Dynamic material flow analysis of zinc resources in China

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\textbf{A B S T R A C T}

Zinc is one of the most widely applied nonferrous metals in China. Study on the applications and recurrent situation of zinc resources is of great strategic importance for the sustainable development of China’s economy. In this paper, a dynamic material flow analysis (MFA) method has been adopted to analyze quantitatively zinc resources in China, as well as to analyze and predict the quantity of zinc product scrap and their recycling situation. The weighted average method was applied to calculate average lifetimes of six major zinc products in China. The average lifetimes of battery, zinc oxide, zinc die-casting alloys, zinc material products, galvanized zinc and brass are 0.17, 5.3, 11.1, 12, 21 and 30 years, respectively. Assuming the lifetime of zinc product group obeys the Weibull distribution and the consumption of zinc products varies linearly with time, the future consumption and scrap generation of zinc products will increase continuously. It is expected that they would increase from 49% to 76% during 2004–2020, respectively. Assuming the recycling rate remains unchanged with time, the zinc old scrap index, both the theoretical and actual values, would continue increasing in China. The values are expected to reach 0.402 and 0.076 by 2020, respectively. Therefore, the regeneration resource of depreciated zinc is actually insufficient in China. According to the scenario analysis, the actual value of old scrap indexes is positively correlated with the recycling rate of zinc products. Because galvanized products are the largest consumption area of zinc products in China, the influence of their recycling rate on old scrap index is obviously larger than other zinc products. Through the analysis, this paper suggests that the increase of the recycling rate of zinc products could not only improve to a certain degree China’s relative shortage of zinc resources, but greatly relieve the supply pressure of zinc in the world.

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1. Introduction

Zinc is one of the most widely distributed elements in nature. The main existing states of zinc in nature are sulfide and oxide. Minerals from which zinc is extracted mainly include sphalerite, smithsonite, willemite, hemimorphite and hydrozincite (Guo et al., 2010). Zinc has many merits such as anti-corrosion, low melting point, ease of processing, favorable thermal and electrical conductivity, which is one of the most important nonferrous raw materials in manufacturing production. Zinc can also be employed to form alloys with some other nonferrous metals. An extensively used alloy which contains zinc is brass, in which copper, tin and lead are alloyed with zinc. Due to its anti-corrosion property and wear resistance, zinc is widely used in rust-proof applications for steel materials and a variety of castings. In addition, zinc is a necessary nutrient for humans and other living beings. Therefore it is also widely adopted in drugs, foods, feeds and fertilizers (Spatari et al., 2003).

Zinc reserves are very rich on the world. However, with the sustainable and rapid development of the global economy, the demand for zinc products is rising very fast. At present, there has been the worldwide zinc supply crisis. According to the estimate of the Information Center of the Ministry of Land and Resources, the guarantee period of static mining of global zinc reserves is about 24 years (Dai and Zhang, 2004). In order to alleviate the zinc resource crisis, many countries, especially some developed countries such as European countries, America and Japan, have been paying attention to the recycling of zinc resources for many years. According to the estimation of U.S. Bureau of Mines, the regenerated zinc consumption in 2000 accounted for 40% of total domestic zinc consumption in America (Lan, 2002; Queneau et al., 1998). With the rise of China’s economy, zinc industry in China has reached a stage of rapid development since 1990s (Fig. 1). Zinc production and consumption in China has undergone an average annual growth of 18% and 13.8% in 1990s, respectively. Since 2000, with the rapid development of automobiles and construction industries in China, the zinc consumption has increased significantly, much faster than the increase of zinc production. During 2000–2004, the average annual...
growth of zinc production and consumption in China was 8.1% and 15.9%, respectively. Since 2002, China has surpassed America as being the largest zinc consumer. It is reported that the total global zinc production was around $1.091 \times 10^6$ Gg in 2010, 47.7% of which was contributed by China (World Metal Statistics Yearbook, 2011). The rapid growth of zinc production has inevitably brought about a series of resource and environmental problems, which mainly lies in three aspects: (1) Raw materials such as zinc ore are in short supply; (2) Energy consumption and greenhouse gas emission resulted from zinc industry are increasing year by year; (3) Pollutants arising from zinc production and consumption are becoming increasingly grim. To alleviate the crisis, proper measures must seriously be taken into consideration. On one hand, zinc resources should be preserved, while advanced manufacturing techniques must be promoted and applied in ore dressing, smelting and processing. On the other hand, zinc regeneration related industries should be developed and promoted, as well as the use of scrapped zinc resources to reduce the consumption of non-renewable zinc resources.

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined spatially and temporally (Paul and Helmut, 2004). It connects the sources, the pathways, the intermediated and final sinks of a material. The distinct characteristic of MFA makes it attractive as a decision-support tool in resource management, waste and environmental management. MFA has become one of the most powerful tools for analysis of resource consumption, energy production and consumption. Meanwhile, MFA is a core control measure for developing recycling economy and sustainable development (Brunner and Rechberger, 2004; Xu and Zhang, 2005; Zhou and Liu, 2005). In recent years, many European and American scholars have done numerous studies on various levels of zinc recycling with the MFA method. Gordon et al. proposed technical features and parameters for describing zinc circulation in 2003. Spatari et al. (2003) and Harper et al. (2006) quantitatively analyzed the stock and flow of zinc during 1994 in Europe. Latin America and the Caribbean area, from the national and regional levels with the stock and flow model. In 2005, Bradley analyzed the main recycling path, major regeneration process and related parameters of global zinc metal. In the same year, based on the statistics and calculation of zinc circulation data in 54 countries in 1994, Graedel et al. analyzed the zinc circulation condition from the national, regional and global levels, as well as achieved some results as follows: (1) The accumulation ratio (i.e. addition to in-use stock as a function of zinc entering use) is relatively large, about 2/3 of zinc entering use is added to stock; (2) Secondary input ratios (i.e. fractions of input to fabrication that are from recycled zinc) and domestic recycling percentages (i.e. fractions of discarded zinc products that are recycled) differ at various regional levels; (3) Around 40% of the zinc worldwide that was discarded in various forms was recovered and reused or recycled. In this work, the life cycle of zinc resources in China has been analyzed with the dynamic MFA model based on previous studies above, as well as predicted the flow situation of zinc resources and annual scrap generation.

2. Materials and methods

In the static MFA method, material flows and stocks are identified within predefined spatial and temporal boundaries systematically. The static MFA is conducted using only the material balances of inputs, stocks and outputs. In contrast, dynamic MFA is used to quantify past material flows, establish the material flow patterns and apply the lifetimes of such material containing products to these patterns in order to track the temporal changes in the material flows (Park et al., 2011; Lu and Yue, 2006). Spatari et al. proposed the dynamic MFA method for the first time in 2005 and further analyzed quantitatively the complete life cycle flows of copper products extracted and used during the twentieth century in North America using a dynamic product residence time model. In 2007, with the same method, Davis et al. and Hatayama et al. conducted time-dependent MFA of iron and steel in the UK and aluminum in Japan, respectively.

Generally, the procedures of the dynamic MFA involve the following 4 steps (Park et al., 2011):

1. System boundary definition and product classification, in which the study objectives are identified and the scope is defined spatially and temporally.
2. Determination of the lifetime and its distribution of each metal product group. The products discussed in this work are with lifetimes exceeding one year (the temporal boundary), which stay within the system boundary for a certain period of time. The products with a lifetime less than a year are not discussed herein.
3. Trend prediction of time-dependent scrap generated by each product group in the future.
4. Result analysis performed through a quantified material flow. Depending on the study goal, data results are analyzed quantitatively and interpretations formulated using the elicited quantitative information.

![Zinc production and consumption in China (1990–2004).](image-url)
2.1. System boundary definition and product classification

The spatial system boundaries of this study refer to the whole territory of mainland China, except Hong Kong, Macao and Taiwan regions. Namely, the boundary refers to the region covered by The Yearbook of Nonferrous Metals Industry of China. The temporal boundary refers to 1990–2020. The life cycle of zinc products can be divided into four stages as shown in Fig. 2 (Spatari et al., 2003; Gordon et al., 2003). Stage I is the smelting process of raw materials for zinc products, which mainly consists of three steps (mining, mineral dressing and smelting). Stage II refers to the processing and manufacturing of zinc products. During the processing step, zinc ingots are processed into semi-finished products such as zinc alloys, galvanized sheets, galvanized pipes, zinc rods, zinc plates and zinc oxides. During the manufacturing step the semi-products are further assembled and manufactured into a variety of zinc products, meanwhile yielding some zinc scrap such as galvanized steel slag, casting slag, leftover materials of zinc plate and brass borings.

Part of the scrap would be recycled and applied in Stage I or II, while the other part fail to be recycled, just be wasted into the environment. Stage III refers to the usage of zinc products. In this stage the zinc products will be scrapped after a period. The zinc products in this stage include not only personal items, such as automobiles and personal computers, but also construction and infrastructure, such as different kinds of galvanized steel. Similarly, some zinc products after using and scrapping will be recycled, while the other part is wasted and end up in the environment. Stage IV contains the management and recycling of zinc scrap. In this process, various kinds of recycled zinc scrap are collected, disassembled and sent to Stage I or II. It is worth noting that Stage IV occurs in parallel with the other three stages, namely, zinc scrap generated in each stage whenever would be sent to the recycling step.

There are mainly two forms in which metal zinc turns into zinc scrap, namely, prompt or new scrap and end-of-life or old scrap (Gordon et al., 2003). Prompt scrap refers to a variety of zinc contained scrap generated during production, processing and manufacturing of zinc products. The annual prompt scrap can be calculated with the annual production of zinc products and loss rates of zinc metal in various stages. Old scrap refers to the zinc contained in producer and consumer goods leaving the use phase. All the zinc scrap discussed in this work refers to old scrap, not including prompt scrap. In addition, zinc products will lose a small portion of zinc through external erosion in use as anti-corrosion coating. However, this loss is hard to be statistically calculated. Consequently, this part of zinc will not be discussed in this paper.

Besides, the main function of zinc or zinc-contained compounds in zinc products lies on the improvement of the products function. For example, zinc plays an important role in rust prevention and plasticity enhancement for galvanized sheets and brass, respectively, while zinc oxide is usually employed to enhance the anti-friction property of tires. Zinc elements exist generally in zinc products in the form of additives and coating materials. So the zinc products in this article refer not only to all kinds of zinc products with zinc as main, such as zinc pills and zinc sheets, but also all kinds of the products which contain zinc elements, such as batteries.

2.2. Determination of the lifetime distribution of each product group

The lifetime of a metal product has been defined as the whole period from the production of raw material until the generation of scrap. In this paper, the weighted average method is employed to calculate the average lifetime of zinc products. The so-called “weighted average method” is a method used to calculate the average lifetime of metal product through weighting the proportion of a metal in all kinds of consumed products in a country or a region during a history period, multiplying the lifetime of all kinds of products of this metal and adding them together (Zhang and Lu, 2007). Assuming there are $n$ kinds of products made of a certain metal, the metal-containing rates of each product are $\alpha_1, \alpha_2, \ldots, \alpha_n$ and their corresponding lifetimes are $\Delta t_1, \Delta t_2, \ldots, \Delta t_n$ (years), respectively. With the weighted average method, the average lifetime $\langle \Delta t \rangle$ of a metal product can be calculated with Eq. (1).

$$\Delta t = \sum_{i=1}^{n} \alpha_i \Delta t_i$$  (1)
There are generally four types of lifetime distributions of a product group as follows: (1) \( \delta \) distribution, namely the lifetime is fixed; (2) Weibull distribution; (3) log-normal distribution; (4) exponential and normal distribution. Due to its strong flexibility and superior adaptability compared with normal distribution, which means it can take many different shapes depending on the shape parameter \( \beta \), the Weibull distribution is widely adopted in the simulation of product lifetime (Davis et al., 2007; Park et al., 2011; Spatar et al., 2005). In this work, the double-parameter Weibull distribution model was introduced to determine the lifetime distribution of each zinc product group and its shape and scale parameters were determined using the Minitab program. The probability density function \( f(t) \) and distribution function \( F(t) \) can be expressed as Eqs. (2) and (3), respectively:

\[
f(t) = \left( \frac{\beta}{\eta} \right) \left( \frac{t}{\eta} \right)^{\beta-1} \exp \left[ -\left( \frac{t}{\eta} \right)^\beta \right] \tag{2}
\]

\[
F(t) = 1 - \exp \left[ -\left( \frac{t}{\eta} \right)^\beta \right] \tag{3}
\]

In Eqs. (2) and (3), \( t, \eta \) and \( \beta \) stand for the lifetime \( (t>0) \), the scale parameter \( (\eta>0) \) and the shape or slope parameter \( (\beta>0) \), respectively (Suhir, 1997; Davis et al., 2007).

2.3. Calculation of time-dependent old scrap generated by each product group

After being released to the society for consumption, a certain kind of products made of metal would not be scrapped in the year when the product reaches the end of its average lifetime. Instead, they are scrapped according to the Weibull distribution. Therefore, the amount of old scrap is equal to the sum of the entire consumption amount in each previous year multiplied with its scrap probability in the current year. In this paper, the concept of “consumption” is employed to calculate the old scrap. It differs from the concept of “input” proposed by Davis et al. (2007). Consumption is taken into account as the main source of old scrap in the field of use is the final quantity consumed by the society, instead of the amount of metal products input to the society. The two values are equal only when the import and export of the metal products, including related metal scrap, are not taken into consideration. Therefore, the concept of “the final consumption” is more suitable for scientific analysis (Zhang, 2007).

It is assumed that in this work, the rate of scrap generation in year \( n \) is \( f(n) \), while the cumulative rate of scrap generation in this year is \( F(n) \). Therefore, the probability of scrap generation throughout year \( n \), \( P(n) \), can be derived from: \( F(n) \) to \( F(n-1) \) (Park et al., 2011).

\[
F(n) = \exp \left[ -\left( \frac{n-1}{\eta} \right)^\beta \right] - \exp \left[ -\left( \frac{n}{\eta} \right)^\beta \right] \tag{4}
\]

Assuming the amount of final consumption of metal products in year \( t \) is \( T(t) \) without considering the imports and exports, the amount of corresponding scrap generated in year \( n \) is defined as \( P(n) \).

\[
P(1) = T(0) \cdot F(1)
\]

\[
P(2) = T(0) \cdot F(2) + T(1) \cdot F(1)
\]

\[
P(3) = T(0) \cdot F(3) + T(1) \cdot F(2) + T(2) \cdot F(1)
\]

Given the above, Eq. (5) can be expressed as follows:

\[
P(n) = \sum_{i=0}^{n-1} T(i)F(n-i) \tag{5}
\]

2.4. Data sources and processing

The data used in this work consist of two parts. Part I: domestic production and consumption of zinc products: Part II: the generation rates of zinc scrap and lifetimes of zinc product groups. Data contained in Part I come from, “The Yearbook of China Nonferrous Metals Industry” and the National Bureau of Statistics. Data contained in Part II are mainly achieved from reported works, as well as calculated according to the related zinc-contained products standard and mathematical models.

In the dynamic MFA model, the final consumption of each kind of zinc product in the field of use (i.e. annual domestic production and import or export amounts of each kind of zinc product) and its Weibull distribution of lifetime can be applied to determine or predict the stock variation and the old scrap of the zinc product. Because the lifetime of a zinc product has a close relationship with the field where it is applied, the consumption structure should be realized to calculate accurately its lifetime. In this work, the zinc consumption field in China has been classified as six types as follows: (1) Galvanized zinc including galvanized sheets and galvanized metal products; (2) Battery; (3) Zinc oxide which is generally applied in rubber, coating, glass and ceramic, catalyst, desulfurization agent and so on; (4) Brass which is widely used in the electrical industry, light industry, machinery, manufacturing industry, post and telecommunications industry; (5) Zinc die-casting alloys widely applied in the automobile industry (such as the carburetor, vehicle components and interior components), metals industry (such as household hardware, building hardware, sanitary ware, kitchen utensils and appliances, locks, zipper, stationery), toy industry (such as car or airplane models), electric equipment industry (such as electrical products, telecommunication equipments and instrumentation) and machinery industry (such as various spare parts); (6) Zinc material products such as zinc tubes, rolling roof sheets, zinc printing sheets and offset printing sheets (Zhang, 2007). The final consumption amounts of various zinc products between 1990 and 2004 are shown in Fig. 3. They are derived from the statistics of the China Nonferrous Metals Industry Association and China Nonferrous Metals Industry Association Recycling Metal Branch and relevant literature (Zhang, 2007; Chen, 1999).

As shown in Fig. 3, the consumption of zinc products in the field of use has shown a rising trend over the past 20 years. With rapid progress made in power industry and automotive industry in China, the consumptions of galvanized zinc and brass are the two fastest-growing units. As the gradually increasing consumption of zinc in galvanized zinc and brass, they have been China’s largest consumption areas of zinc products. Among them, the proportion of the zinc consumption in brass increased from 10.28% to 19.82%, with an enhancement of nearly 10%. The proportion of zinc consumption in galvanized products increased from 41.49% to 50.3%. According to the statistical data during 1990–2004, the consumption trend function of each product group can be calculated roughly. Assuming a steady development in the domestic zinc industry, the annual trend line of consumption amount of each zinc product can be supposed to be a linear equation in Table 1.

The lifetimes of six classes of zinc products can be achieved based on Eq. (1), Fig. 3, The Yearbook of Nonferrous Metals Industry of China and other related works (see Table 2). Based on the average lifetime data in Table 2, the shape and scale parameters and function formulae of the Weibull distribution for each zinc product group are indicated in Table 3 (Oliver, 2004; Davis et al., 2007).
Because its average lifetime is much shorter than one year, zinc battery is different from the other five classes and its lifetime does not meet the Weibull distribution. Therefore, it is assumed in this work that the old scrap is approximately equal to the final consumption of the zinc battery in the current year.

Scrap recycling rates for individual metal product groups were widely applied to analyze the amounts of scrap recycling and disposal for each product group. The recycling rate is defined as the “fraction of post-consumer discards that are recovered and reused” (Park et al., 2011). Scrap recycling rates for six zinc product groups are presented in Table 4, where the data of scrap recycling rate for brass were derived from related studies (Zhang, 2003; Xu, 2004; Wu, 2003), while the data of zinc die-casting alloys and zinc material products were achieved with enterprise investigation and the results estimated by Zhang Jianghui (Zhang, 2007). According to the enterprise investigation, few scrap recycling work for galvanized zinc has been carried out in China for the consideration of economic efficiency, which caused that the scrap recycling rate for galvanized zinc in China is nearly zero (Shang and Yuan, 2006). Because of the various categories of zinc oxide, different applications, as well as mainly applied in the form of additives and fillers, zinc element contained in zinc oxide is unsuitable for recycling economically and technically, just being lost in the environment. The recycling rate of this kind is almost 0% at present. Although zinc battery consumption in China is tremendous, zinc recycling from scrapped zinc battery is around 0% as well. The main reason lies in unobvious economic benefit, too dispersive consumption which is difficult for centralized recycling, as well as recycling policy obstacles, namely, according to the rules in Technology Policy for Battery Scrap Pollution Prevention released by the State Environmental Protection Administration of China, in press; State Environmental Protection Administration of China, centralized treatment of scrapped batteries is not advocated at present (Zhang, 2007).

3. Results analysis

3.1. Results

In this work, a dynamic MFA method has been employed to calculate the annual consumption and the annual waste production of each zinc product until 2020, as shown in Fig. 4. According to the zinc product consumption trend lines during 1993–2004 (Table 1 shows the specific consumption trend function formulas of various zinc products), we can extrapolate the corresponding estimated values from 2005 to 2020. Based on these values, the annual scrap generation of each product can be further calculated with Eq. (5). It is expected that the total zinc product consumption and total zinc scrap generation for 2020 would increase by as much as
49% and 76%, respectively, compared to 2004. The reason that the growth rate of zinc scrap generation exceeds the total zinc product consumption mainly lies in the nonlinear increase of scrap generation, which equals to the sum of the consumption amount in each previous year multiplied with its scrap probability in the current year.

According to scrap recycling rates for various zinc product groups as shown in Table 4, it was analyzed that the scrap generated from the product groups were either recycled or disposed (Fig. 5). Based on calculated results achieved from the dynamic MFA model, it is predicted that the annual scrap generation will continue to increase. The amount of scrap recycling is far less than the amount of scrap disposal, which can be understood as follows: iron and steel industry keep a high development speed driven by the rapid development of China’s economy, which results in an enormous galvanized zinc consumption and an extremely low recycling rate. In addition, zinc battery and zinc oxide which account for a large part of China’s zinc consumption have not been recycled at all. If this situation continues unchanged as it is, the amount of scrap recycling will be always far below the amount of scrap disposal in China.

Raw materials for a metal product production mainly consist of its mineral resources and regenerated resources, thus making use of the regenerated metal resources play a key role in alleviating the mineral demand pressure. As long as there is a demand for metal in society, metal products will enter the scrap stage after usage, thus the old scrap of this metal would always exist. With continuous improvement in the level of recycling techniques, more and more old scrap could be used again. Therefore, the old scrap would gradually be a key factor influencing the metal production and consumption structure.

Old scrap index of zinc products ($\rho_o$) equals to the ratio of old scrap ($r$) against the final zinc product consumption ($P$) in the same statistic period, which reflects the adequacy degree of old scrap in the domestic zinc industry. In this analysis process, only the regenerated metal resource derived from local metal is taken into consideration. Other regenerated resources, such as imports and exports of scrapped metal, are not taken into account.

<table>
<thead>
<tr>
<th>Product group</th>
<th>Galvanized zinc</th>
<th>Battery</th>
<th>Zinc oxide</th>
<th>Brass</th>
<th>Zinc die-casting alloys</th>
<th>Zinc material products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycling rate</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>45%</td>
<td>66.5%</td>
<td>56%</td>
</tr>
</tbody>
</table>

Fig. 4. Amounts of zinc consumption and scrap generation.

Fig. 5. Amounts of scrap recycling and disposal.

Table 4
Recycling rates for different product groups.
When all the potential old scrap are recycled and made full use (i.e. the recycling rate is 1), the calculated result is regarded as the theoretical value of old scrap index, as shown in Fig. 6. The amounts of scrap recycling from Fig. 5 were used to calculate the old scrap index. As mentioned above, the recycled scrapped zinc products in China consist mainly of copper products, die-casting zinc alloys and zinc materials. Assuming their recycling rates keep constant respectively, the actual values of old scrap indexes during 2004–2020 can be calculated with Table 4.

It is predicted that both the theoretical and actual values of old scrap indexes in China will increase gradually in future, which would reach 0.402 and 0.076 by 2020, respectively, as shown in Fig. 6. According to the extrapolation of consumption trend lines, it is expected that the consumption of brass, zinc die-casting alloys and zinc material products would increase faster than those of galvanized zinc, zinc battery and zinc oxide. Therefore, the actual recycling increment value of total depreciated zinc products would be larger than the theoretical value, which would result in a faster actual increase in the old scrap indexes than theoretically. It is expected that the actual old scrap index will be enhanced by 67% in 2020 compared with the value in 2004. Even so, nearly 90% of old scrap will still fail to be recycled by 2020 in China. The actual old scrap index in China is only several percent. It shows that the old scrap constitutes to only a small portion of the zinc supply in society. Therefore, enhancing the recycling rate of old scrap, as well as developing new recycling techniques, can play a key role in alleviating the lack of old scrap and decreasing the demand for zinc minerals in China’s zinc industry.

3.2. Scenario analysis

As mentioned above, if recycling rates of each zinc product continue unchanged, the actual value of the old scrap index of
zinc products will increase gradually, for the increment speed of old scrap grows faster than that of total zinc resource consumption. Several scenarios with different recycling rates for six product groups were employed to study the relation between the old scrap index and recycling rate of zinc products. Because the recycling rates of zinc batteries and zinc oxides will not change in short term, only the recycling rates of other zinc product groups have been adjusted in scenario analysis. Recycling rates of the three scenarios are presented in Table 5.

The actual value of the old scrap index is positively related with the recycling rates of zinc products (Fig. 7). Namely, as long as the recycling rate of a zinc product increases, the actual value of the old scrap index would increase as well as in Scenario #2 or #3. Because galvanized product is the largest zinc product consumption field, the influence of their recycling rate change on the improvement of zinc old scrap index is bigger than that of other zinc products. In addition, the change trajectories of the old scrap index in Scenario #2 and #3 almost overlap, the reason of which mainly lies in that the consumption of galvanized products being almost equal to the sum of the consumption of the other three kinds of zinc products.

4. Conclusions

In this work, the zinc resource flows in China were analyzed quantitatively with the use of both static and dynamic MFA methodology. The future zinc flow situation and old scrap generation were predicted preliminarily. With the rapid development of global economy (especially in China), China’s zinc production and consumption have already taken the first place in the world. The zinc production in China has accounted for 47.7% of the global total output by 2010. Consumption of galvanized zinc and brass products has grown the fastest, which has increased by 86% and 91% during 1990–2004, respectively. By the end of 2004, consumption of galvanized zinc and brass products accounted for 44% and 22% of total zinc consumption, respectively, making them the biggest market of zinc consumption in China.

Based on the dynamic MFA model, the future consumption and scrap generation of zinc products will continue to increase. It is expected that they would increase by 49% and 76% during 2004–2020, respectively. With increment of reclamation resource of depreciated zinc, the recycled and disposed amounts of zinc scrap keep increasing as well. However, there is a huge consumption expectation and ultra-low recycling rate of galvanized products, as well as no scrap recycling of zinc batteries and zinc oxides which account for a large part of the zinc consumption in China. Therefore, if the current recycling situation continues unchanged, the future the amount of scrap recycling will be always much lower than the amount of scrap disposal. The zinc old scrap index, both the theoretical and actual values, would continue to increase in China. The values are expected to reach 0.402 and 0.076 by 2020, respectively. Even so, nearly 90% of old scrap will still fail to be recycled by 2020 in China. The actual value of zinc old scrap index in China is only several percent. It shows that the old scrap constitutes to only a small portion of the zinc supply in society. In a long run, there is still a shortage of recycled zinc in China.

The scenario analysis demonstrated that the actual value of zinc old scrap index is positively related with the recycling rate, namely, as long as the recycling rate of a zinc product increases, the actual value of the old scrap index would increase proportionally as well. Because galvanized products are the largest zinc product consumption field, variation in their recycling rates mainly affects the zinc old scrap index.

With the rapid increase of China’s demands on zinc, zinc old scrap will greatly increase. But because of the very low recycling rate, the old scrap will never be able to satisfy the needs of the demand. This infers that in the foreseeable future of China, China will have to continue to rely on zinc ore imports in order to satisfy its rapid increase in demand. Therefore, in the globalized mining industry, if China, as the largest zinc consuming market, pays sufficient attention to recycling used zinc, the shortage of zinc resources in China will be relieved and the healthy development of its economy can be promoted. It will also help ease the worldwide supply crisis of zinc ore and stabilize the zinc market around the world.

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References

Chen JY. 50 years development achievements of China’s zinc battery industry. Battery (Bimonthly); 1999; 10: 189–94 [in Chinese].
http://www.sepa.gov.cn/info/gw/huangfa/200310/20031009_86653.htm
State Environmental Protection Administration of China. Technology Policy for Battery Scrap Pollution Prevention [Online].