-support ratio of alumina, aluminum and aluminum industry in China in 1990, 1995, 2000, 2005 and 2010

3) Aluminum scrap use ratio (Figure 5)

Self-produced aluminum scrap use ratio presented downtrend basically, the main reason is that average use life aluminum products is longer, which is about 15–16 years, and now the old aluminum scrap used is generated from aluminum products put into use about 15–16 years ago. Aluminum products consumption 15–16 years ago is much smaller compared with now, so the proportion of old scrap reclaimed and recoveried in the aluminum production is even much small, the scrap use ratio declined gradually on the overall trend.

Since 1995 the imported aluminum scrap use ratio was greater than self-produced aluminum scrap use ratio, which is closely related to China has imported a lot of aluminum scrap in recent years. Due to the imported aluminum scrap use ratio is relatively stable, which compensate the decline of self-produced aluminum scrap use ratio to some extent, so the total aluminum scrap ratio fluctuated, but the change is not large.

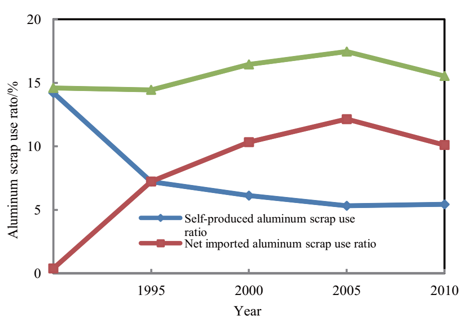

Figure 5 Aluminum scrap use ratio in China in 1990, 1995, 2000, 2005 and 2010

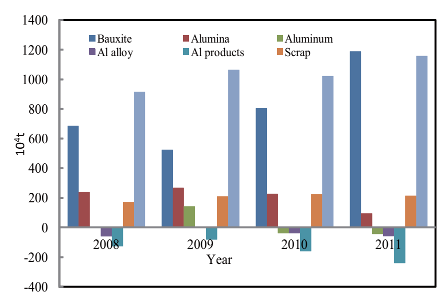

Figure 6 Net imported Al-contained resources in China in 2008–2011

4.2 Indices Analysis for the Year 2008–2011

1) Net imported of Al-contained resources (Figure 6)

Net imports of bauxite increased obviously in 2008-2011, aluminum scrap also had a small increment in general, the net imported alumina had an obvious decrease trend. Aluminum alloy and aluminum products were net exported during this period, and primary aluminum were also in a net exported state in 2010 and 2011. In 2008-2011, net imports of Al-containing resources have edged up on the whole

2) RSR of alumina, aluminum and aluminum industry (Figure 7)

Resource self-support ratio in alumina production has been reduced since 2009, which showed alumina production was more dependent on foreign bauxite

Resource self-support ratio in aluminum production continued to increase during the period 2008-2011, this is because the rapid increase of alumina production in China.

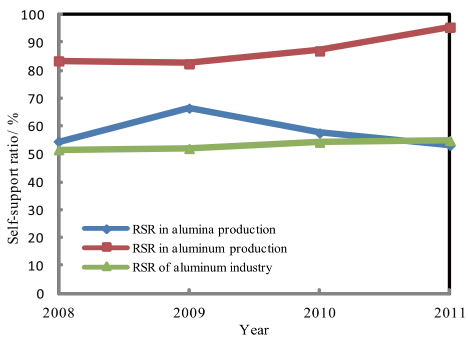

Figure 7 Self-sufficiency rate of alumina, primary aluminum production and the entire aluminum industry in China in 2008–2011

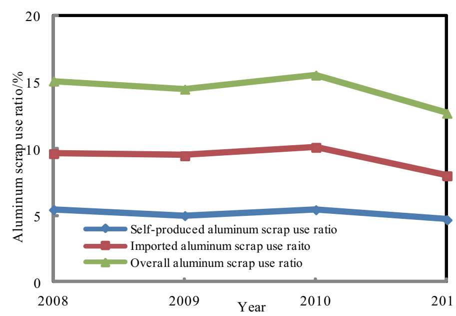

Figure 8 Aluminum scrap use ratio in China in 2008–2011

3) Aluminum scrap use ratio (Figure 8)

Self-produced auminum scrap use ratio were kept constant during 2008–2011. Imported aluminum scrap use ratio was greater than self-produced aluminum scrap use ratio. In 2011, imported aluminum scrap use ratio and overall aluminum scrap use ratio declined obviously, which was mainly affected by the market price of aluminum products, it made the cost of imported aluminum scrap increased.

5 Conclusions

1) From the point of overall analysis, imported bauxite increased in China during the past 20 years, especially after 2005, imported bauxite has increased significantly, which is closely linked to the rapid increase of China's aluminum consumption and shortage of bauxite resources in China. In order to alleviate the shortage situation of bauxite resources, the production of aluminum industry in China depended on imports of raw materials to a certain extent.

Alumina was net imported in this twenty years from 1990 to 2010 on the whole, but the imported alumina was in a significant downward trend in recent years. China's aluminum, aluminum products and aluminum alloy were transformed from net imports to net exports, and these three net exports are increased year by year in recent years.

2) From 1990 to 2011, the variation of resources self-support ratio of aluminum industry in China changed gradually from fully self-support to depencdent on the imports of raw materials. Alumina production was completely on self-support in 1990 and 1995 and close to 50% by 2011. With the rapid increase of alumina production, produced bauxite appears more and more

shortage. During the past 20 years, resources self-support ratio of alumina production reduced and depended on imported bauxite to a certain extent. The self-support ratio of primary aluminum production has increased since 2005 and reached 95.58% in 2011. In addition, the resource self-support ratio of the whole aluminum industry was relatively stable and basically remained unchanged since 2005.

3) Self-produced auminum scrap use ratio presented downtrend basically. Aluminum products consumption 15–16 years ago is much smaller compared with now, so the proportion of old scrap reclaimed and recoveried in the aluminum production is even much small, the scrap use ratio declined gradually on the overall trend.

Since 1995 the imported aluminum scrap use ratio was greater than self-produced aluminum scrap use ratio, which is closely related to China has imported a lot of aluminum scrap in recent years. Due to the imported aluminum scrap use ratio is relatively stable, which compensate the decline of self-produced aluminum scrap use ratio to some extent, so the total aluminum scrap ratio fluctuated, but the change is not large.

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