A macro model for usage and recycling pattern of steel in Japan using the population balance model

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Received 10 March 2000; accepted 10 April 2000

Abstract

A macro model for evaluating the steel flow in Japan is proposed. The steels are classified into four types; virgin steel for machinery and for construction and recycled steel for machinery and for construction. The steel is assumed to be discharged from the society in accordance with the lifetime distribution of each usage. The amount of recycled steel and the accumulation in society are calculated using a population balance model. The comparison with the calculated results and statistics ensures the validity of the model. Since the amount of recycled steel mainly supplied for construction will increase and be oversupplied, recycled steel will have to be used for machinery. The required amount and the available amount to supply recycled steel for machinery are considered from the point of allowable copper concentration for machinery use. Copper contaminates steel during the recycling process of steel used for machinery and the contamination ratio is evaluated with the model. The copper concentration in the recycled steel and the amount of CO₂ emission are predicted for various scenarios. The relationship between recycling ratio and contamination ratio, which enables us to supply recycled steel for machinery, and the allowable CO₂ emission to decrease the contamination ratio are discussed.

Keywords: Steel usage; Lifetime distribution; Recycling; Population balance model; Copper concentration; CO₂ emission

1. Introduction

The accumulation of carbon dioxide gas (CO₂) emission due to various human activities is the cause of global warming. Among these activities, production, use (accumulation), and disposal of industrial goods contribute to it the most and recycling and prolonging the lifetime of products are considered as one of the ways to reduce the CO₂ emission. Substance Flow Analysis (SFA) [1] is one of the techniques to predict the environmental burden of products. It analyzes the environmental burden of products by applying Life Cycle Inventory [2] to flow and accumulation of products in a certain area and duration. However, in case the environmental burden at the time of new manufacturing is large and age for service of products is long, as in the case of steel, another model will be necessary in place of SFA. Namely, a model for predicting the amount of CO₂ emission accompanied by recycling and disposal of products in addition to new manufacturing will be necessary.

Recently, collected steel from used products (post-consumer scrap) tends to increase in Japan, and the production of recycled steel made from scraps is increasing. Recycled steel is mainly used for construction, because impurities contaminate post-consumer scrap during collecting, and lower the workability of steel [3]. If the amount of recycled steel keeps increasing, it will be oversupplied for construction, and it will be necessary to supply it for machinery. However, when recycled steel does not satisfy the requirement of impurity concentration, it cannot be used for machinery. To avoid it, decrease of production or impurity concentration in recycled steel will be necessary. Among impurities, copper is a main impurity and difficult to separate from steel so that the increase of copper concentration in recycled steel is considered in the model.

Steel and copper are taken as an example of products and impurities, respectively, to develop a model that predicts the amount of flow, accumulation and copper concentration of recycled steel, and the analysis of the amount of CO₂ emission. In the previous work [4], steels have been treated in a lump so that the process of copper contaminating steel was not traced in detail. In the present work, steels are classified into four types: virgin steel for machinery, virgin steel for construction, recycled steel for machinery and recycled steel for construction. Along with examining the validity of the model by comparing analyzed results with statistics, copper contamination ratio is estimated, and the relationship...
between recycling ratio and contamination ratio which enable us to supply recycled steel for machinery is discussed.

2. Macro model for steel mass flow in Japan

A schematic drawing for the mass flow of steel in Japan is shown in Fig. 1. Virgin steel made from iron ore and recycled steel made from scrap steel are consumed by manufacturers, and some of them are exported. Recycled steel is used for constructions by priority and a part of it for machinery. Virgin steel corresponds to converter steel and recycled steel mainly corresponds to electric-furnace steel. New scrap discharged at a time of manufacturing is only virgin steel and all of which is recycled. Moreover, only virgin steel is exported as machinery products like automobile etc. Steel in products discharged from society

Fig. 1. Schematic drawing for macro flow of steel in Japan.

Fig. 2. Schematic diagram for the flows of steels and copper contamination.
due to the lifetime is recycled as post-consumer scrap after dismantling and collecting. Recycling ratio, \( r_{rc}(t) \), is defined as the ratio of the amount of post-consumer scrap to that of discharged steel. Export/import scrap is included in the flow and all are the raw material of recycled steel. In-house scrap is not counted in the model because almost all are circulated in company itself. Because steel accumulation amount per person in developed countries, such as in the United States, tends to become constant [5], the society is assumed to have a constant possible accumulation amount, \( V \), which is equivalent to the maximum accumulation amount, \( S_{\text{max}} \).

Copper contaminates steel mainly at the time of collection of the used products. Provided that copper used in machinery products are difficult to separate, and copper wire etc. in constructions are easy to separate, so that copper is assumed to contaminate post-consumer scrap of steel for machinery as shown in Fig. 2. Copper concentration of export/import scrap is regarded as an average copper concentration of total post-consumer scrap.

A lifetime of steel is determined by various factors. However, since most of the steel is used for machinery or for construction, a product is assumed to be discharged from society when its age for service, \( \alpha \), is over its lifetime. Lifetime is given by a lifetime distribution, \( g(\alpha) \), that determines the lifetime of products at a time of manufacturing and is estimated from the distribution of the disposal rate data by compiling various kinds of statistics. If the usage for steel does not change much, distribution of the disposal rate can be considered as a distribution for lifetime. Also, since inventory time is short enough when it is compared to its age for service, years after manufacturing can be seen as age for service. Usage of steel can be classified into the usage for machinery including automobile and the usage for construction. Since lifetime distributions of both differ greatly, they need to be distinguished.

A population balance model [6,7] is applied to the present analysis because balance due to inflow/outflow of steel towards society and its age for service will be considered here. A population balance model is a scheme, which finds balance of material distribution in the space that has both external and internal coordinates. In this work, external variable is time and internal variable is age for service. The schematic diagram of the population balance model is shown in Fig. 3. The figure shows states of inflow, accumulation, and outflow at a time of \( t \). Domestic consumption flows into society, as age for service is 0. In society, as time passes, age for service becomes longer (darker in the figure). Consequently, products have a distribution to age for service. Products in society are discharged according to the lifetime distribution, and similarly in society, discharged products have the distribution to age for service.

3. Analysis method

3.1. Calculation

3.1.1. Population balance model

Manufacturer consumption ratio, \( r_{\text{manu}}(t) \), and new scrap ratio, \( r_{\text{ns}}(t) \), are defined as the ratio of manufacturer consumption to basic steel production, \( Q_{\text{bs}}(t) \), and the ratio of new scrap amount to manufacturer consumption, respectively. Then, the amount of new scrap, \( Q_{\text{ns}}(t) \), will be as follows

\[
Q_{\text{ns}}(t) = r_{\text{ns}}(t)Q_{\text{manu}}(t)Q_{\text{bs}}(t)
\]

Domestic consumption ratio, \( r_{\text{d}}(t) \), is defined as the ratio of domestic consumption to manufacturer consumption. Then, domestic consumption, \( Q_{\text{d}}(t) \), becomes

\[
Q_{\text{d}}(t) = r_{\text{d}}(t)(1 - r_{\text{ns}}(t))r_{\text{manu}}(t)Q_{\text{bs}}(t)
\]

Recycled steel production, \( Q_{\text{r}}(t) \), and virgin steel production, \( Q_{\text{v}}(t) \), will be given as

\[
Q_{\text{r}}(t) = r_{\text{rc}}(t)Q_{\text{d}}(t) + Q_{\text{espress}}(t) + Q_{\text{ns}}(t)
\]

\[
Q_{\text{v}}(t) = Q_{\text{bs}}(t) - Q_{\text{r}}(t)
\]

where \( Q_{\text{espress}}(t) \) is export/import scrap amount and \( Q_{\text{d}}(t) \) is
discharged amount from society. Domestic consumption of virgin steel for machinery, \(Q_{\text{vmd}}(t)\), virgin steel for construction, \(Q_{\text{vccl}}(t)\), recycled steel for machinery, \(Q_{\text{mcm}}(t)\), and recycled steel for construction, \(Q_{\text{rcccl}}(t)\), are classified according to whether steel for construction is occupied by recycled steel or not. The construction ratio, \(r_{\text{const}}(t)\), and machinery steel ratio, \(r_{\text{machine}}(t)\), are defined as the ratio of steel amount for construction to domestic consumption, and ratio of steel amount for machinery to recycled steel amount, respectively. In case that recycled steel does not occupy steel for construction, that is, in case of \(r_{\text{const}}(t)Q_{\text{r}}(t) > (1 - r_{\text{machine}}(t))r_{\text{manu}}(t)Q_{\text{d}}(t)\),

\[
Q_{\text{vmd}}(t) = (1 - r_{\text{const}}(t))Q_{\text{d}}(t) - r_{\text{machine}}(t)r_{\text{manu}}(t)Q_{\text{d}}(t) \quad (5)
\]

\[
Q_{\text{vccl}}(t) = r_{\text{const}}(t)Q_{\text{d}}(t) - (1 - r_{\text{machine}}(t))r_{\text{manu}}(t)Q_{\text{d}}(t) \quad (6)
\]

\[
Q_{\text{mcm}}(t) = r_{\text{machine}}(t)r_{\text{manu}}(t)Q_{\text{d}}(t) \quad (7)
\]

\[
Q_{\text{rcccl}}(t) = r_{\text{const}}(t)Q_{\text{d}}(t) \quad (8)
\]

On the other hand, in case that recycled steel occupies all steel for construction, that is, in case of \(r_{\text{const}}(t)Q_{\text{r}}(t) \leq (1 - r_{\text{machine}}(t))r_{\text{manu}}(t)Q_{\text{d}}(t)\),

\[
Q_{\text{vmd}}(t) = Q_{\text{d}}(t) - r_{\text{manu}}(t)Q_{\text{d}}(t) \quad (5')
\]

\[
Q_{\text{vccl}}(t) = 0 \quad (6')
\]

\[
Q_{\text{mcm}}(t) = r_{\text{manu}}(t)Q_{\text{d}}(t) - r_{\text{const}}(t)Q_{\text{d}}(t) \quad (7')
\]

\[
Q_{\text{rcccl}}(t) = r_{\text{const}}(t)Q_{\text{d}}(t) \quad (8')
\]

Since there is no formation and no annihilation inside the society, change in the amount of accumulation is equivalent to the amount which is subtracted the amount of discharge from the amount of inflow. The population balance equation for each steel becomes

\[
V \frac{\partial n_j(\alpha, t)}{\partial t} + V \frac{\partial}{\partial \alpha} \left( \frac{\partial n_j(\alpha, t)}{\partial t} \right) = [Q_{\text{jdm}}(t)n_{\text{jdl}}(\alpha, t) - Q_{\text{jdm}}(t)n_{\text{jdl}}(\alpha, t)] \quad (9)
\]

\((i = v, r, j = m, c)\)

where \(v\), \(r\), \(m\) and \(c\) mean virgin steel, recycled steel, steel for machinery, and steel for construction. Also, \(n_j(\alpha, t)\), \(n_{\text{jdl}}(\alpha, t)\), and \(n_{\text{jdl}}(\alpha, t)\) represent the steel amount ratios which are arranged by age for service to the amount of possible accumulation, \(V\), the amount of domestic inflow, \(Q_{\text{jdm}}(t)\), and the amount of discharge \(Q_{\text{jdm}}(t)\), respectively.

Since usage pattern of steel products stays the same until they are discharged from society, \(d\alpha/dt = 1\). Age for service for every steel at the time of inflow into society is regarded as 0, then it becomes \(n_{\text{jdl}}(\alpha, t) = \delta(0, t)\), and Eq. (9) will be as given below

\[
V \frac{\partial n_j(\alpha, t)}{\partial t} + V \frac{\partial}{\partial \alpha} \left( \frac{\partial n_j(\alpha, t)}{\partial t} \right) = Q_{\text{jdm}}(t)\delta(0, t) - Q_{\text{jdm}}(t)n_{\text{jdl}}(\alpha, t) \quad (10)
\]

where \(\delta(0, t)\) is the Dirac delta function. Products accumulated in society will be discharged when their lifetime is over. The discharged amount of steel \(ij\) that has age for service \(\alpha\) at the time of \(t\) (the second term of right side of Eq. (10)) will become

\[
Q_{\text{jdm}}(t)n_{\text{jdl}}(\alpha, t) = h_j(\alpha)Vn_j(\alpha, t) \quad (11)
\]

where discharged rate distribution, \(h_j(\alpha)\), is defined as the ratio of discharged amount to accumulation amount which have age for service \(\alpha\). The discharged rate distribution is derived from lifetime distribution by the following equation.

\[
h_j(\alpha) = \frac{g_j(\alpha)}{1 - \int_0^\alpha g_j(\alpha) \, d\alpha} \quad (12)
\]

Consequently, Eq. (10) becomes

\[
V \frac{\partial n_j(\alpha, t)}{\partial t} + V \frac{\partial}{\partial \alpha} \left( \frac{\partial n_j(\alpha, t)}{\partial t} \right) = Q_{\text{jdm}}(t)\delta(0, t) - \frac{g_j(\alpha)}{1 - \int_0^\alpha g_j(\alpha) \, d\alpha} Vn_j(\alpha, t) \quad (13)
\]

Also, since it is \(\int_0^\infty n_{\text{jdl}}(\alpha, t) \, d\alpha = 1\), it will be

\[
Q_{\text{jdm}}(t) = V \int_0^\infty h_j(\alpha)n_{\text{jdl}}(\alpha, t) \, d\alpha \quad (14)
\]

from Eq. (11). Total amount discharged from society will be obtained by the following equation.

\[
Q_o(t) = Q_{\text{vmd}}(t) + Q_{\text{vccl}}(t) + Q_{\text{mcm}}(t) + Q_{\text{rcccl}}(t) \quad (15)
\]

Also, accumulation amount \(S(t)\) is given as

\[
S(t) = V \int_0^\infty (n_{\text{vcm}}(\alpha, t) + n_{\text{vcm}}(\alpha, t) + n_{\text{rm}}(\alpha, t) + n_{\text{rsc}}(\alpha, t)) \, d\alpha \quad (16)
\]

By solving four simultaneous Eq. (13) with initial condition \(n_j(\alpha, 0) = 0\) \((\alpha > 0)\) and \(n_j(0, t) = Q_{\text{jdm}}(t)/V\), accumulation amount and each flow can be found by iterative calculation under the constraint condition that both values of input and output \(Q_o(t)\) become the same.

### 3.1.2. Copper contamination

Contamination ratio, \(r_{\text{max}}(t)\), is defined as the ratio of copper amount to post-consumer scrap of machinery steel. Amount of newly contaminating copper, \(I_c(t)\), will be

\[
I_c(t) = r_{\text{max}}(t)r_{\text{rec}}(t)(Q_{\text{vmd}}(t) + Q_{\text{rmo}}(t)) \quad (17)
\]

Since copper accumulates only in recycled steel, copper
Fig. 4. Time change of basic steel production and export/import scrap amount in Japan: (a) basic steel production; (b) export/import scrap amount. Solid line and broken curve represent statistics and approximated equations, respectively.

Fig. 5. Time change of manufacture consumption ratio, new scrap ratio, domestic consumption ratio and construction ratio in Japan: (a) manufacture consumption ratio; (b) new scrap ratio; (c) domestic consumption ratio; (d) construction ratio. Solid lines and broken curves represent statistics and approximated equations, respectively.
amount in total post-consumer scrap will be

\[
I_a(t) = r_{re}(t) \
\times \left( Q_{rmo}(t) \int_0^t c(\alpha, t) n_{rmo}(\alpha, t) \, d\alpha + Q_{rco}(t) \int_0^t c(\alpha, t) n_{rco}(\alpha, t) \, d\alpha \right) \
= r_{re}(t) \left( Q_{rmo}(t) \int_0^t c(0, t - \alpha) n_{rmo}(\alpha, t) \, d\alpha + Q_{rco}(t) \int_0^t c(0, t - \alpha) n_{rco}(\alpha, t) \, d\alpha \right)
\]

\[Q_{required}(t) = (1 - r_{machine}(t)) r_{manu}(t) Q_1(t)\]

\[-r_{const}(t) Q_{d1}(t) (Q_{required}(t) \geq 0)\]  \hspace{1cm} (22)

On the other hand, recycled steel within the allowable copper concentration \(c_{allow}\) can be used for machinery. Up to now, copper concentration in recycled steel has been treated as mean values, but it has distribution in reality. Thus, recycled steel that can be used for machinery \(Q_{available}(t)\) is given as

\[Q_{available}(t) = r_{manu}(t) Q_1(t) \int_0^{c_{allow}} f(c) \, dc\]  \hspace{1cm} (23)

where \(f(c)\) is probability density function of concentration distribution, and \(c\) is concentration.

Total \(CO_2\) emission amount from steel production, recycling, and abolition within Japan is

\[Q_{CO2}(t) = a_1 Q_1(t) + a_2 Q_2(t) + a_w Q_w(t)\]  \hspace{1cm} (24)

where \(a_1, a_2, a_w\) represent \(CO_2\) emission amount of virgin steel, recycled steel and waste steel per unit, respectively.

### 3.2. Statistic value

Basic steel production, \(Q_{bs}(t)\), and export/import scrap amount, \(Q_{es}(t)\), are found from statistics \([5,8]\) (Fig. 4(a) and (b)). Manufacturer consumption ratio, \(r_{manu}(t)\), is found as the ratio of apparent basic steel consumption to basic steel production using statistic values \([5]\) (Fig. 5(a)). New scrap ratio, \(r_{new}(t)\), is derived as new scrap amount divided by apparent basic steel consumption in Ref. \([9]\), and approximated constant value 9% is used for calculation (Fig. 5(b)). Domestic consumption ratio, \(r_d(t)\), is derived as following. First, indirect export/import amount is subtracted from total of general steel final domestic consumption in Ref. \([5]\). Then, it is divided by total of steel domestic consumption (Fig. 5(c)). Construction ratio, \(r_{const}(t)\), is found as the ratio of steel amount for construction to domestic consumption in Ref. \([5]\), and is approximated constant value 61% (Fig. 5(d)). Using for machinery ratio, \(r_{machine}(t)\), is assumed to be a constant value 15% using the Ref. \([10]\). Solid lines represent statistics and broken curves represent approximated ones in Figs. 4 and 5. These statistics are


Approximated by equations in Table 1, and used for calculation.

### 3.3. Numerical calculation

First, Eq. (13) is solved by using an explicit finite-difference scheme on age for service and time. Delta function in Eq. (13) is not included in the difference equation because it is under the condition of $\delta(\alpha, t) = 0 (\alpha > 0)$

$$
n_{ij}(\alpha, t + \Delta t) = \left(- h_j(\alpha) \frac{\Delta t}{\Delta \alpha} + 1 \right) n_{ij}(\alpha, t) + \frac{\Delta t}{\Delta \alpha} n_{ij}(\alpha - \Delta \alpha, t)
$$

Eq. (25) under initial condition $n_{ij}(0, 0)$ and $n_{ij}(\alpha, 0) = 0$ from $\Delta \alpha$ to $\Delta t$ on $\alpha$. Then, $n_{ij}(\alpha, 2\Delta t)$ is found using initial condition $n_{ij}(0, \Delta t)$ and $n_{ij}(\alpha, \Delta t)$ from $\Delta \alpha$ to $2\Delta t$ on $\alpha$. Similarly, $n_{ij}(\alpha, t + \Delta t)$ is found using initial condition $n_{ij}(0, t + \Delta t)$ and $n_{ij}(\alpha, t + \Delta t)$ from $\Delta \alpha$ to $t + \Delta t$ on $\alpha$. Here, $\Delta t$ is 0.05 years and $\Delta \alpha$ is 0.1 years.

Lifetime distribution of steel is assumed to be approximated by a gamma distribution from the Ref. [11]. Its variance is determined so as to satisfy a condition that integral value form 0 to double average lifetime occupies 99% of the integral value from 0 to infinity, because products used for twice as long as average lifetime will be mostly discharged from society. Average lifetime of steel for machinery and for construction is 10.06 years [12]. Steel for construction used over 50 years is not unusual, so its average lifetime is assumed to be 35.0 years. The variance of steel for machinery and for construction is calculated as 12.50 and 153.5, respectively. These lifetime distributions used for calculation are shown in Fig. 6.

Concentration distribution $f(c)$ is derived from the concentration distribution of post-consumer scrap of recycled steel in the Ref. [13]. Concentration distribution $f(c)$ is defined as that at a time of production. These two distributions are assumed to be the same because concentration distribution at a time of electric-furnace steel production will be determined by the concentration distribution of post-consumer scrap. Normal distribution is used for an approximated concentration distribution. Expectation is set at average concentration of recycled steel and variance is assumed as one fourth of expectation. Concentration distribution which has 0.298% copper concentration (broken curve) and normalized data from Ref. [13] (solid line) are shown in Fig. 7 together.

From Ref. [3], allowable copper concentration for machinery is 0.1% of hot- or cold-rolled sheet steel. From Ref. [14] recycling ratio $r_{fe}$ is 80%, and $a_r, a_v, a_w$ are inventory factors for electric-furnace steel production, converter steel production, and abolition management, respectively, and the values of 0.458, 0.136, and 0.013 C-ton/Fe-ton are used, respectively.

Relationship of input data, reference data and calculation results is arranged in Fig. 8. Input Data 1 is applied to the population balance model, then Output Data 1 is obtained. Comparison of these results with Reference Data ascertains the validity of the model. Also, contamination ratio, $r_{min}(t)$, is estimated by this comparison. Output Data 2 is obtained by the calculation with Output Data 1 and Input Data 2.

### 4. Result and discussion

#### 4.1. The amount of recycling and accumulation steel

Calculation result of accumulation amount within Japan, $S(t)$, (broken curve) is shown with statistics [15] (solid line) in Fig. 9. Accumulation amount begins increasing from
about 1960, and reaches nearly 1200 million ton in about 2000. From calculation result, the increase rate becomes slow in future and maximum accumulation amount becomes nearly 1600 million ton. The calculated result of recycled steel production, $Q_{rt}$; and the sum of post-consumer scrap, export/import scrap, and new scrap in statistics [8,16] are shown in Fig. 10. In this figure, broken curve and solid line represents calculation result and statistics, respectively. Recycled steel production tends to increase with increase of post-consumer scrap, and will exceed 500 million ton. Consequently, recycled steel will be oversupplied for construction and have to be used actively for machinery. Ratio of recycled steel post-consumer scrap to total post-consumer scrap is shown in Fig. 11. Solid squares, ■ in the figure are the values in Ref. [17]. Recycled steel post-consumer scrap, which occupied about 24% in all post-consumer scrap at 1996, will occupy about 40% at 2015 and 70% at about 2050. In future, the amount of recycled steel that has higher copper concentration tends to increase, consequently dilution of copper concentration becomes difficult.

4.2. Required amount and available amount of recycled steel for machinery

Average copper concentration of recycled steel post-consumer scrap is shown in Fig. 12. These results are calculated based on three patterns that recycling ratio is constant 80%, contamination ratio is 0.3, 0.4, and 0.5%. Solid square,
in the figure represents findings in Ref. [18]. Contamination ratio is estimated 0.4%.

In this model, because domestic consumption amount for construction is given to be constant from 2000, recycled steel that has to be used for machinery appears with increase of recycled steel production. This is referred as the required amount (“Required” in Fig. 13). On the other hand, the amount of recycled steel that has less copper concentration than allowable concentration is the available amount for machinery. This is referred as the available amount (“Available” in Fig. 13). If available amount is less than required amount (left hand of the figure), recycling ratio has to be decreased to increase virgin steel amount or contamination ratio has to be decreased to increase the amount of recycled steel which can be used for machinery (right hand of the figure).

Following results are calculated based on three scenarios that recycling ratio is constant 80%, contamination ratio varies linearly from 0.4% at 2000 to achieve the goal value 0.2, 0.3, and 0.4% at 2005. The required amount (broken curve) and the available amount (solid curves) are shown in Fig. 14(a). Average copper concentration decreases, as contamination ratio decreases. Consequently, the amount of recycled steel, which can be used for machinery, increases. In case that the goal value is 0.4, 0.3, and 0.2%, available amount will exceed the required amount until 2032, 2040, and 2090, respectively. Average copper concentration of recycled steel is shown in Fig. 14(b). As soon as recycling begins, copper concentration increases rapidly, and decreases slowly afterwards. Copper concentration decreases even when contamination ratio is constant because copper concentration is diluted by virgin steel scrap used for construction and new scrap. Because the ratio of recycled steel post-consumer scrap to total post-consumer scrap increases, copper concentration becomes hard to dilute and tends to increase monotonously from about 2010. The symbol, £, in the figure means an available year until when recycled steel is not available for machinery.

Following results are calculated for three scenarios that contamination ratio is constant 0.4%, recycling ratio varies linearly from 80% in 2000 to achieve the goal value 70, 80, 90% in 2005. The required amount (broken curves) and the available amount (solid curves) are shown in Fig. 15(a). In case that the goal value is 90% and 80%, the available amount will exceed the required amount until 2014 and 2033, respectively. In case of 70%, the required amount becomes 0. As recycling ratio increases, required amount increases rapidly. On the other hand, recycling ratio decreases consequently required amount disappears. The effect of recycling ratio on the required amount is larger than that on copper concentration. Average copper concentration of recycled steel is shown in Fig. 15(b). As recycling ratio increases, average concentration increases. Because the effect of recycling on copper concentration has time lag, the change of concentration is slower than previous case that concentration ratio varies.

The goal recycling ratio and contamination ratio determine available years. This relationship is shown in Fig. 16 supposing available years as a contour line. Under the condition of constant available year, decrease of the goal contamination ratio makes it possible for recycling ratio to increase dramatically. Decreasing contamination ratio from 0.4% to about 0.3% does not increase recycling ratio very much. The longer the available year becomes, the bigger the change in available years against the change in contamination ratio and in recycling ratio. After 2050, a little decrease in recycling ratio or contamination ratio extends available years.

4.3. The additional CO2 emission amount allowed decreasing contamination ratio

The calculation result of CO2 emission amount is shown in Fig. 17. These results are calculated based on three scenarios that recycling ratio vary linearly from 80% until 2000 to the goal value 70, 80, and 90% at 2005. Also, available years for the goal contamination ratio 0.25 and
0.4% are shown. The amount of steel flow determines CO₂ emission amount, because the additional amount, which is emitted by reduction of contamination ratio, is not considered. The amount of CO₂ emission increases with rapid increase of basic steel production and has passed its peak around 1980 (approximately 37 million C·t) and slowly decreases along with increase in the ratio of recycled steel to basic steel. Also as recycling ratio increases, CO₂ emission amount decreases but to supply the recycled steel for machinery will be impossible sooner.

Fig. 16 shows that the maximum allowable recycling ratio becomes 77% in order to supply machinery steel for

Fig. 12. Time change of average copper concentration in recycled steel post-consumer scrap with various contamination ratio. Curves represent calculation results and a solid square is the value in Ref. [10].

Fig. 13. Schematic diagram for the required and available amount of recycled steel for machinery.

Fig. 14. Time change of the required and available amount of recycled steel for machinery and copper concentration in recycled steel. (a) The required and available amount in case recycling ratio is constant 80% and contamination ratio varies in 0.2, 0.3 and 0.4%. Solid curves represent available amount and broken curve represents required amount. (b) Copper concentration in recycled steel in the same case as (a). The symbol, ×, means an available year until when recycled steel is not available for machinery.
50 years with contamination ratio 0.4%. The CO₂ emission amount with contamination ratio 0.4% is taken as standard and the reduction of CO₂ emission can be quantitatively discussed. The amount of CO₂ emission reduction, \( Q_{\text{CO}_2}^{\text{allow}} \), by increase in recycling ratio is the amount allowed to achieve contamination ratio, which is available to supply recycled steel for machinery. Then the allowable additional CO₂ emission or inventory factor of post-consumer scrap management per unit, \( a_{\text{allow}}(t) \), will be defined by

\[
 a_{\text{arrow}}(t) = \frac{Q_{\text{CO}_2}^{\text{allow}}(t)}{Q_{\text{re}}(t)} Q_{\text{oc}}(t)
\]

In case of the goal recycling ratio 80%, the goal contamination ratio is about 0.26% and \( a_{\text{allow}}(t) \) becomes about 0.013 C-ton/Fe-ton. In case of the goal recycling ratio 90%, the goal contamination ratio is about 0.14% and \( a_{\text{allow}}(t) \) becomes about 0.048 C-ton/Fe-ton. These values will give the standard of inventory factor that society should permit in order to reduce the total amount of CO₂ emission.

5. Conclusion

The model of Japanese steel industry that consists of new manufacture, recycling, accumulation, and disposal is constructed. This model is developed based on the idea that steel is discharged from society according to lifetime distribution. Lifetime distribution is assumed to be approximated by gamma distribution and searched for different usage; usage for machinery and for construction. Basic steel production, export/import scrap, manufacturer consumption ratio, new scrap ratio, domestic consumption ratio, construction ratio and using for machinery ratio are approximated from statistic values. Recycled steel amount and accumulation amount are calculated by applying a population balance model. The comparison between calculation results and statistics ensures the validity of the model. Copper concentration in recycled steel scrap is calculated, and contamination ratio is estimated to be 0.4%. In case of recycling ratio and contamination ratio having changed from 2000, copper concentration in recycled steel and CO₂ emission are calculated. Concentration distribution in recycled steel is assumed from the reference and the required and available amounts of recycled steel for machinery are calculated. Then relationship of the available years, recycling ratio and contamination ratio is discussed. Consequently, contamination ratio should be decreased to
increase recycling ratio and recycling ratio should be decreased when the present contamination ratio is maintained. Increasing recycling ratio reduces the amount of CO₂ emission only when contamination ratio is decreased to a certain level. The reduction amount of CO₂ emission is shared to achieve the goal contamination ratio and the allowable CO₂ emission amount for scrap management that decreases contamination ratio should be considered from the national point of view.

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