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A State of the Art and Development in Materials Process Design and Technology for Sustainable Society

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It has been required to reduce waste and by-products, to save resources and energy, and to recycle materials such as steels, aluminum alloys, polymers and so on. A feasibility study, *Feasibility Study on Materials Design with Low Environmental Load for Resources Circulating Society*, had been carried out from Y2000 to Y2002. The present paper summarizes findings on the interview and discussion in the study. The ever larger spread of customer requirements, the trend towards smaller batches and the increasing scrap yield in the densely populated areas are all factors that increase the pressure towards the development of smaller and more profitable production units with short production chains. In addition to this, it is more cost-effective to reuse scrap there instead of transporting it to far areas. This concept should be started from zero-emission in the factory. Novel technologies building high performance and/or service in the reclaimed materials and products are also important. Thus advanced manufacturing technology for sustainable materials is necessary to develop and realize economically, ecologically and socially justifiable system.
Key words: Social technology, Materials processing, Recyclable design, Benign manufacturing

1. INTRODUCTION

It has been generally said to change from *mass-production, mass-consumption and mass-disposal society* to *more sustainable production and consumption (green) society* in the 21st century. Visible problems such as increasing volume of solid wastes have already arisen because of ground pollution and shortage of disposal site. Hidden problems behind high dependency on imported natural resources and/or raw materials also remain. Now our society demands a production system that protects the environment and makes the best possible use of resources. Then it has been required to reduce waste and by-products, to save resources and energy, and to recycle materials such as steels, aluminum alloys and polymers. At the same period, the concept of *Ecomaterials* was proposed in Japan, and research and development activities in the field of *Ecomaterial* have been spreading widely.[1] Both materials design and process design have been changing to environmental green. These trends commonly aim to minimize total environmental load. In addition, the materials are imbalance between production and waste or recycle due to the conditions of economy, technology and resource. Then the material flow in each step such as resource, material, product, use, disposal, recovery and recycle covers not only local but also international.

As a result, secondary materials accepted for recycling should be considered followings: materials separation, immunize impurities, materials design, and other considerations in society. In order to look into the current status of research and development on materials process design and technology for sustainable society in the world, therefore, a feasibility study has been carried out in the typical industrialized regions.[2] The present paper summarizes findings on the interview and discussion in the study.

2. PROCEDURE

The *ECOMATERIAL Forum* in the Society of Non-Traditional Technology had carried out a feasibility study, *Feasibility Study on Materials Design with Low Environmental Load for Resources Circulating Society*, from Y2000 to Y2002.[2] The committee in the forum consisted of researchers from universities and national institutes in the materials and resources engineering. Findings in the discussions at visits and workshops were summarized, and proposals were made.

In this study, three economic zones such as North America, Europe (EU) and East Asia were established (Table 1). The East Asia zone made

Table 1 Estimated condition of the area studied.

Economic zone		Resources	Urban mine	Disposal site	Scrap market	Developing area
East Asia	Japan	None	Building	Shortage / sea	Asia/Russia	China
	China	Little	None	Sufficient / land, sea	Inland	
North America		Rather	Formative	Sufficient / land	Canada/ Central America	None
EU		Little	Formative	Sufficient / land	East Europe	East Europe

Japan and China to be a core. The industrialized countries have a lot of common problems on the materials recycling, although their details appear different aspects. Most of companies have put in serious efforts to tackle recyclable material selection, product design and waste treatment technology towards total management of manufacturing and recycling without asking the economic zone, even if there is a difference between each character and purpose. The committee put the guideline of industry accommodated to sustainable society which was to integrate green manufacturing through the chain of materials, parts and products, and recycling in scrap collection, disassemble/sorting and recovery steps. From the viewpoint, the activity and R&D on both recycling and manufacturing were interviewed and analyzed in North America, EU and Japan as shown in Table 2.

3. SUBJECTS OF LIFE-CYCLE ENGINEERING

Engineering subjects for the ideal recycling of materials are to reduce impurity content from scrap, to immunize materials against impurities or make materials innocuous from impurities, and finally to replace materials with inherently recyclable materials. Firstly, however, it is necessary to minimize total environmental load. Thus concepts such as reject, reduce and reuse have priority. Moreover product design for high performance, process design for low environmental load and life-cycle design for longevity must be also considered.

3.1 Practical research and development of disposal in recycling industry

Secondary materials accepted for recycling should be considered. The technology development in recycling industry was focused on three issues such as 1) easy scrap sorting, 2) refine of secondary materials and 3) research and development of polymer recycle.

Shredder operation and shredder-less operation: Advantage and disadvantage of both manual separation and fine shredding were discussed in the disassembly, recovery and waste treatment stages. In the bulk sorting, manual operation has a big advantage for not only removal of hazardous and reusable-parts separation but also reproduction of ferrous/non-ferrous metals with higher quality and plastics collection, although its excessive personnel costs are problem. Advanced shredder operation in which both manual sorting and fine shredding are installed provides a good disassembly shredding. Furthermore, the combination with a recycling system of shredding residues like ASR (automotive shredder residues) can extremely reduce dust (about 5% weight of scrap). In the advanced shredder operation, however, sorting of grade in a material is impossible, and it is difficult to remove trump element in a metal, i.e. contamination of copper in steel, iron in aluminum alloys and so on. Then it is unavoidable that secondary materials are reclaimed as a cascade-recycle only.

Shredder-less operation in automotive recycle is a fully manual operation and supplies a high quality steel scrap to BOF (basic oxygen furnace) steelmaking process. Even that it is anxious for lowered quality of secondary alloys due to difficult separation with coated materials and mixed or composite materials in the higher functional products, when amount of scrap increases.

Therefore, the developments of product design for easy disassembly and of easier recyclable material design such as *simpler-alloy design* concept are needed, even if they remove a flexibility of product design. Neither shredder nor shredder-less operation fully renews second alloy itself.

Growing market of reuse-parts: From the viewpoint of low environmental load, reduce and reuse is priority idea rather than recycle. High-class used cars in West Europe have been exported to East Europe as either product or parts. In Japan, the number of used-cars exports to China, Russia and South-east Asia has remarkably increased. Such trading earns profit in recycling business. Developments of disassemble and reproduction technology may contribute for growing market of reuse-parts in East Asia and recycling industries in Japan.

Innovation of distribution system: It was confirmed that following considerations in society are very important for recycler:

Table 2 List of interviews and categories (marked D: direct point of interview, and I: indirect point of interview).

Formation of industry		*Example* Company / institute	Country	*Process* materials	parts	products	collection	disassembly	recycle	*Section*	*Objectives*
Development of waste treatment technology	Recycling	Frunhofer Institute for Chemical Technology	Germany					I	I	3.2	Advanced materials sorting and recycling technology development
		Argonne National Laboratory	USA				I	I	D	3.2	Automotive materials recovery technology development
		West Japan Auto Recycle	Japan				I	D		3.1	Car disassembly with shredder-less operation
		ECRIS/VOLVO	Sweden				I	D	I	3.1	Car disassembly
		Higashi-hama Recycle Center/RICOH	Japan				I	D		3.1	Advanced disassembly of electric products
		Toyota Metals	Japan				I	I	D	3.1	Car disassembly with advanced shredder operation and reduction of dust
		Arra terra Verbundstoff	Germany				I	I	I	3.1	Disassembly of electric products
		DSD System Technology	Germany				I	D	I	3.1	Total management of containers and packing recycle
		Rethmann Entsorgungs	Germany	I			I	D	D	3.1	Containers and packing recycle
Integration with component design	Manufacturing	AUDI Aluminum Center	Germany		D	I				3.3	Material selection and product design for aluminum automotive body
		RYOBI	Japan	I	D					3.2	Aluminum die-casting
		Miyamoto Industry	Japan		I					3.3	Advanced aluminum forging
		Mitsubishi Heavy Industry, Nakasaki	Japan	I	I	I				3.3	Long-life design
Benign manufacturing and material design	Manufacturing	Nakayama Steel	Japan	I	I					3.2	Energy-saving and value-added secondary material
		CORUS	Netherland	I	I					3.2	Energy-saving and value-added secondary material
		Thyssen-Krupp Stahl	Germany	I	I					3.2	Energy-saving and value-added secondary material
		CSM Terni/AST	Italy	I	I					3.2	Energy-saving and value-added secondary material
		IRSID-USINOR	France	I	I					3.2	Energy-saving and value-added secondary material
		Mitsubishi Heavy Industry, Hiroshima	Japan		I					3.2	Energy-saving and value-added process design
Advanced utilization of scrap	Manufacturing	Aichi Steel	Japan	I	D					3.2	Energy-saving and value-added secondary products
		Tokyo Steel	Japan	I	I					3.2	Energy-saving and scrap-based steelmaking
		TRICO (now NUCOR)	USA	I	I					3.2	Energy-saving and scrap-based steelmaking
		SDI	USA	I	I				I	3.2	Energy-saving and value-added secondary material
Total management of manufacturing and product design	Manufacturing	Toyo Seikan	Japan	I		D				3.3	Zero emission in factory
	Manufacturing /Recycling	YKK	Japan	I	I	I	I	I	D	3.3	Zero emission in factory
		TOAGOSEI	Japan	I			I		D	3.3	Local loop in recycling
		ALCOA Technical Center	USA	D	I		I	I	I	3.3	Total management of alloy design and recycling
		ALCOA Wheel Product	Japan			D	I			3.3	Local loop in recycling
	Recycling	INMETCO	USA	I			I	I	D	3.2	Recovery of Ni and noble metals
		DAIKI Aluminum	Japan	I			I	I	D	3.2	Recovery of aluminum scrap
		AIES	Japan	I	I				D	3.2	Bottle-to-bottle recycle of PET

- Economic:
  - scrap has good value
- Health, safety and regulatory issues
- Recycling must be easy for the customer:
  - Acceptable costs for both recycling and transportation
  - Education by recycler

Hereafter innovation of distribution system will be much more important.

Polymer scrap: The most important subject for mixed polymer scrap is the development of recycling technology for residues. Agreements on the problems of waste plastics recycling in which various ideas exist were summarized as follows;

- Designate substances for chemical recycle and expand them: polyethylene (PE) and polypropylene (PP)
- Recyclable material design
- Developments of simplifying materials types, materials separating and oil recovery
- Compromise and diverse design between product and material performance to enable cascade-recycle
- Neither exception nor restriction for thermal recycle
- Material recycle and no thermal recycle for polyvinyl chloride (PVC): easy sorting and limited use
- Material recycles of polyethlen-terephthalate (PET)
- Regulatory issues for collection system of scrap: high transporting costs due to lightweight and big volume of body
- Consider replace plastics by other materials
- Study the nature of plastics and make the most of advantage

3.2 Advanced process technology for sustainable materials [3]

Steel industry gives the highest impact on building sustainable society, since it consumes the great deal of energy and the produces the large amount of materials. The environmental technology employed in steelmaking has attained a high standard around the world. However, the regulations concerning protection of the air, water and land lead to substantial increases in costs with the production of steel from ore and coal. There is no doubt that productivity of a modern *integrated* steelworks fully contributes to reduction of costs, but only on the assumption that it is possible to supply customers who order sufficiently large amounts. The ever larger spread of customer requirements, the trend towards smaller batches and the increasing scrap yield in the densely populated areas are all factors that increase the pressure towards the development of more profitable production units with short production chains.

Advanced utilization of scrap: Electric arc furnace (EAF) steekmaking has an advantage of low environmental load, since it produces steels and their parts from steel scrap. The thin slab casting (TSC)-EAF has produced flat-rolled steels in *mini-mill* steelworks, especially in USA, where energy cost is very low (Fig. 1). In addition to this, scrap arises in densely populated areas of the industrially advanced nations and it is more cost-effective to reuse it there instead of transporting it to far areas. Today, the *mini-mill* steelwork in USA joins automotive manufacturer to develop high quality materials. This may enable advanced utilization of scrap and process technology with low cost, low environmental load, excellent flexibility and value-added production.

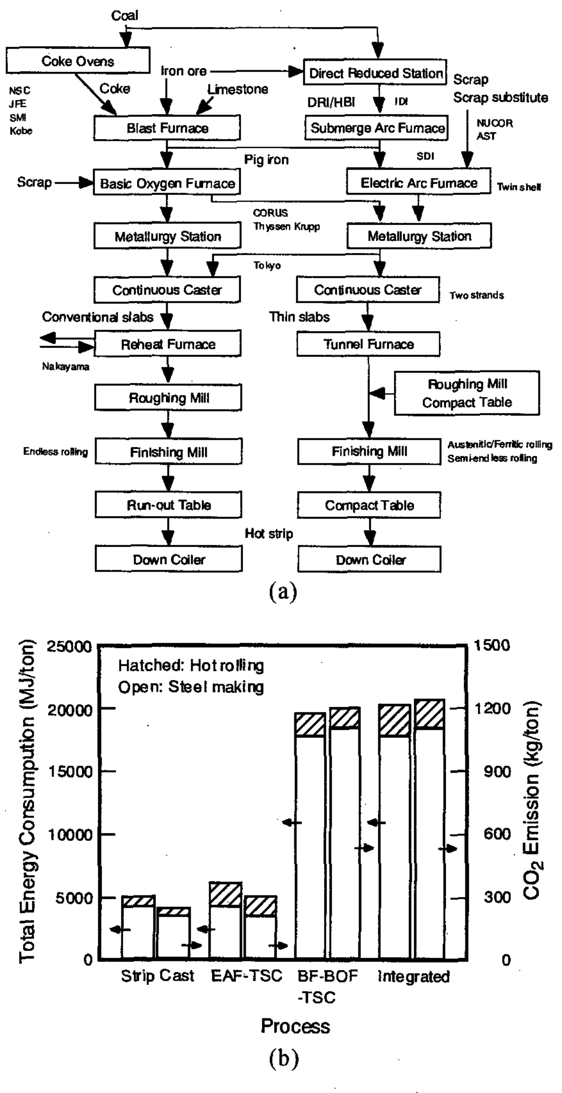

Fig. 1 Steelmaking processes for low carbon flat products (a) and their predicted environmental load (b).

Benign manufacturing and materials design: Although the environmental technology employed in a modern *integrated* steelmaking has attained a high standard around world, the environmental load of *integrated* steelworks is substantially large because of a large consumption of energy, ore and coal (Fig. 1). On the other hand, the products by EAF steelmaking can hardly satisfy all kinds of requirements in customer and society.

In Europe the different variants of near net shape casting, i.e. strip casting and TSC, have been installed to produce flat-rolled steels in *mini-mill* steelworks, where liquid steel produced by blast furnace (BF)-BOF steelmaking is applied (Fig. 1). The advanced *mini-mill* process for low carbon flat products has been replaced in a part of old *integrated* steelworks, since it has an advantage of smaller and more profitable production units with various materials design. No TSC + *mini-mill* works has been installed in Japan. Thus developments of material design and advanced manufacturing technology for high quality products, lower costs and more profitable production are needed.

3.3 Material selection and product design

Good coordination of material manufacturing and product design: It is worried that manufactures in Japan flow out and lose their potential. The *integrated assembly* type company which develops material and product together harmonizes component design and material selection. Here the policy "material is a part of product" is clear. From this point manufacturing technology and know-how for sustainable society should be encouraged in Japan.

Novel developments of aluminum space frame automotive body are a good example for the integration of product design and material selection. One of primary strategies to design car is the light body which is directly related with saving energy for running. There are still problems on dissimilar metals joint such as joining, electric corrosion, recycle, etc, although automotive companies have paid efforts on materials selection. New aluminum frame design car has launched with the developments of die-casting material for B-posts accepted welds, joining technology, deep drawing etc, where there was no prepossession of conventional facilities.

Total management of product in a manufacture: The *totally managed* type company is doing all of material development, production, recovery and recycle in a manufacture or group, where manufacturing and recycling are harmonized. For an example, a fastening products manufacturer has been managed the loop from material, product, facilities, scrap recovery (PP), recycle (wooden chips, old scrap A6063, etc.) to zero emission in factory. The concept, zero emission in factory, e.g. no dust, drain water, oil and chemicals, is a stage of green manufacturing and has been adopted in others such as dry forming process of steel beverage can. In addition to the policy "material is a part of product", proper and flexible management in those manufactures has been carried out from the viewpoints of manufacturing and recycling.

4. KEY POINTS AS SOCIAL TECHNOLOGY

4.1 Technology development for sustainable society

Viewpoints of technology development to establish and grow the sustainable society are summarized as follows;

- Consider distribution area of scrap accompanying flow and variability
- Recovery and reproduction process to answer for various needs
- Novel technologies building high performance and/or service with low costs, low environmental loads and good flexibility

Material systematized in product: The concept "material systematized in the product" is promoted more including service, performance and risk management. This enables manufactures to respond flexibly to emerging market needs.

Secondary materials accepted for product: To provide a flexibility in secondary materials, the concept "material systematized in the product" should be also applied as follows;.

- Developments on not only refinement of secondary materials but also making secondary materials innocuous from impurities to utilize widely
- Developments on advanced material separation and new material substituted for material containing toxicity such as PVC

4.2 Civic system for sustainable society

Formation of the recycle loop: A concept of material flow should be started from local loop such as factory zero emission. Figure 2 illustrates three types of materials flow such as local loop, intra-economic-zone loop and inter-economic-zone loop. Scrap can be reused in the local loop as large as possible, since it is more cost-effective instead of transporting it to far area. However, the materials are imbalance between production and waste or recycle due to the conditions of economy. Then outflow and inflow of scrap are admitted in the intra-economic-zone. In the inter-economic-zone, outflow and inflow of products are considered. These enable local characteristics to be taken into account in recycle business activities, and allow marketing to be conducted more efficiently.

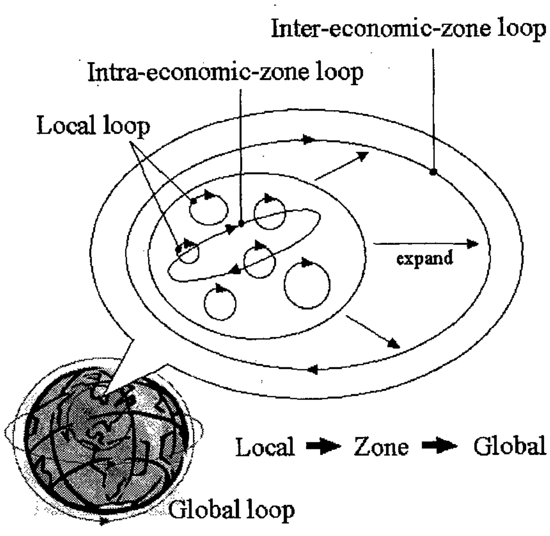

Fig. 2 Schematic illustration of materials flow.

Environmental conditions in area: The material flow considers the global body which involves the local and intra-/inter-economic zone loops. It is reasonable to make total environmental loads and resources consumption minimized. Environmental pollution in China is under serious condition. The problem is the most important subject not only in China but also in Japan. Furthermore the scrap yield in the Tokyo areas is remained, and is transported to west Japan area or China. These are the solution of the moment. Thus the proposal of international collaboration work on environmental technology is important.

Building urban mine: In Japan, urban mine is still under building (Table 1). The instability of quantity and quality in output is a problem in scrap use. In the case of steels, large amount and various products such as buildings, bridges, steel constructions, automotive, electrical devices, furniture and so on have been in stock with our life for long time. Thus the fluctuation of steel scrap has not been problem, which enable steel scrap to realize urban mine. Aluminum scrap is mainly used for beverage can, frame, automotive parts and so on. Quantity of aluminum products in usage is not enough and does not come to urban mine. Life of plastic products is much shorter than that of metals, and their quantity in usage is low. Thus it is unclear to build urban mine of plastics.

5. CONCLUSIONS AND PROPOSALS

A feasibility study on the materials process design and technology for sustainable society has been done in Japan, USA and EU. To respond flexibly to emerging market needs and various type resources without increasing environmental load, demands on materials for simple recycling and scrapping will take towards remarkable recyclability, advanced utilization of scrap, low costs, and smaller and more profitable production. There is no doubt that a modern *integrated* manufacturing can be existed by sufficiently large amounts of products and can hardly fulfill widely spread requirements. Some directions on technology development are proposed to answer the requirements on sustainable materials.

(1) Development of more profitable production system to answer for social requirements and increasing scrap

The trends mentioned in above increase the pressure towards the development of more profitable and smaller production units. In the case of steelmaking, the development of near net shape technology such as strip casting has been done. In the case of PET bottle, the development of chemical recycle with low cost and reduced by-products and wastes has been done. However, it is difficult to replace the conventional process fully to new one, since large investment for facilities is needed. In addition, energy and material industries are key manufacturing and make a role in social system. Thus the advanced technology is necessary to develop and realize economically, ecologically and socially justifiable system. It should here be stated that the various processes are complement each other and that a better production balance of those is controlled in the recycling-based society as follows;

- The conventional process also covers a part of the new process
- Rather recyclable materials are produced in the conventional process
- More profitable processes with short production chains are developed and replace conventional ones gradually

(2) Development of totally managed industry in manufacturing and recycling to minimize materials flow

The material recycling depends on conditions in area. It is more cost-effective to reuse scrap in yielded are instead of transporting it to far areas. This concept should be started from zero-emission in the factory. Thus the *ecology town* plan, where recycling industries park is located near key manufacturing industry, gives a good solution.

- Keep the *ecology town* system in good working order
- Technology transfer of the *ecology town* system as a fundamental unit of sustainable society to East Asia in order to contribute for global green engineering

(3) Utilization of urban mine as the resources in sustainable society

The ratio of scrap yield in the densely populated areas against manufacturing demands will increase regardless materials. Output and life of products have been taken statistics, and feedback of the data will give a prediction of output of scrap with each material. Utilization of such urban mine will make rather clear for social investment on industrial technology and its scale.

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REFERENCES

[1] K. Halada and R. Yamamoto, *MRS Bulletin*, Nov., 871-879 (2001).

[2] http://snet.sntt.or.jp/sntt/junkan/

[3] O. Umezawa, *Bulletin Iron Steel Inst. Jpn. (Ferrum)*, 7, 545-554 (2002).

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