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Material Flow Analysis of Aluminum Dross and Environmental Assessment for Its Recycling Process

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Approximately 400,000 tons per year of aluminum dross are generated during a melting process of aluminum metal in Japan. The Al dross and the residue, which have high concentration of metallic Al, are mostly used as an Al resource for Al production or as a deoxidizer in the steel industry. On the other hand, the lower grade residue with the Al content less than 20%, is difficult to be recycled and is therefore landfilled.

This paper deals with (1) a material flow analysis (MFA) of the domestic aluminum dross in order to achieve clear targets for recycling of aluminum dross and residue, and (2) an environmental assessment of newly developed technologies for its recycling, such as the process of hydrogen production from residue.

The result of material flow analysis on the domestic aluminum dross in 2003 shows that 234.4×10^3 t of aluminum is recovered and 215.0×10^3 t of residue is generated from the dross. The residue is mostly used in the steelmaking process, whereas 50.0×10^3 t of residue is landfilled in the final disposal site. As the result of the environmental assessment through the material flow, there is a possibility of reduction of CO_2 emission and waste emissions by using residue (Al content: 10%) as a hydrogen resource, which is presently landfilled.
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1. Introduction

The Japanese aluminum (Al) industry consists of various producers such as the manufacture of rollers, extruders, etc. Most of the primary Al ingots that are required for manufacturing various kinds of end products are imported. Further, Japan has large scale of secondary Al industry. In recent years, the production of secondary Al ingots and Al products (Al rolled, cast, and die-cast products, etc.) is increasing. In the production of Al, dross is generated during remelting. In order to establish a sound Al cycle in the Al industry, it is essential to establish the recycling and waste management of Al dross without increasing the burden on the environment.

Figure 1 shows the production amounts of secondary Al ingots and aluminum products. The Ministry of Economy, Trade and Industry (METI) of Japan reports the production amounts of Al ingots,[1)] and the Japan Aluminum Association reports the supply and demand balance of Al products.[2)] In 2003, 1257.7×10^3 t of secondary Al alloy ingots (including secondary Al ingots) was produced, and 2383.9×10^3 t of Al-rolled products, 393.1×10^3 t of Al-cast products, and 869.8×10^3 t of Al die-cast products were made from Al ingots. It appears that approximately 400×10^3 t per year of Al dross is generated in Japan, as a by-product in the melting process.

The Al dross and the residue, which have high concentration of metallic Al, are mostly used as an Al resource for Al production or as a deoxidizer in the steel industry. On the other hand, the residue with the Al content less than 20%, is difficult to be recycled and is therefore landfilled. The residue, which is also called as non-metallic product, contains aluminum, aluminum nitride, aluminum carbide, and aluminum sulfide, and generates harmful gases by exothermic chemical reactions with water. Therefore, the treatment of residue requires careful management of generated gas such as NH_3, H_2, CH_4, and H_2S, and the average cost of treatment is 23,000 [JPY/ton].[3)] Environmental emissions from the waste treatment of such aluminum residue result in serious problems with regard to resource management and environmental policy. Therefore, it is essential to reduce the environmental load and generation of waste in the dross treatment process. In spite of such importance, the material flow of aluminum dross is still uncertain.

This paper deals with (1) a material flow analysis (MFA) of the domestic aluminum dross in order to achieve clear targets for recycling of aluminum dross and (2) an environmental assessment of newly developed technologies for its recycling, such as the process of hydrogen production from Al residue.

2. Material Flow Analysis

2.1 Method

It is important to clarify the material flows of primary and secondary resources for establishing a sound material cycle system. A material flow chart of domestic Al dross in 1994 was reported[3–5)] by the Japan Light Metal Association (currently the Japan Aluminum Association). However, it has not reflected the actual condition of the dross treatment, because the production amounts of Al ingot and Al products has been increasing as shown in Fig. 1.

Material flow analysis (MFA) and substance flow analysis (SFA) are systematic methodologies to assess the flows and stock of materials within a system with a defined area and period. From national statistics, we can get supply and demand information of materials, but we cannot trace the flow of materials. In order to supplement for the national statistics, the MFA of metals has been conducted by the Japan Oil, Gas and Metals National Corporation (JOGMEC) and various academic institutes including the universities in Japan.[6,7)] In the rest of the world, the Yale Center for Industrial Ecology in USA have demonstrated a newly developing MFA method,[8,9)] the Wuppertal Institute in Germany reported that resource flows constitute the materials

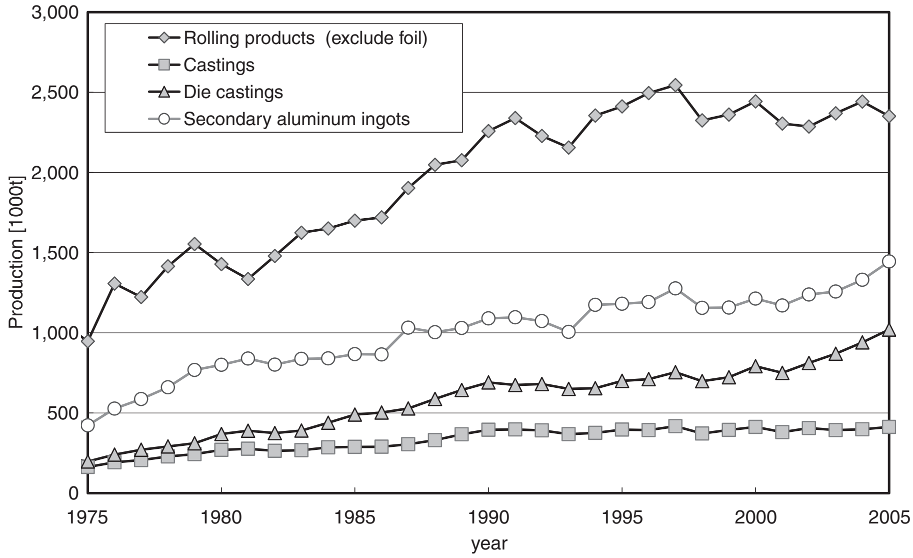

Fig. 1 Production amounts of aluminum ingots and aluminum products.

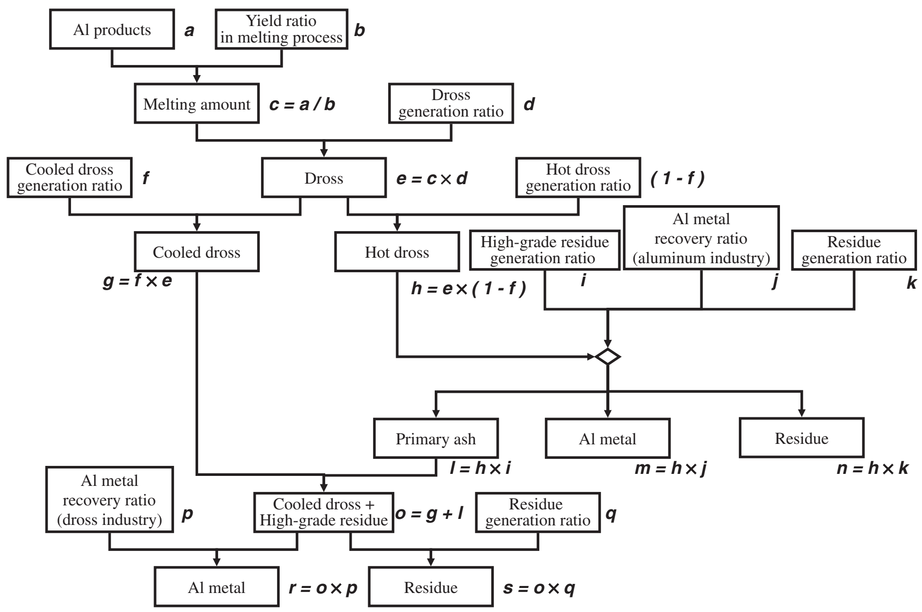

Fig. 2 Estimation chart for aluminum dross flow chart.

basis of the economy,[10] and Brunner and Rechberger have reviewed the history, methodologies, and future of MFA.[11] In this paper, MFA approach is applied for aluminum dross flow in Japan in order to trace the material flow of Al dross in 2003 quantitatively and thus to achieve clear targets for its recycling.

In order to trace the material flow of Al dross in 2003, we have applied the MFA approach to domestic Al dross.

2.2 Data

Al dross generally consists of aluminum, aluminum oxide, aluminum nitride, oxides of other alloy additives, haloids added in the dross treatment processes, etc. The dross discharged from the melting furnaces is usually called as "hot dross" which it contains 75–85% metallic Al. A certain amount of Al is recovered from the hot dross using the metal reclamation machine or mechanical compression machine. In Al industries, the "high-grade residue" generated from the recovery process still has high Al content and is used as an Al resource for the Al dross treatment industry. The residue generated in the recovery process is recycled or transported to a controlled landfill site.

The material flow chart of Al dross in 2003 was developed in the present work based on the method of the Japan Light Metal Association. Figure 2 shows the estimated flow of Al dross in Japan, and Table 1 provides the remarks on the estimation.

In order to develop the flow chart, we have referred to the following items; (a) the production amounts of Al from the statistics of METI[1] and those of the Japan Aluminum Association,[2] (b) the yield ratio in a melting furnace, (d) the dross generation ratio in a melting furnace, (f) the cooled dross generation ratio in a melting furnace, (i) the high-grade residue generation ratio in the recovery process in the Al

Table 1 Remarks for estimation of aluminum dross flow chart.

		Remarks
(a)	Production amounts of aluminum products	Ref 1), 2)
(b)	Yield ratio in melting furnace	Ref 3) pp. 107
(c)	Melting amount in aluminum melting furnace	estimated from (a) and (b)
(d)	Dross generation ratio in melting furnace	Ref 3) pp. 132
(e)	Amount of total dross	estimated from (c) and (d)
(f)	Cooled dross generation ratio in melting furnace	Ref 3) pp. 11
(g)	Amount of cooled dross	estimated from (e) and (f)
(h)	Amount of hot dross	estimated from (e) and (f)
(i)	High-grade residue generation ratio in recovery process in aluminum industry	Ref 3) pp. 11
(j)	Al metal recovery ratio in recovery process in aluminum industry	Ref 3) pp. 11
(k)	Residue generation ratio of recovery process in aluminum industry	Ref 3) pp. 7
(l)	Amount of high-grade residue	estimated from (h) and (i)
(m)	Amount of Al metal recovered in aluminum industry	estimated from (h) and (j)
(n)	Amount of residue generated in recovery process in aluminum industry	estimated from (h) and (k)
(o)		estimated from (g) and (l)
(p)	Al metal recovery ratio in recovery process in dross industry	Ref 3) pp. 18
(q)	Residue generation ratio of recovery process in dross industry	Ref 3) pp. 11
(r)	Amount of Al metal recovered in dross industry	estimated from (o) and (p)
(s)	Amount of residue generated in recovery process in dross industry	estimated from (o) and (q)

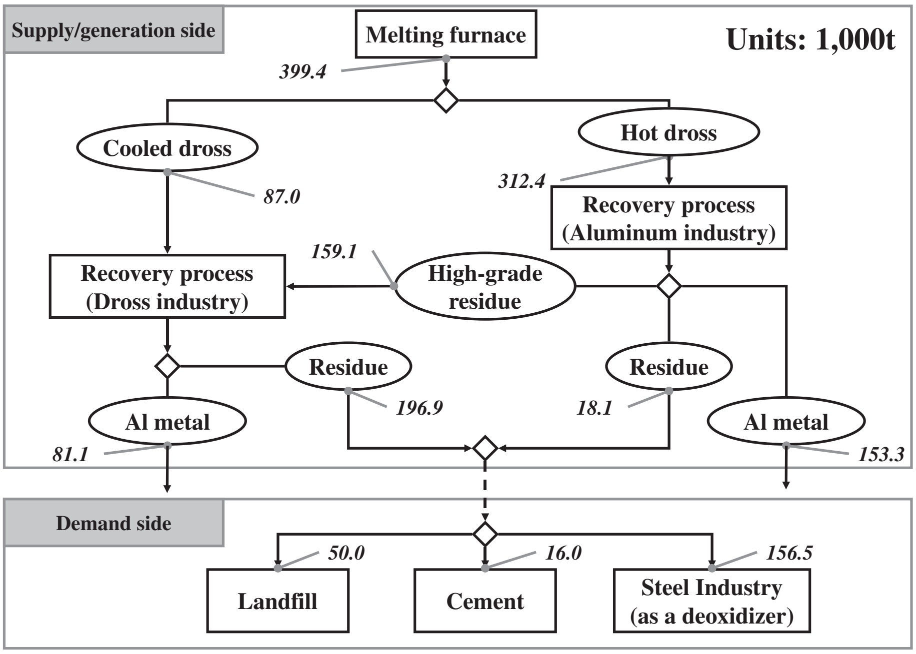

Fig. 3 Estimated material flow chart of aluminum dross (2003).

industry, (j) the Al metal recovery ratio in recovery process in Al industry, (k) the residue generation ratio of recovery process in Al industry, (p) the Al metal recovery ratio in recovery process in dross industry, and (q) the residue generation ratio in the dross industry from the data of the Japan Aluminum Association.[3)] The data on the residue demand in the cement industry and the amount of landfilled ash were derived from the literature reported by Namba and Ohnishi,[12)] while the data on the residue demand in the steel industry have been derived from the report of the Japan Aluminum Association.[13)]

2.3 Result of MFA

Figure 3 shows the estimated material flow of Al dross in Japan. In 2003, 234.4×10^3 t of Al is recovered and 215.0×10^3 t of residue was generated from dross. The residue was mostly used in the steelmaking process, whereas 50.0×10^3 t of that was landfilled in the final disposal site.

As shown in Fig. 3, the material balance in the "recovery process" is not satisfied because of the increased mass resulting from the formation of aluminum oxide and nitride during the melting process and the flux input in the extraction process.

3. Environmental Assessment

3.1 Method

Life cycle assessment (LCA) is applied to evaluate the

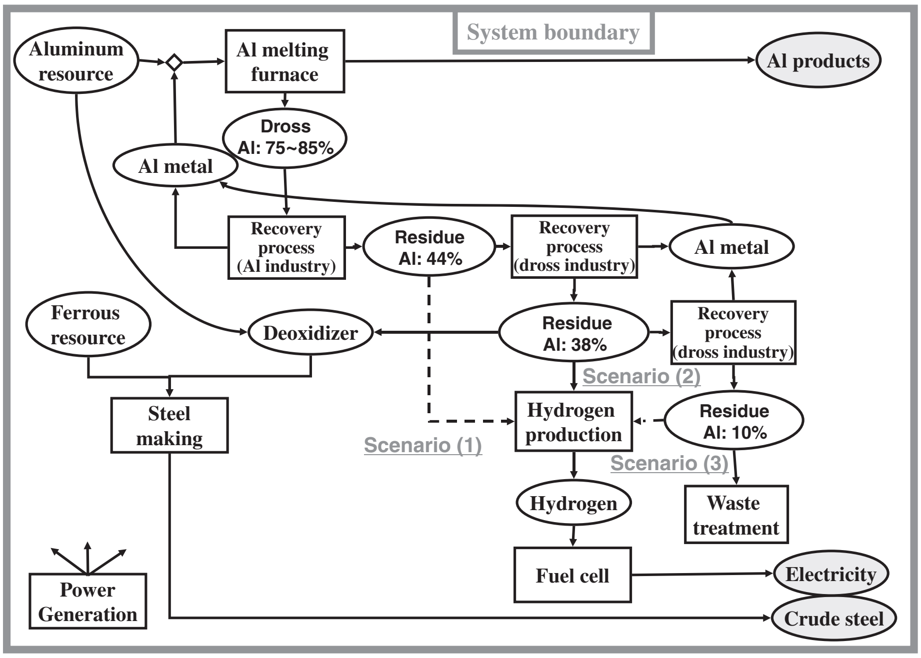

Fig. 4 Simplified illustration of target system.

environmental burden associated with a "product system." Currently, it is expected that LCA can be used to assess not only a "product system" but also a "social system" such as a recycling system, energy system, etc. During the 7th international conference on ecobalance (ICEB7) held in 2006, "systems thinking" for designing our future society was discussed based on the idea of "life cycle thinking".

In this paper, the "multi-function units system LCA" method[14] developed by the authors is applied in order to evaluate the environmental effects (CO_2 emissions and waste generation) of the dross recycling system. The "multi-function units system LCA" is a method to evaluate open-loop recycling systems or systems for producing several kinds of products and is based on the matrix LCA method proposed by the authors.[15]

3.2 Predictions and Data

A hydrogen production technology based on the hydroxylation of Al is being developed in the project "Establishment Green-Hydrogen Based Society in Honjo-Waseda Area".[16] According to this project, the present paper deals with the environmental assessment of an Al dross recycling technology such as the process of hydrogen production from Al dross.

For this purpose, one baseline scenario and three hydrogen production scenarios are considered as follows.

(s0) Conventional system (base line)

(s1) Utilization of high-grade residue (Al content: 44%) as a hydrogen resource, which is presently used as Al resource for Al recovery

(s2) Utilization of residue (Al content: 38%) as a hydrogen resource, which is presently used as deoxidizer for steel making

(s3) Utilization of residue (Al content: 10%) as a hydrogen resource, which is presently landfilled.

In each scenario, 3646.8×10^3 t of Al products, 1105×10^6 t of crude steel, and 1 GWh of electric power are set as the functional units of the system.

Figure 4 shows a simplified illustration of the evaluated system and the system boundary for evaluation. The system mainly consists of sectors for (i) Al products production, (ii) Al dross recovery, (iii) steel making, (iv) hydrogen production and fuel cell-based power generation, (v) power generation, and (vi) waste treatment.

The inventory data for evaluation have been derived from the following references; (i) the data of the Japan Aluminum Assosiation[17] and the report of Japan Environmental Management Association for Industry (JEMAI),[18] (iii) statistics by METI,[19] (v) the data of the Federation of Electric Power Companies of Japan[20] and (vi) the report of New energy and industrial technology development organization (NEDO).[21] On the other hand, the inventory data obtained from references (ii) and (iv) were estimated based on our own investigation. Aluminum hydroxide ($Al(OH)_3$) and ammonia (NH_3) are generated as by-products in the hydrogen production sectors. The values of these products are assumed as equivalent to those of the existing products, and "expansion of system as material"[22] is used for allocation in order to deduct an environmental load for production of these products. The inventory data of $Al(OH)_3$ and NH_3 production have been derived from JEMAI's report[23] and NEDO's report,[24] respectively.

In scenario 1 and scenario 2, because of the utilization of the high-grade residue and residue, other Al resources are needed in order to produce 3646.8×10^3 t of Al products. Therefore, the following assumptions were made. In scenario 1, the Al element for the production of Al products was replaced by primary Al and the Al element for the deoxidizer was replaced by primary Al in scenario 2.

3.3 Result of LCA

Figure 5 shows the environmental effect of the dross

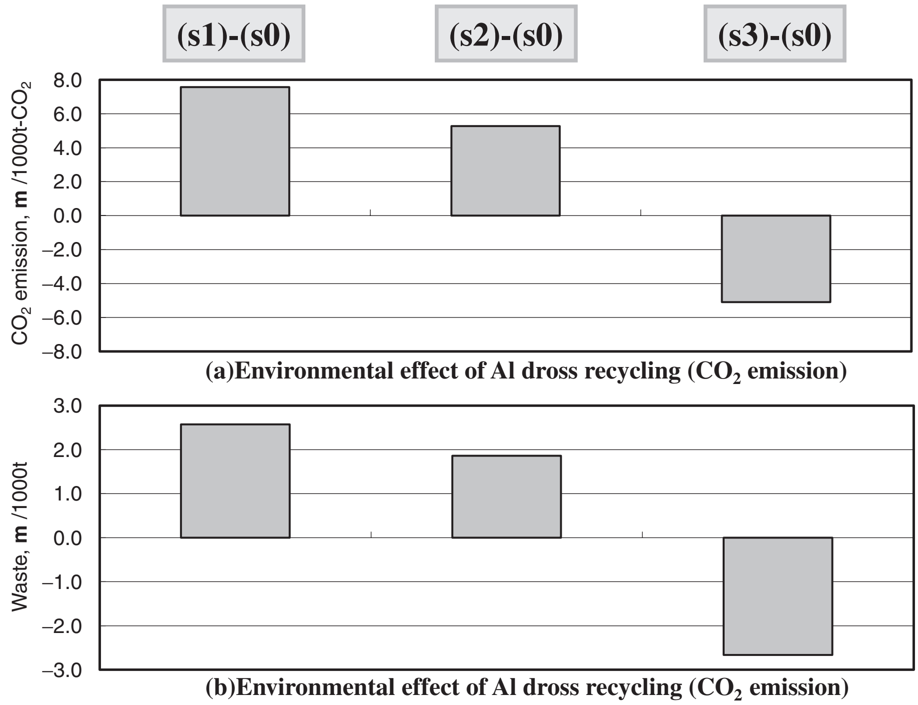

Fig. 5 Environmental effect of Al dross recycling system.

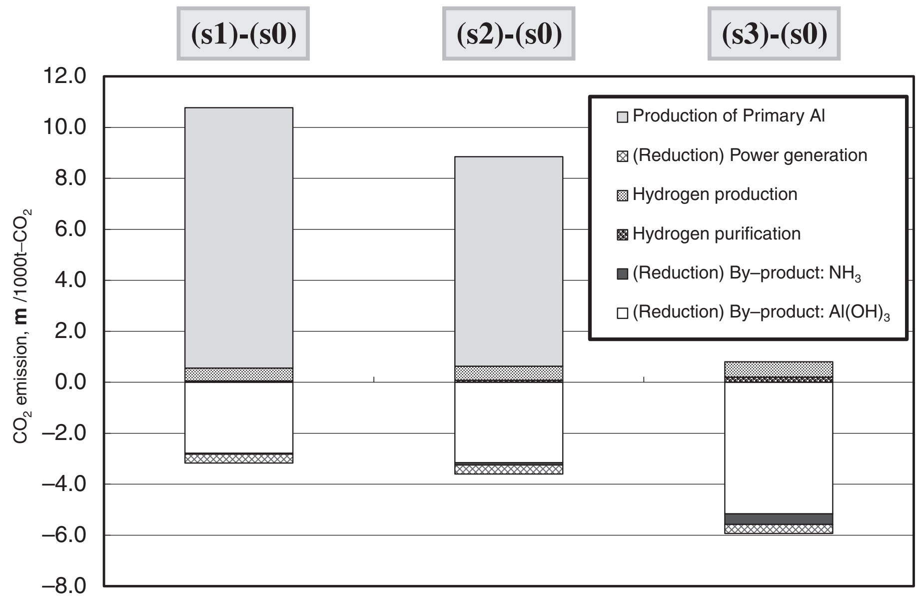

Fig. 6 Environmental effect of Al dross recycling system (CO_2 emission).

recycling system with hydrogen production. The result shows that the utilization of residue (Al content: 10%) as a hydrogen resource (scenario 3) is effective for the reduction of CO_2 emissions and waste as compared to the baseline scenario (scenario 0). The analysis shows that the environmental effect in terms of CO_2 emissions and waste reduction is -5.1×10^3 t-CO_2 and -2.7×10^3 t in scenario 3, respectively, where the negative value implies an effective result in comparison with scenario 0. On the other hand, the CO_2 emissions and waste reduction in scenario 1 and scenario 2 are high as compared to those in scenario 0.

Figures 6 and 7 show the classification of environmental effects according to the sources of CO_2 emission and those of waste reduction. As shown in Fig. 6, CO_2 emissions from the aluminum production process constitute the largest part of the emissions in scenario 1 (94.8%) and scenario 2 (92.9%). As shown in Fig. 7, reduction in landfill constitutes the largest part of waste reduction in scenario 3 (95.3%).

4. Conclusions

This paper deals with (1) material flow analysis of the domestic Al dross and (2) the environmental assessment of the emerging technology developed for Al dross treatment

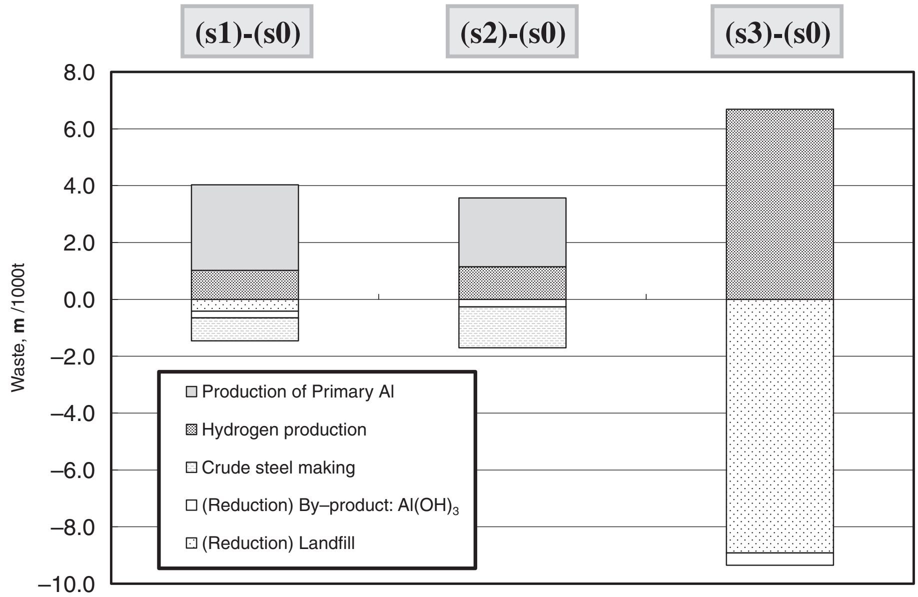

Fig. 7 Environmental effect of Al dross recycling system (Waste).

such as the hydrogen production process that employs Al dross. In this study, we have arrived at the following main conclusions.

(1) In 2003, According to the estimation, in 2003, 234.4×10^3 t of Al was recovered and 215.0×10^3 t of residue was generated from the dross. The residue was mostly used in the steelmaking process, whereas 50.0×10^3 t of residual ash was landfilled in the final disposal site.

(2) The utilization of residue (Al content: 10%) as a hydrogen resource can possibly reduce CO_2 emissions (-5.1×10^3 t-CO_2) and waste (-2.7×10^3 t) as compared to the base existing system.

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