1. Introduction

More than 90% of all produced Cr is used as an alloying element in stainless steel, other special steels (e.g., heat-resistant steel, bearing steel, spring steel, structural alloy steel), and a few kinds of carbon steel. As the world’s largest importer of Cr, Japan consumes some 500 kt (kilo tons) of Cr per year. In terms of metals consumed, Cr is the fifth-ranked element after Fe, Al, Cu, and Zn. In addition to Cr, steel contains many other kinds of alloying elements, and the material flow analysis (MFA) of steel leads to the analysis of the substance flows of alloying elements Mo, P, and Mn. Although more Cr is used in steel materials than any of these other elements, the material flow of Cr has rarely been analyzed. Most of the Cr in carbon steel is added unintentionally; it is mixed in at the stage in which consumed market scrap is recycled. At low concentrations, this mixed-in Cr is difficult to extract, and is considered to have an adverse effect on cold working.

Various studies on the flow of Cr have focused on stainless steel flow, which accounts for more than 80% of Cr consumption for steel making. These studies were conducted utilizing dynamic MFA. Igarashi et al. and Daigo et al. pointed out that while the recovery rate of nonmagnetic stainless steel scrap is estimated to be high, much of the magnetic stainless steel scrap might be recovered as carbon steel scrap. The material flow of carbon steels and alloy steels other than stainless steel, however, has not been investigated from the perspective of Cr flow. Johnson et al. conducted a static substance flow analysis of Cr on a global scale for the year 2000. They estimated the Cr content in waste scrap recovered from end-of-life products by multiplying the amount of waste stream (including scrap) by the percentage of Cr content, which was assumed to be the same throughout the world. Although recyclability was assumed to vary according to the material, Johnson did not distinguish between types of steel or consider any possible relationship between Cr flow and the flow of materials; i.e., different kinds of steel. To discuss the recyclability of Cr, one must consider the differences in recyclability depending on materials. As long as Cr is contained and used in different materials, the recyclability of Cr should be considered in terms of individual materials. To date, the material flow of Cr in materials other than stainless steel has not been analyzed.
been addressed. In this study, we clarify the Cr flow associated with the flow of special steels, carbon steels, and all other steel materials, with the goal of assessing the recyclability of Cr.

2. Study Methodology

2.1. Objects of Evaluation

In this study, we consider the flow of Cr contained in steels. On the basis of the differences in the dynamics of the recovery and consumption of steel scrap, we classified steel material cycles into three broad categories: the alloy steel cycle, BOF steel cycle, and EAF steel cycle. The steel material flows that we analyzed are shown in Fig. 1 for each cycle. We assumed that BOF carbon steel scrap flows into both the alloy steel cycle and the EAF carbon steel cycle, and that there is a flow from the alloy steel scrap into the EAF carbon steel cycle. Previous studies have considered only the flow of alloy steel to be a flow of Cr-containing steel materials. However, to track the flow of Cr over its entire life cycle, it is also necessary to analyze the Cr flow in the EAF carbon steel cycle, into which alloy steel scrap is mixed, as shown in Fig. 1.

The Cr concentrations in the Cr-containing steels evaluated in this study are presented in Table 1. The Cr contents were determined by referencing JIS (Japan Industry Standard) for representative types of steel and by consulting the manufacturers of stainless steel. For steels having substantially different alloy compositions (e.g., heat-resistant steels and structural alloy steels), we show the typical composition for each alloy, and we determine the weighted average based on the production volume of hot-rolled steel. Alloy steels other than those listed here were not considered in our analysis because they were not considered to make a significant contribution to the substance flow of Cr, either because they do not contain Cr or because they are produced in relatively small quantities. For BOF carbon steels, we obtained measurement data from a published study of the Cr concentration in steel scrap generated from BOF steel production. The scrap that was analyzed came in the form of steel rods and section steel, with an arithmetic mean Cr content of 0.019%. It was assumed, however, that the permissible concentration of impurities in steel rod and section steel is higher than that in sheet steel, thereby creating the assumption of a Cr concentration level of 0.01% for BOF carbon steel scrap on average, based on catalog data and consultations with steel manufacturers. As regards the Cr concentration of EAF carbon steel, its variation over time can be obtained as the result of estimation. The flow of Cr was classified for every steel type given in Table 1, for phases spanning from production and use, to scrap.

2.2. Dynamic Material Flow Analysis (Dynamic MFA)

In this study, we classified scrap into three types: in-house scrap generated from steel production processes, industrial scrap generated from steel manufacturing and fabrication processes, and obsolete scrap generated from end-of-life products. The data of the amount of in-house scrap was obtained either from statistics or surveys (see Sec. 2.5.2). To determine the amount of industrial scrap, we used the rate of generated industrial scrap relative to steel consumption, which was obtained by means of a survey (see Sec. 2.5.2). The amount of obsolete scrap was estimated using a dynamic analysis. This analytical method estimates the output of an end-of-life material generated by an application by utilizing the input to the usage stage for each application from the past and the lifetime distribution of product use for that application, which is known as the population balance model (PBM). The generated amount estimated by this method is a theoretical value. In practice, up to the point when it is collected as scrap, there is the question of yield in product collection, disassembly, and separation processes. For this reason, the total amount is divided into recovered obsolete scrap and unrecovered materials. We estimated both the recovered obsolete scrap and unrecovered materials by setting an end-of-life recovery rate for each application (see Sec. 2.4.4). Furthermore, magnetic selection is often used in mechanical separation processes, in which ferritic alloys, which are magnetic, are considered to be included in both scrap recovered as alloy steel and BOF carbon scrap.
steel and scrap recovered as carbon steel. In this study, the difference between estimated amount of the total of the recovered obsolete alloy steel scrap and the generated industrial alloy steel scrap and statistical value of alloy steel scrap purchased from market was recognized as the amount of alloy steel recovered as carbon steel scrap. In addition, through dynamic analysis, it is possible to derive the quantity of stock in use. This study does not, however, take into account the dissipation of steel materials caused by corrosion during use.

2.3. Material Balance

2.3.1. Verification by Material Balance of Raw Materials and Products

In steel production, the quantity of Cr contained in the consumed raw materials must be equal to the quantity of Cr contained in the product. From this material balance, we confirmed the validity of the raw materials and products that we considered in this study. The raw materials were in-house scrap, industrial scrap, imported scrap, and obsolete scrap, for various kinds of steel, as well as Cr ore and ferrochrome. From other studies we learned that ferrochrome, which makes up a large proportion of these raw materials, has a Cr content ranging from 52 to 62%. Therefore, the percentage of Cr content in ferrochrome was calculated by dividing the quantity of Cr contained in ferrochrome, obtained from the Cr material balance, by the ferrochrome consumption obtained from statistics. The result confirmed the range quoted above. For Cr ore, we obtained an estimate of its direct consumption in steelmaking from a previous study. The methods used to estimate the consumption of other raw materials are detailed in Sec. 2.4. For products, we considered crude steel and slag. The method used to estimate crude steel production is described in Sec. 2.5.1. In the manufacture of stainless steel, 1.4% of the Cr consumed in its production ends up in slag. We applied this same rate to all alloy steels. The proportion of the Cr consumed for BOF carbon steel that was dispersed as slag was assumed to be the same as the proportion of Cr consumed for EAF carbon steel that was dispersed in slag, as will be explained in the next section. Material balance calculations were conducted for 2003-2005, the years for which we could acquire data on stainless steel scrap. We considered the Cr material balance only in the production of alloy steels and BOF carbon steels, because ferrochrome is not consumed in the production of EAF carbon steel.

2.3.2. Estimating the Cr Concentration of EAF Carbon Steel and Slag

The Cr concentrations of EAF carbon steel were obtained from literature for nine survey points between 1982 and 2007. At the same time, we estimated the Cr concentration of EAF carbon steel from the Cr material balance in EAF carbon steel production, confirming the validity of the estimated scrap flow. To conduct a dynamic analysis based upon the past, we used a fixed value of 0.17% as an initial value for Cr concentration in EAF carbon steels up to 1990, which was the average of the recorded measurements. From 1991 onward, Cr concentration was estimated on the basis of the Cr material balances in EAF carbon steel production. We also forecast changes in Cr concentration into the future. For this forecast, the values of future production for each type of steel and the relative proportions of alloy and carbon steels were assumed to remain constant at 2006 levels.

The source of Cr in EAF carbon steel was considered to be from consumption of alloy steel scrap, BOF carbon steel scrap, and EAF carbon steel scrap. The quantity of Cr in obsolete EAF carbon steel scrap was estimated using the PBM, which reflects the differences in Cr concentration in the EAF carbon steel produced each year. The Cr concentrations of in-house and industrial EAF carbon steel scrap were considered to be the same as the Cr concentration of the EAF carbon steel produced in a given year.

Crude steel and slag were taken into account as products. The method used to estimate crude steel production is described in Sec. 2.5.1. The values related to slag were estimated on the basis of data from a survey of steel byproducts conducted in 1993. This survey determined the per-unit slag generation in EAF for stainless steel, other alloy steels, and carbon steel, as well as the average Cr concentration in slag for all EAF. Although separate values were obtained for oxidizing slag and reducing slag, the Cr concentration in slag could not be obtained for each type of steel. From the proportions of production, we determined that the Cr content in EAF for each type of steel was such that the weighted average was equal to the Cr concentration of slag for all EAF. Here, we assumed that 1.4% of the Cr input in stainless steelmaking ended up in slag, and that the Cr concentration in the slag for other alloy steels was equal to that for carbon steel slag. Using the measurements of Cr concentration and production volume for EAF carbon steel in 1992, we estimated the distribution ratio of Cr (Cr concentration in slag/Cr concentration in molten steel). This distribution ratio is considered to be constant from year to year. Also, year-to-year data on per-unit slag generation could only be obtained for EAF as a whole. Thus, the proportional change in per-unit slag generation was determined from year to year, and the changing rate was used to estimate the per-unit slag generation for EAF carbon steel production in each year. These figures, in turn, were then used to estimate the quantity of Cr in EAF carbon steel slag for each year.

2.4. Estimating the Flow of Scrap

2.4.1. Types of Scrap and Destinations of Scrap

As mentioned above, in the present study, steel types were classified as alloy steels, BOF carbon steels, and EAF carbon steels. Scrap was therefore also classified according to the type of furnace (i) in which the steel was produced, the type of steel (j), and the stage of scrap generation (m). We expressed the quantity of scrap of steel type j originating in a furnace of type i and generated at stage m as Sm(i,j). Here, furnace (i) is either a basic oxygen furnace (BOF) or an electric arc furnace (EAF), with the total of both types denoted by (total). Steel type (j) can be carbon steel (cs) or alloy steel (as), or a total of the two types (total). The sources of generation (m) are in-house (in-house), industrial (ind), obsolete (obs), export (exp), or import (imp). In the case of a scrap import or export, the quantity refers to the amount exported or imported, not the amount generated. In addition, we classified scrap consumption according to the

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specified in available statistics. We expressed this as a statistical difference between carbon steel scrap and the total for both types of furnace \((i)\), and the type of steel \((j)\), as well as the furnace in which the scrap was to be consumed \((k)\) and the type of steel to be produced \((l)\). This quantity is expressed as

\[ S(i;j|k;l) \]

where \(k\) and \(l\) can take the same values as \(i\) and \(j\), respectively. When referring to the total for all furnaces and steel types, the total for both \(i\) and \(j\), or for both \(k\) and \(l\), is intended. However, the quantity of collected alloy steel scrap that is mistakenly identified as carbon steel is considered separately and is expressed as MS, which is counted in the consumption of scrap of type \(j\) in BOFs. EAF carbon steel scrap is collected as alloy steel, except carbon steels destined for mechanical and structural applications, as alloy steels. To avoid any confusion caused by the terms ordinary/special and carbon/alloy, we defined all special steels, except carbon steels destined for mechanical and structural applications, as alloy steels. We concluded that this excess consumption of alloy steels is considered to consist of the alloy steel scrap collected as alloy steel, \(S(\text{total} \cdot \text{as}|\text{total})\), and carbon steel scrap from BOFs. EAF carbon steel scrap is collected as carbon steels are considered to be consumed only in the production of EAF carbon steels. The relationships between the supply sources for this scrap and its consumption points are summarized in Table 2.

### Table 2: Relationship between scrap source \((i,j)\) and its consumption \((k,l)\)

| i | j | k | l | Carbon steel | Alloy steel |
|---|---|---|---|-------------|-------------|
| | | | | BOF | EAF |
| | | | | * as | |
| | | | | bof cs | eaf cs |
| Carbon steel | | | v | v | v |
| EAF | | | 0 | v | 0 |
| Alloy steel | * as | | 0 | v (MS) | v |

Note: Asterisk indicates any of the furnaces such as BOF and EAF.
the generation of discarded steel (estimated by the PBM) as the denominator, and the quantity of recovered obsolete scrap as the numerator. We then applied the mean value for these three years, which was 86%, for each year from 1990 onwards.

2.4.3. Magnetic Alloy Steel Scrap

Because all alloy steels other than austenitic stainless steel possess magnetism, it is possible that some of these are mistakenly identified as carbon steel scrap. First, we multiplied the generation of discarded steel, as determined by the PBM, by the end-of-life recovery rate, which was set in advance (see Sec. 2.5.3 and Table 3), and considered this to be the quantity of recovered obsolete scrap. Then, by adding the generation of industrial scrap and taking into account the imported and exported scrap, we determined the collection potential as market scrap. At the same time, by obtaining the alloy steel scrap consumption data from the available literature\textsuperscript{15,21} and a survey,\textsuperscript{22} and subtracting from this the quantity of generated in-house scrap considered to be consumed completely by in-house processes, we estimated the consumption of market scrap, which consists of obsolete scrap and industrial scrap. The difference between the collection potential as market scrap and the consumption of market scrap is estimated as the quantity of alloy steel scrap that is mistakenly collected as carbon steel scrap (MS). In this estimate, when data was available only for the total of alloy steels, we deleted austenitic stainless steel from the data.

Here, the mix rate of magnetic alloy steel scrap into the carbon steel cycle was defined as the quantity of alloy steel scrap mistakenly mixed in with carbon steel (numerator), divided by the collection potential of market alloy steel scrap (denominator). Assuming that this mix rate does not vary with each alloy steel type, we estimated the amount of alloy steel scrap misclassified as carbon steel scrap for each alloy steel type, based on the generation of industrial scrap and the collection of obsolete scrap for each steel type. For the years 2003–2005, we were able to obtain data on scrap consumption and generated in-house scrap for ferritic stainless steel only.\textsuperscript{22} Accordingly, for these three years, we distinguished ferritic stainless steel from other alloy steels.

2.4.4. Carbon Steel Scrap

To examine the material balance of the alloy steels and BOF carbon steels in Sec. 2.3.1, and the EAF carbon steels in Sec. 2.3.2, we made two classifications for the quantity of carbon steel scrap consumed in EAF: one for carbon steel and one for alloy steel. First, we assumed that the amount of scrap consumed per unit of crude steel production in EAFs was the same for both alloy and carbon steels. As mentioned before, all alloy steel scrap is used in the production of alloy steel, so we estimated the quantity of carbon steel scrap consumed in EAF alloy steel production by subtracting the consumption of alloy steel scrap from the consumption of total scrap in the production of EAF alloy steel. All of the carbon steel scrap consumed for EAF alloy steel is regarded as BOF carbon steel scrap. The remaining carbon steel scrap is consumed in the production of EAF carbon steel.

2.5. Data Development

2.5.1. Crude Steel Production, Steel Orders, and Steel Consumption

To determine the crude steel production of alloy steel, we converted hot-rolled steel production\textsuperscript{31} into crude steel terms for each steel type, using a yield rate of 90%, in accordance with the estimation method of the Japan Stainless Steel Association.\textsuperscript{23} To estimate the crude steel production of carbon steel, we used published data\textsuperscript{33} on crude BOF carbon steel production. The orders for each steel type were obtained from statistics\textsuperscript{81} for more than 15 separate end uses for each year between 1955 and 2006. In this study we consolidated the end-use categories from which these statistics were compiled into the following eight categories: buildings and construction, industrial machinery, electrical and electronic equipment, household and commercial appliances, passenger vehicles, other transportation, containers, and other products. The end uses of carbon steel were classified into nine categories by sub-dividing the category that combined buildings and construction into two separate categories: one for buildings and one for construction. In the 15 end uses in the statistics, there are some categories in which the end uses are unclear, such as “the next process”, “the dealer”, “unknown”, and “non-reporters”. The quantities in these categories were therefore distributed in proportion to the order quantity for the eight or nine end-use categories of this study. As for the order quantity for stainless steel, we could not obtain order quantities by steel type. We, therefore, proportionally divided them based on the proportion of orders by steel type for the previous year.

We obtained the amount of steel consumption from steel order quantities, taking into account steel import and export quantities. The import and export quantities for each steel type were obtained from a steel industry yearbook.\textsuperscript{33} Although the amount of consumption for alloy steels could be distinguished from that of carbon steels, the distinction between steel types could not be obtained for some years. In these cases, the proportions of orders were used in order to distribute the quantities among the more detailed steel type categories. In addition, the obtained steel import quantities were distributed to correspond with orders for the eight end uses for each year. By adding imports to domestic orders, we obtained the amount of steel consumption (quantity of material flow to the product manufacturing process).

2.5.2. Quantity of Generated In-house Scrap and Industrial Scrap

By considering the figures for “production or generation” found in statistics\textsuperscript{15,21} as the quantity of in-house scrap, we obtained in-house scrap figures for each of the alloy steels, BOF carbon steel, and EAF carbon steel. Separately, we also obtained the in-house scrap figures for ferritic and austenitic stainless steels for three years from 2003 to 2005, using data from a survey\textsuperscript{22} by the Japan Stainless Steel Association. In this way we determined the in-house scrap generation rate for stainless steel in terms of the order quantities for ferritic and austenitic stainless steels as average values for the three-year period, and applied the results (ferritics 28%, austenitics 23%) for each year from 1990 onward. In addition, we considered the in-house scrap of
other alloy steel to be the in-house scrap of alloy steels, minus the stainless steel in-house scrap. Due to the significant difference in the Cr concentration of alloy steels among steel types, the in-house scrap was divided proportionally according to the proportion of orders for each other type of alloy steel.

The amount of generated industrial scrap was estimated based on the results of a survey of industrial scrap generation rates relative to the amount of steel consumption by end use. Industrial scrap generation rates for each of the ferritic and austenitic stainless steels were obtained from published data. As for other alloy steels, we applied the same industrial scrap generation rate as that for ferritic stainless steels for the following two reasons. First, because stainless steels does not differ for different end uses, except for kitchenware and tableware, and second, because only a very few types of alloy steel include Ni. As for carbon steel, data on the industrial scrap generation rates for carbon steel were obtained for 1988, 1993, and 2003. We did not take into account differences in the scrap generation rates for BOF and EAF. Also, we assumed a linear change in industrial scrap generation rates between 1989 and 1992, and between 1994 and 2002. For 1987 and before, and for 2004 and after, we used the values for 1988 and 2003, respectively.

2.5.3. Steel Inputs (Entering Use)

To obtain the quantity of steel used in finished products, we subtracted the amount of generated industrial scrap from the amount of steel consumption for each type of steel and each end use. By taking into account the quantity of imported and exported steel included in finished products (quantity of indirect imported/exported steel) for each end use, we estimated the quantity of domestic inputs in the form of finished products, as described below. Because of the difficulty of obtaining the quantity of indirect imported/exported steel for each steel type, these values were distributed from indirect imports and exports of steel in total. The proportion of imported and exported steel included in finished products (quantity of indirect imported/exported steel) for each end use is defined as the indirect import/export rate, and we applied this rate for each steel type. We could, however, obtain yearly data on indirect steel import and export quantities, and we used the indirect import/export rates derived from this data for the applicable years.

2.5.4. Product Lifetime and End-of-life Recovery Rate

The quantity of steel discarded from end-of-life products was estimated on the basis of the obtained time-series for domestic inputs using the PBM. The lifetime distribution adopted for this study is the same as that prepared by Daigo et al. for alloy steels, and the same as that prepared by Igarashi et al. and Daigo et al. for carbon steel. Table 3 shows the specified lifetime distributions. Note that in the table refers to the shape parameter, is the scale parameter, and is the position parameter.

The end-of-life recovery rate was obtained from the literature as the recovery rate for carbon steel, which did not distinguish between BOF and EAF. The same value was applied for alloy steels, as well (see Table 3). Here, we applied the recovery rate of machinery that was obtained from published data for the categories of industrial machinery, electrical machinery, consumer and office equipment, and other transportation.

2.5.5. Scrap Imports and Exports

Data on the quantities of stainless steel scrap imports and exports was obtained from Japanese trade statistics. Because this data was not classified by steel type, the scrap price was used in order to distinguish between and create a distribution of the quantities of ferritic and austenitic stainless steel scrap, as analyzed in an earlier study. We also referred to trade statistics to obtain the quantities of imports and exports of other alloy scrap. These quantities were also not classified by steel type, and were distributed proportionally. We classified import and export scrap by steel type using the total of the generated industrial scrap and the recovered obsolete scrap for each steel type. For carbon steel scrap, too, we used trade statistics to obtain import and export quantities. Just as we did for alloy steels, we divided the total of the generated industrial scrap and recovered obsolete scrap proportionally into BOF carbon steel scrap and EAF carbon steel scrap.

2.5.6. Future Demand for Steel

In order to estimate the future Cr concentration level of carbon steel through 2030, future steel demand was prepared as a scenario. To forecast future steel demand, Crompton conducted an estimate based on an analysis of consumption trends that began far in the past. However, as pointed out by Vuuren et al. as an IU (intensity-of-use) hypothesis, an analysis of consumption trends from the past is not capable of explaining future scenarios. The IU hypothesis is that material consumption increases with economic growth in an early stage, then shows a peak and an eventual decline in demand due to factors such as servicing, alternative materials, and technical developments. If the stock of steel is considered as an accumulation of consump-

| End-uses          | Mean lifetime [year] | Parameters of Weibull distribution functions | Collection rate [%] | Alloy type for which parameters used |
|-------------------|----------------------|---------------------------------------------|---------------------|-------------------------------------|
| Buildings         | 28.9                 | m=3.1, n=40.4, 8=7.5                         | 70                  | CS                                  |
| Infrastructure    | 34.5                 | m=3.1, n=48.4, 8=8.8                         | 30                  | CS                                  |
| Buildings and construction | 28.9 | m=3.1, n=40.4, 8=7.5 | 70 | AS                                  |
| Industrial machinery | 30.0 | m=2.7, n=33.7, 8=0   | 80                  | CS, AS                              |
| Electrical and electronic equipment | 12.1 | m=3.5, n=13.4, 8=0 | 80 | CS, AS                              |
| Household and commercial appliances | 20.5 | m=3.5, n=22.8, 8=0 | 80 | CS, AS                              |
| Passenger vehicles | 8.7–10.8 (Across the age) | Nonparametric | 85 | CS, AS                              |
| Trucks            | 8.5–14.1 (Across the age) | Nonparametric | 85 | CS, AS                              |
| Other transportation | 40.0 | m=2.7, n=45.0, 8=0 | 80 | CS, AS                              |
| Containers        | 30.0                 | m=2.9, n=34.4, 8=0                           | 85                  | CS, AS                              |
| Other products    | 15.0                 | m=2.7, n=10.9, 8=0                           | 80                  | CS, AS                              |
tion, there is the possibility of an S-shaped curve, which would indicate that the stock of steel sooner or later reaches saturation. Some examples of this pattern are the future demand forecast\cite{34} of Dargay et al., related to automobiles, and the future demand forecast by Toi et al., related to steel materials.\cite{35} In addition, comparisons by Dargay et al. in the case of automobiles, and similarly by Igarashi et al.\cite{36} in the case of steel, indicate that different forecasting techniques produce future demand forecasts that are substantially different. Thus, it is difficult to assemble reliable existing forecast data on future production and demand trends for individual kinds of finished products. For this reason, in this study we assumed that future steel production and the demand for specific end uses will remain fixed at the levels of 2006, the most recent year for which we have data. The simplicity of this hypothesis offers the advantage of making it possible to easily compare scenarios of increasing or decreasing future demand. In addition, because the stock of steel in Japan is trending toward saturation,\cite{37} as shown by Daigo et al., our hypothesis will not yield results that are substantially different from those that assume saturation in the stock of steel, as confirmed by Igarashi et al.\cite{36}

3. Results and Discussion

3.1. Material Balance for Alloy Steels and BOF Carbon Steel

The results of the estimate of the Cr content in ferrochrome based upon the material balance of Cr in the production of alloy steel and BOF carbon steel in 2003, 2004, and 2005, were 60, 60, and 53%, respectively. These values are within the range shown in the literature\cite{13,14} (i.e., a Cr content of 52–62%). Hence, we can conclude that an adequate number of the Cr raw materials were taken into account.

The results of estimates of the mix rate of alloy steel into the carbon steel cycle, as determined from the flow of scrap, are shown in Fig. 2. As can be seen in the figure, this rate increases steadily over the years, reaching approximately 80% in recent years. The denominator of this mix rate is the total alloy steel industrial scrap and obsolete scrap, after the exclusion of all austenitic stainless steel. It is relatively easy to differentiate between steel types in industrial scrap, which means that there is a low possibility that alloy scrap is mistakenly recovered as carbon steel scrap. That said, the mix rate results suggest that there is some level of mistaken recovery in the industrial scrap figures. Furthermore, between 2003 and 2005 the mix rate could be derived after differentiating between ferritic stainless steels and other alloy steels, and resulted in estimates of 40–50%. Accordingly, we found that the proportion of ferritic stainless steel collected separately from carbon steel scrap is relatively high compared to that of other alloy steels.

When we estimate the quantity of Cr in carbon steel scrap from the mix rate, the Cr contained in ferritic stainless steels accounts for approximately 40% of all the Cr in alloy steels mistakenly recovered as carbon steel scrap. We can attribute this to the fact that while the mix rate of ferritic stainless steel is relatively low, the quantity of production is high, and the Cr concentration is relatively high.

3.2. Estimating the Cr Concentration in EAF Carbon Steel

From the material balance of Cr in the production of EAF carbon steel, we estimated the Cr concentration in EAF carbon steels. Figure 3 shows the Cr material balance at the time of EAF carbon steel production in 2005. The Cr sources input as raw materials were ferritic stainless steel scrap (29%), other alloy steel scrap (41%), and EAF carbon steel scrap (28%). Here, ferritic stainless steel and other alloy steel scrap were mistakenly mixed and input as carbon steel scrap. This quantity of alloy scrap comprises approximately 10% of the carbon steel scrap in terms of weight of bulky scrap, but it accounts for a substantial proportion of the Cr input. In addition, the distribution of Cr to crude steel and slag in production was approximately 2:1.

We estimated the Cr concentration in EAF carbon steel for 1990 and successive years, based on the material balance of Cr at the time of EAF carbon steel production for each year. The time-series results were plotted with data derived from measurements of EAF steel composition, as shown in Fig. 4. The reason for the discontinuity between 2002 and 2003 is that we were able to obtain survey data on ferritic stainless steel scrap consumption beginning in 2003, after which we began estimating the mix rate of ferritic stainless steel scrap into carbon steel cycle separately from other alloy steel scrap. Although our estimates were slightly lower than the measurements for the early 1990s, our results were otherwise generally consistent with measurement data.

The future change in the Cr concentration of EAF carbon steel was estimated. We estimated the Cr content in discarded steel for different steel types through 2030, as
shown in Fig. 5. As described in Sec. 2.5.6, we assumed that future steel production would be fixed at the 2006 level. Even if production is fixed from this point forward, we can expect the quantity of discarded steel to continue to increase for some time due to the increase in production over recent years. In terms of steel type, the highest quantity of Cr is found in austenitic stainless steels due to the fact that they are produced in large quantity and have a high Cr content. From 2006 to 2030, the amount of discarded ferritic stainless steel is estimated to approximately double. This represents the highest rate of increase. From these results, the Cr concentration in EAF carbon steel in 2030 is estimated to increase to 0.24% (see Fig. 4), presuming that the system of collection continues in its current state. The trend toward increasing Cr concentration is due to an increase in the amount of scrap mistakenly mixed in with carbon steel scrap, which is in turn due to the increase in the amount of scrap generated from discarded steel. These results are based on the assumption that production will continue at the current level, even though the results depend on how production varies in the years ahead. Furthermore, it is assumed that the distribution ratio of Cr to crude steel and slag will continue to reflect the data in past surveys, even as Cr concentration can be controlled through the operating conditions in practice. This means that actual operations may not conform to our estimates of the future. Our estimates are based on current preconditions, and the estimation results show a tendency to an increasing quantity of dissipative flow of Cr to EAF carbon steel as an impurity, presuming that the recyclability of alloy steels is not improved.

### 3.3. Flow and Stock of Cr Contained in Japanese Steel

From the time-series results on the material balance of EAF carbon steel production that were obtained using dynamic analysis, we estimated the material stock of Cr in steel and the cumulative dissipation to slag. The result is shown in Fig. 6. The material stock appears to continue to increase and shows no sign of approaching saturation. Also, in 2006 the material stock of Cr in steel amounted to 4.7 million t, which corresponds to approximately 37 kg per capita. Compared to the amount of consumption, the current material stock of Cr is equivalent to about eight years of annual consumption of this natural resource. As for the material stock by steel type, the highest proportion (58%) of the stock is found in austenitic stainless steel, due to the large amount of production and high Cr concentration, followed by ferritic stainless steel (16%), and EAF carbon steel (15%). These results show that the amount of Cr contained in EAF carbon steel, which does not serve any particular function as an alloying element, is more or less equal to the amount of Cr contained in ferritic stainless steels. In addition, the total cumulative dissipation of Cr to slag between 1970 and 2007 is estimated at approximately 620 kt. The amount of the current cumulative dissipation of Cr is similar to the current stock of Cr in ferritic stainless steels or in EAF carbon steels.

Based on the results of material balances and the dynamic analysis carried out thus far, we created a material flow diagram for the Cr included in steel materials in 2005. The results are shown in Figs. 7(a), 7(b), and 7(c). The estimated flow includes not only the Cr present in alloy steels, but also the Cr present in carbon steels. In the present study we took into account the loss of Cr in the form of “uncollected” material and the quantity of Cr dissipated as slag. The results for 2005 show a 19 kt loss of Cr in the form of uncollected materials (alloy steel: 12 kt; BOF carbon steel: 1 kt; EAF carbon steel: 6 kt), and a 32 kt dissipation of Cr as slag (alloy steel: 10 kt; BOF carbon steel: 3 kt; EAF carbon steel: 19 kt). The Cr dissipated in EAF carbon steel slag amounts to more than half of all the Cr dissipated as slag. As for Cr dissipation in the alloy steel cycle, alloy steels mistakenly recovered as carbon steel scrap account for two-thirds of all dissipation from the cycle. The Cr in EAF carbon steel is considered an impurity from the perspective of effective Cr utilization. It is therefore desirable for the alloy steels discarded from end-of-life products to
be collected as alloy steel scrap, without being mixed with carbon steel scrap.

4. Conclusion

In this study we have analyzed the material flow of Cr in Japan, taking into account not only alloy steels but also carbon steels. Our analysis tracks the complete material life cycle of Cr, from its beginning flow out from the alloy steel cycle to its ultimate dissipation in the form of slag. In practice, after Cr flows out from the alloy steel cycle to the EAF carbon steel cycle, we estimated the material stock of Cr in the form of EAF carbon steel, and estimated the quantity of Cr discarded as EAF carbon steel slag or uncollected mate-

![Image of material flow diagrams]

**Fig. 7.** Substance flow of Cr in 2005 associated with (a) alloy steel, (b) BOF carbon steel, and (c) EAF carbon steel. The units are kt of Cr per year (kt-Cr/yr).
rials. In addition, we determined that approximately 70% of the industrial scrap and obsolete scrap of magnetic alloy steels that is actually recovered has been mistakenly mixed in with carbon steel. We estimate that approximately 40% of ferritic stainless steel scrap is mistakenly mixed in with carbon steel. We estimate that approximately 40% of ferritic stainless steel scrap is mistakenly mixed in with carbon steel, as well. Furthermore, assuming the continuation of the current state of production and recovery, we expect that the quantity of Cr flowing into the EAF carbon steel cycle will continue to increase. From these results, we conclude that in order to improve the material circulation of Cr, it is desirable to construct a recovery system that has the capacity to perform the precision recovery magnetic alloy steels as alloy steels.

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