A rationalization guideline for the utilization of energy and resources considering total manufacturing processes

— An exergy analysis of aluminum casting processes —

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In order to increase manufacture efficiency and lower environmental impact, it is necessary to know the processes of consumption and emission of resource and energy, as the processes span out widely after originating from one process. In this paper, analysis and comparison of exergy were conducted in case when heater tube used in the molten aluminum was made of steel and ceramics. Exergy analysis was done for complete operation of aluminum casting. We then created a guideline for rationalization of casting process for efficient use of resource and energy.

Keywords **:** Exergy, environment, manufacturing, system, efficiency, rationalization

1 Introduction

"Manufacturing," where useful products are obtained by processing raw material, is a system that converts resource that originally exists in nature into matter and energy in useful form, while it also releases useless substance and energy into the environment. Manufacturing is a series of processes starting from mining, transportation, use, and disposal. It is an assembly of subsystems of individual processes. The product becomes useless with passage of time and is disposed, and returns to the environmental though it takes considerable amount of time. In the expanse of space and time, all systems related to manufacturing affect the environment, as matter and energy are exchanged with the surrounding environment while maintaining mutual relevance (Figure 1).

During the period of rapid economic growth in Japan in the 1960s, orientation of manufacturing was mass production and mass consumption, and waste could be buried. Today, environment and economy must both be sustained, and uncontrolled consumption and emission from individual systems cannot be allowed, although problems cannot be solved simply by optimization, sizing down, or combination of the two. It is normal for individual and group to be in conflict, and a manufacturing system that seems to consume only small amount may have underlying system of large consumption and emission, and the load may increase in total sum. To reduce consumption and emission as total while maintaining competitive edge, it is necessary to know the process of consumption and emission that originates from individual and spreads out to entirety, to clarify its size and significance, and to strategically utilize this knowledge. In this paper, we decided to consider exergy as main concept for both evaluation and development. Exergy is Gibbs free energy based on environment, and is defined as maximum work that can be achieved until system and environment reach thermal equilibrium[1]-[3].

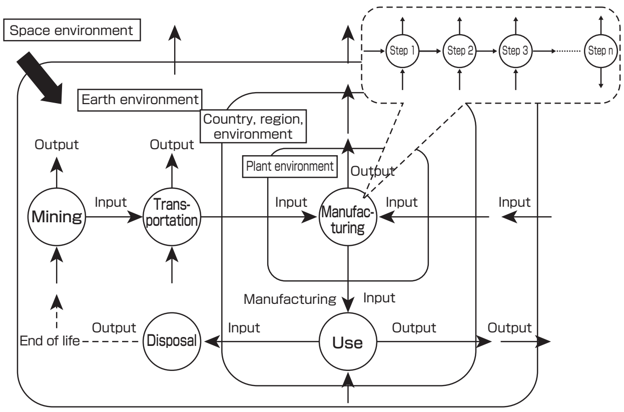

Fig. 1 Relationship between manufacturing system and environment.

Exergy is consumed unilaterally through production activities, and is a suitable indicator to quantify resource consumption level that is common to matter and energy. By using exergy, it is also possible to clarify the energy value of things and input and output energy in the cycle, as well as theoretical limit. It can be used to set guideline for rationalization of process. Although it is important to evaluate the situation using exergy as index, this alone will not cause any revolution. We believe it is necessary to present rational hardware and process that are useful in mitigating environmental impact and resource consumption while linking evaluation result with development, and presenting them as new value where environmental impacts are reduced at wide-ranging levels (Figure 2).

Exergy is described as measure of efficient use of heat

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according to JIS[4], and has been used as guideline for heat engines and architectural designs[2], [5]-[7]. In the manufacturing field, it is used in rationalizing iron and steel making and chemical processes, but there was no case that addressed resource consumption process or rationalization guideline for system in which manufacturing of different fields are integrated. In this paper, exergy analysis was conducted for use and disposal of ceramics and steel members, and when these were used as production members in aluminum casting line for engine parts. First, we looked at the point where consumption and emission of exergy are in conflict depending on the definition of "boundary" such as operation, manufacture, and use, and attempted clarify the significance and scale of consumption process. Based on this analysis, we then created a guideline for process rationalization.

2 Analysis method

2.1 Calculation of exergy

①Chemical exergy of matter[1]

If reference compound has composition $X_xA_aB_b$ … (X, A, B are elements; x, a, b are composition ratios), is produced by chemical reaction (1), and change of Gibbs free energy is $\triangle G^0$, then chemical exergy $E_x^{\,0}$ can be calculated by equation (2).

$$xX+aA+bB+\cdots\rightarrow X_xA_aB_b\cdots \quad \text{...... (1)}$$

$$E_x^{\,0}=\frac{1}{x}\left[-\triangle G^0-aE_x^{\,0}(A)-bE_x^{\,0}(B)-\cdots\right] \quad \text{...... (2)}$$

Reference material is matter that does not chemically react alone in an environment, and its exergy is zero accoroding to the definition. Reference materials are listed in JIS[4], but for unlisted materials, we set the material with lowest free energy as reference material.

②System accompanying chemical reaction[5][7]

The value of free energy available as thermodynamic data is mostly value at standard condition, i.e. 1 mol of pure material, and adjustment is necessary in exergy calculation. Reactant r_1 is matter that does not exist in surrounding environment, while reactant r_i (i = 2, 3, ... L) and product p_j (j = 1, 2, ... N) are matters that exist in surrounding environment. Molar fractions of reactant r_i and product p_j are x_{ri} and x_{pj} respectively, and their molar fractions differ according to the surrounding environment. Also n_{ri} and n_{pj} are quantities of material (mol) of reactant and product respectively.

$$\left[\sum_{j=1}^{N} n_{pj}RT_0\ln\frac{1}{x_{poj}}-n_{r1}-\triangle G-\sum_{i=2}^{L} n_{ri}RT_0\ln\frac{1}{x_{roi}}\right]+\sum_{i=2}^{L} n_{ri}RT_0\ln\frac{x_{ri}}{x_{roi}}-S_gT_0=\sum_{j=1}^{N} n_{pj}RT_0\ln\frac{x_{pj}}{x_{poj}} \quad \text{...... (3)}$$

The first section in [ ] on left side of the equation shows the chemical exergy of reactant r_1. The second section on left side is separation exergy when reactant r_i (i= 2, 3, ... L) has molar fraction x_{ri}, and first section on right side is separation exergy when product p_j (j = 1, 2, ... N) has molar fraction x_{pj}. Also, S is entropy, T_0 is environmental temperature (K), and R is gas constant.

③Organic material

Although equations of Rant[8] and Szarut[9] are known for calculation of chemical exergy for organic material, we used the following equation[10] derived by Nobusawa et al who modified the equations for practical use.

$$E_X=m\cdot H_l\cdot\left[1.0064+0.1519\frac{\phi_H}{\phi_C}+0.0616\frac{\phi_O}{\phi_C}+0.0429\frac{\phi_N}{\phi_C}\right] \quad \text{...... (4)}$$

m and H_l are dry mass (kg) and lower heating value (J/kg) of organic compounds respectively. ϕ_C, ϕ_H, ϕ_O, and ϕ_N are weight fractions of carbon, hydrogen, oxygen, and nitrogen in the organic compound.

④Electric power and gas fuel

Electric power is energy that does not contain entropy, so it was used as value for exergy. On the other hand, exergy of fuel gas was calculated using the following equation[10].

$$e^0=\sum x_i e_{ci}^0+RT_0\sum x_i\ln(x_i) \quad \text{...... (5)}$$

e_c is exergy and superscript 0 indicates standard temperature (25 °C), and subscript i is for ingredient i. x_i is volume fraction of ingredient i.

2.2 Organization of system and input/output data

In this paper, overall composition in manufacturing is called "system," and mining, transportation, use, and disposal

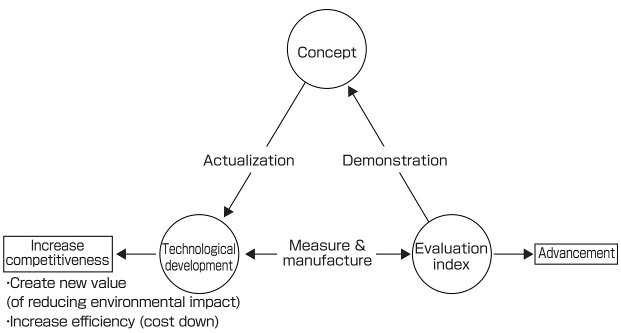

Fig. 2 Importance of linkage between technology and index.

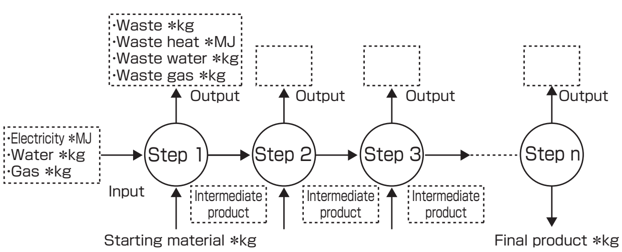

Fig. 3 Input-output and flow to operation.

are called "processes." The process is aggregation of "operations."

Figure 3 shows the input/output flow of matter and energy during operation. While raw fuel is introduced and intermediate product is produced for each operation, waste material and heat are also produced and these are emitted outside the system. The intermediate product becomes raw material for the next operation, and final product is made after series of operations.

To calculate exergy, it is necessary to know the type and the quantity of all raw materials and energies that are introduced into and emitted from the operations, from material to final product. In this study, we were able to obtain data in actual manufacturing by cooperation of major manufacturer. In most cases, we used data while some parts were unknown, and unknowns were filled in with estimate values based on experience.

2.3 Manufacturing efficiency

The percentage of exergy of product against sum of exergies of all input fuel and energy was called fixed ratio of exergy within members (η).

$$\eta = E_X(\mathrm{p}) / E_X(\mathrm{in}) \qquad \text{...... (6)}$$

Here, $E_X(p)$ is chemical exergy of product, and $E_X(in)$ is sum of input exergies. In this paper, we evaluated manufacturing efficiency by considering both fixed ratio of exergy within member and exergy needed for input.

3 Case study

3.1 Aluminum casting line operation and role of heater tube

Aluminum has excellent heat conductivity and is lightweight, and therefore is used widely in engine parts. Also, aluminum is highly recyclable, so disposed engines are collected as scraps and recycled as engine after undergoing some processes. Figure 4 shows the recycling system mainly for aluminum casting line operation. First, recovered waste engine (scrap) are melted in centralized furnace. They are made into solid ingots, delivered within the plant, melted again in centralized furnace, and then transferred to holding furnace. The molten metal is adjusted for temperature and content, distributed to die cast machine, and formed into products. In this cycling system, there are many factors that decrease efficiency including heat loss, oxidation of molten aluminum, and inclusion of impurities. Input of energies and things from outside is unavoidable to maintain certain quality level and production volume, and reducing these inputs is expected to increase the efficiency of the cycling system.

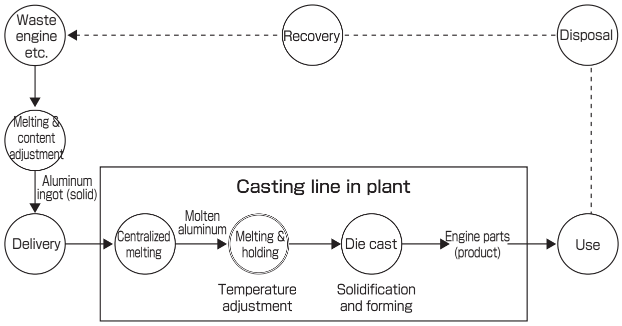

Fig. 4 Aluminum cycle and casting line operation.

As one of measure, use of ceramics in production member has been attempted. Heater tube (Figure 6) used in holding furnace (Figure 5) is one example. It is a protective tube that envelops the heating wires, and is used to maintain constant temperature of molten aluminum. Heat efficiency increases by using highly conservative silicon nitride, which allows horizontal dip structure where the tube is fixed horizontally in the bottom of the furnace (Figure 5). However, ceramic tube is much more expensive than iron tube. We conducted exergy analysis for manufacture-use-disposal in cases where the heater tube (weight 19 kg) was made with silicon nitride and when it was made with iron[11][12].

3.2 Calculation of chemical exergy

In conducting the analysis, it is necessary to calculate the exergies of all materials involved in the manufacture. The process of calculation of exergy is shown using silicon nitride (Si_3N_4), the main material. The reference material of silicon nitride is silica and air.

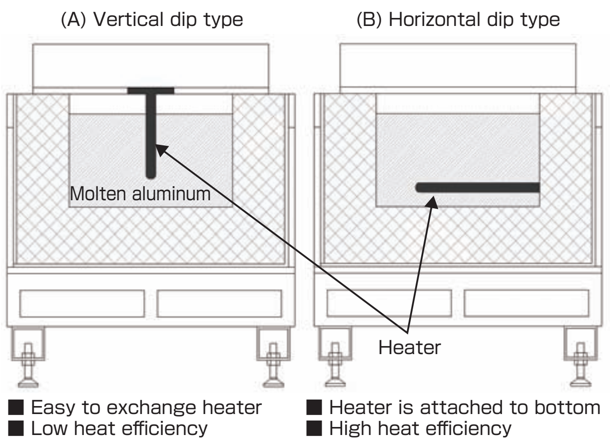

Fig. 5 Structure of holding furnace.

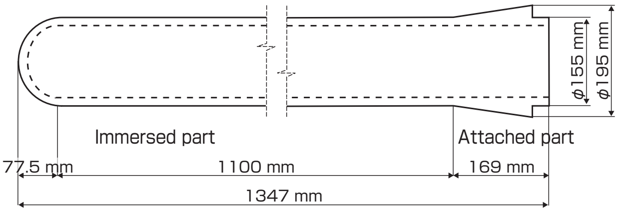

Fig. 6 Form and dimensions of heater tube.

$$E_x(N_2) = RT_0 \ln(101.3/76.57) \quad \text{...... (7)}$$

$$Si + (2/3)N_2 \rightarrow (1/3)Si_3N_4 \quad \text{...... (8)}$$

$$E_x(Si) = (-\Delta G^0) + E_x(SiO_2) - E_x(O_2) \quad \text{...... (9)}$$

$$E_x(Si_3N_4) = 3(\Delta G^0) + 3E_x(Si) + 2E_x(N_2) \quad \text{...... (10)}$$

Ex(Xi) shows the exergy for material Xi. The section in parenthesis in equation (8) is ratio of total pressure of air and partial pressure of nitrogen. From the above equations, exergy of silicon nitride was calculated to be 1877 kJ/mol. Using similar method, exergies values for major fuels were calculated (Table).

Table. Calculation of exergy for related main fuel.

Raw material and fuel	Exergy
Y_2O_3	47 kJ/mol
Al_2O_3	0 kJ/mol
Si_3N_4	1877 kJ/mol
N_2	7×10^{-1} kJ/mol
Fe_2O_3	0 kJ/mol
Si	851 kJ/mol
Fe	368 kJ/mol
Al	788 kJ/mol
CO_2	20 kJ/mol
O_2	4 kJ/mol
PVA	49 MJ/kg
LPG	48 MJ/kg

3.3 Consumption and efficiency by operation

Figure 7 shows the values of exergies that come in and go out throughout manufacturing operation of silicon nitride member and during complete manufacturing. The silicon nitride material is input to this system as artifact made by melting and reducing silicon oxide at a different plant and then reacted with nitrogen. The exergy of material was calculated as 291 MJ for one product. The product begins as starting material in powder form, and is created by mixing, granulation, forming, dewaxing, and sintering. Looking at each operation, large exergy is required for granulation and sintering of 2547 MJ and 776 MJ, respectively, and this is about 80 % of all exergy input. It was found that these were almost entirely emitted outside the system as waste heat, while powder raw material was collected and there was almost no loss between the operations. Exergy fixed in final product was 229 MJ, and this was only 5.5 % of exergy input (4175 MJ). This was an extremely inefficient process where 94.5 % or 3946 MJ was disposed.

Figure 8 shows the input-output of exergy by operation in manufacturing using steel member. In case of steel, starting material is iron oxide (Fe_2O_3) whose exergy is 0 by definition. It was manufactured by effectively utilizing the reaction of material such as reduction, and was found that exergy input and output at all operations was small and equalized. Exergy fixed in product was 126 MJ, which was about 20 % of exergy input (621 MJ), and the amount of exergy input was extremely low, about 1/7 compared to ceramics. Therefore, looking at the system of manufacturing one product, it was confirmed that ceramics consumed significantly higher amount of exergy compared to steel, and efficiency was low.

3.4 Exergy analysis at each process

3.4.1 Use

①Wear and material disposal

When steel heater tube is used in molten aluminum, it is corroded by aluminum and worn down by passage of time *t*. It was assumed that wastage progressed according to the following equation.

$$D = D_0 \cdot (2 - \exp(kt)) \quad \text{...... (11)}$$

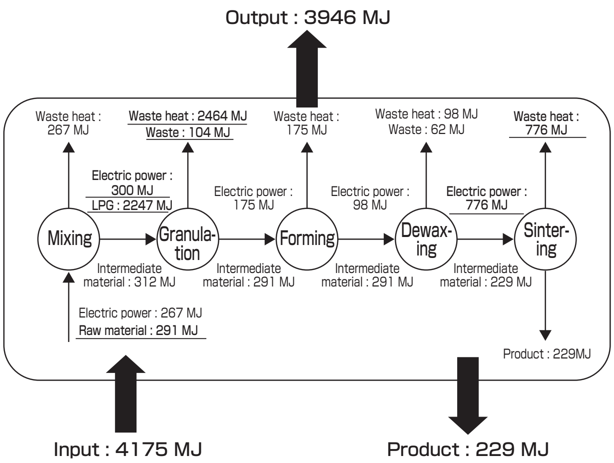

Fig. 7 Operations for ceramics parts and exergy balance during manufacture (for one product with weight 19 kg).

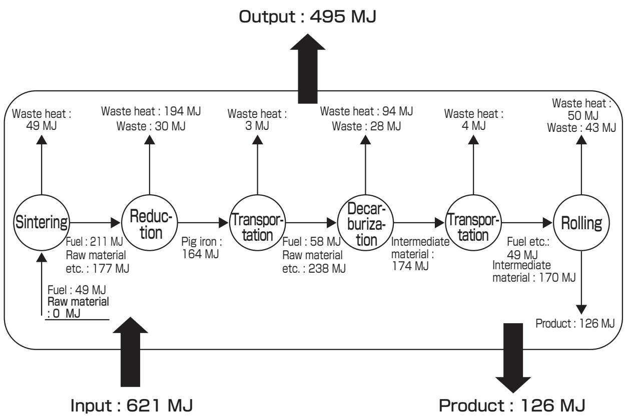

Fig. 8 Operations for steel parts and exergy balance during manufacture (for one product with weight 19 kg).

Here, D is thickness of heater tube (mm), D_0 is initial thickness (mm), k is apparent reaction speed coefficient, and D_i is thickness at time of replacement (mm). Assuming D_0 = 3 mm (from data) and D_i = 0.5 mm, under condition of replacement every half year, the reaction constant k was calculated to be 0.067578.

Consumption exergy is expressed by following equation.

$E=E_0 \cdot \exp(kt)$ …… (12)

Exergy of steel is 6.6 MJ/kg (= 368 KJ/mol) and total weight of the product is 19 kg, and when it is disposed when damage reaches Di, consumption is 126 MJ/tube. While steel heater tube is exchanged once every half year, silicon nitride is stable and does not react, and is exchanged and disposed along with furnace that has lifespan of 7 years. Figure 9 shows the change with time of exergy consumption in 7 years. Exergy consumed by disposal during this time is as shown in the following equation.

・Steel: 126 (MJ/tube) × 14 (tubes) = 1764 MJ
・Silicon nitride: 229 (MJ/tube) × 1 (tube) = 229 MJ

When steel heater tube is used, damage and disposal are repeated and exergy consumption increases in step-like form. In contrast, there is hardly any consumption in 7 years using ceramics, and exergy value (229 MJ) is released at the end of furnace lifespan. Also, using ceramics, there is less chance of inclusion of impurities compared to steel, so clean molten metal can be obtained, and this is another advantage of ceramics.

②Running

(a) Melting and holding furnace

In vertical dip type using steel heater tube, 9.4 kW is required during run and 4.0 kW at rest, while in horizontal dip type using silicon nitride, electricity consumptions at run and rest are 6.8kW and 3.8 kW respectively, due to improved heat efficiency. While it will be running 60 % (40 % rest) per day and is in operation 360 days a year, the total electricity consumed in 7 years, or exergy input, will be as follows.

・Steel: (9.4×0.6×24+4.0×0.4×24) × 360 × 7 × 3.6/1000 = 1576 GJ
・Silicon nitride: (6.8×0.6×24+3.8×0.4×24) × 360 × 7 × 3.6/1000 = 1219 GJ

(b) Die cast machine

Assuming that electricity consumption of die cast machine is 20 kW, running 60 % per day for 360 days per year, the total electricity consumption, or exergy input, for 7 years is as follows.

・20 × 0.6 × 24 × 360 × 7 × 3.6/1000 = 2612 GJ

3.4.2 Manufacture, use, and disposal

As result of interview with companies, the total manufacture volume of cast product in 7 years was estimated to be about 4300 ton. In this paper, material loss is not considered. Therefore, the amount of molten aluminum is 4300 ton or same as final product, and the exergy was calculated as 126802 GJ in molten condition (temperature 700 °C), and 125582 GJ in solid condition.

Figure 10 shows the amount and flow of exergy input and output for manufacture using ceramics and steel heater tube, their use in melting and holding furnace when casting was conducted for 7 years. As mentioned above, when the furnace is run for 7 years, 14 steel tubes are required since they are subject to damage. Therefore, energy input and output during the manufacture process is as follows.

・Input: 621 (MJ/tube) × 14 (/tubes) = 8694 MJ
・Output: 495 (MJ//tube) × 14 (/tubes) = 6930 MJ

On the other hand, only one silicon nitride tube is required during same time, and exergy for input and output will be 4175 MJ and 3946 MJ respectively according to Figure 7. Next, exergy accompanying damage and disposal during use is as follows.

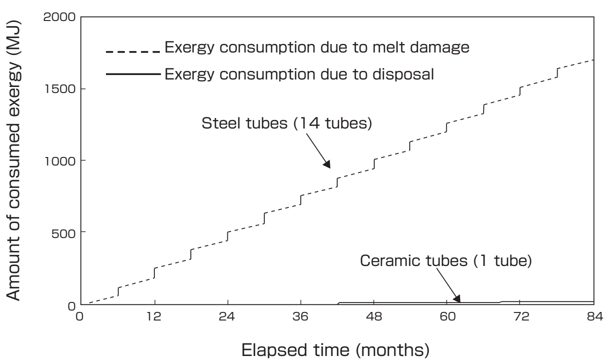

Fig. 9 Comparison of exergy consumption due to melt damage and disposal during use (calculation for 7 years).

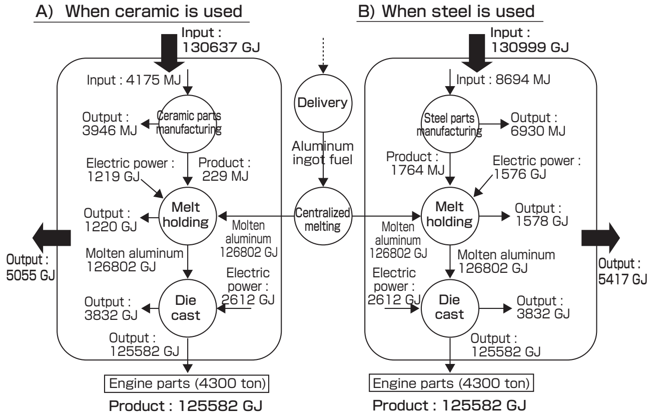

Fig. 10 Exergy balance in casting aluminum engine parts (7 years).

- Steel: 126 (MJ/ tube) × 14 (tubes) = 1764 MJ
- Silicon nitride: 229 (MJ/ tube) × 1 (tubes) = 229 MJ

Looking over the entire process, the exergy inputs for steel and silicon nitride were 130999 GJ and 130637 GJ respectively, while exergy outputs were 5417 GJ and 5055 GJ. Using silicon nitride reduced 362 GJ of input and output exergy compared to steel.

From the above results, it was shown that although one silicon nitride tube required 7 times more exergy in manufacturing process, frequency of replacement decreased due to its high conservative property, which allowed furnace with highly efficient structure that reduced electricity consumption, and therefore, exergy consumption level was smaller compared to steel in total throughout the lifecycle of manufacture, use, and disposal.

3.5 Rationalization consideration

Assuming current system, we proposed guideline for rationalization for using ceramics or steel. Then we summarized the current state and direction of rationalization of casting system.

3.5.1 Steel member

Highly economical steel member is mainstream of heater tube. When use of steel member is assumed, development of material or coating technology to prevent corrosion by molten aluminum is necessary to increase lifespan. Also, steel has excellent recyclability, and it is important to increase recycling efficiency.

3.5.2 Ceramics member

To promote rationalization of ceramics manufacture, as mentioned above, increased efficiency of granulation and sintering operations that have particularly high consumption among all operations is mandatory. This improvement is highly significant to reduce environmental impact and to counter steel members that are highly economical.

①Granulation

While metal process such as in steel involves melting raw material at high temperature and mixing and reaction by dispersal ability of liquid medium, ceramics use solid powder without dispersal ability in gravitational field. Therefore, it is a process with inherent inefficiency, where water and binder that do not remain in the final product are added between solid particles for mixing, and energy is required to remove them.

When water is introduced, distance between particles can be reduced and mixing becomes easy, but large amount of latent heat must be consumed to evaporate the water in the slurry in the post-operation dry granulation. The input energy is transferred to water as heat, evaporates, and released outside the system along with entropy as steam. Therefore, to reduce exergy consumption during granulation, although reduction of water including selection of deflocculant and adjustment of granularity are necessary, the time required for mixing in preliminary operation will increase. To reduce exergy consumption in the granulation operation, optimization of water content while considering effect on preliminary and following operations is necessary.

LPG is used as fuel in granulation. When LPG is used, input exergy will produce water and carbon dioxide unavoidably during combustion, other than in drying of slurry and granulation, and exergy is consumed for releasing them from the system. If electricity is used instead of LPG, input exergy may seem to be reduced. In this case, exergy consumption in plant may be reduced, but exergy is actually consumed outside (at a power plant). This time, LPG was used in the granulation operation since cost was prioritized.

②Sintering

Figure 11 is a conceptual diagram that summarizes the relationships of material, product, and input exergy for rationalization. It is assumed that reference material (exergy = 0) and material have chemical exergy and exergy derived from surface energy, and material and product (sintered body) have difference in exergies derived from surface and interface, as well as arrangement.

Stable material with highly covalent silicon nitride requires large amount of exergy in running the furnace and heating the refractory materials, in addition to exergy equivalent to the barrier of activation energy. These unavoidably become waste exergy, and waste heat recovery must be considered.

To reduce exergy consumption, input and output can be lessened by using low exergy material and by utilizing the energy of the material. Chemical exergy of silicon nitride is high at 1877 kJ/mol. Moreover silicon nitride particles undergo separate operations for nitrification of silicon and sintering of silicon nitride obtained, and each operation produces waste heat.

On the other hand, chemical exergy of silicon is calculated to be 851 kJ/mol, or about half of silicon nitride. To reduce exergy consumption, it is effective to shift from silicon nitride powder to silicon, powder and to conduct nitriding and sintering in one operation. Although this process is known as post sintering involving reaction-bonding, it is not widely done because control of heating in nitrification process is difficult and mixing using water medium is difficult since silicon itself is active. In the future, to make the process practical, it is necessary to develop a catalyst that allows mixing with water medium in short time and allows nitrification at low temperature using rough silicon particles. Also, to increase efficiency, one way is to increase sintering temperature by increasing size of drying and sintering furnaces that will increase production volume per unit time, but optimization of total system must be conducted while considering facilities investment and production volume.

Exergy, which was born from heat engineering, is considered as common thread between effective energy and materials, but it is not sufficiently systematized from physical perspective such as dealing with interface and surface as mentioned above. This is future issue in increasing the accuracy of the index.

③Design and others

As mentioned earlier, since ceramics is extremely stable in molten aluminum, it does not have to be solid body. Not only does hollow structure design and process reduce amount of material used, but also will decrease heat stress by thinning and will shorten sintering time, and these are extremely useful for improving efficiency.

On the other hand, ceramics is not suitable for recycling. Both company and consumer must become conscious of using ceramics members as long as possible because they were manufactured using great amount of exergy input. In technological development, considering the characteristics of ceramics, development of design and process that allows exchange of damaged parts and reparable structure is necessary.

3.5.3 Innovation in casting system

Looking at the overall casting operation, there are two operations in which solid is melted, and heat is radiated considerably in delivery process (Figure 4). Exergy necessary to melt solid was calculated to be about 19000 GJ (4300 per ton). To decrease this, development of molten metal delivery system, where molten aluminum melted outside is placed in insulating container, delivered directly into plant in molten state, temperature adjusted in holding furnace, and then formed, is being done by major automobile companies. It is expected that efficiency will increase since one process of melting-solidification is reduced. However, currently there are problems such as insufficient insulation of the transporting container that demands external heater during delivery process, as well as high fuel consumption in transportation process because the container itself is heavy. Delivery of molten metal is highly efficient system in principle and diffusion is expected, but development of lightweight container with excellent insulation is the key.

The centralized melting furnace, which will become the center of the above delivery system, will be on continuous run once aluminum is melted in the furnace to maintain the molten state. Considering that it is necessary to put in energy regardless of amount, the ultimate system will be to deliver the metal into the plant as solid, and to melt only necessary amount to produce the product. There are several issues before this system can be realized, such as heating source that enables instant melting, excellent insulation which is component of system, large ceramic tube and container that the molten metal will not adhere, engine design that allows easy disassembly, and establishment of recovery system of disposed engine in the society. It is necessary to solve individual issues while considering the overall exergy balance.

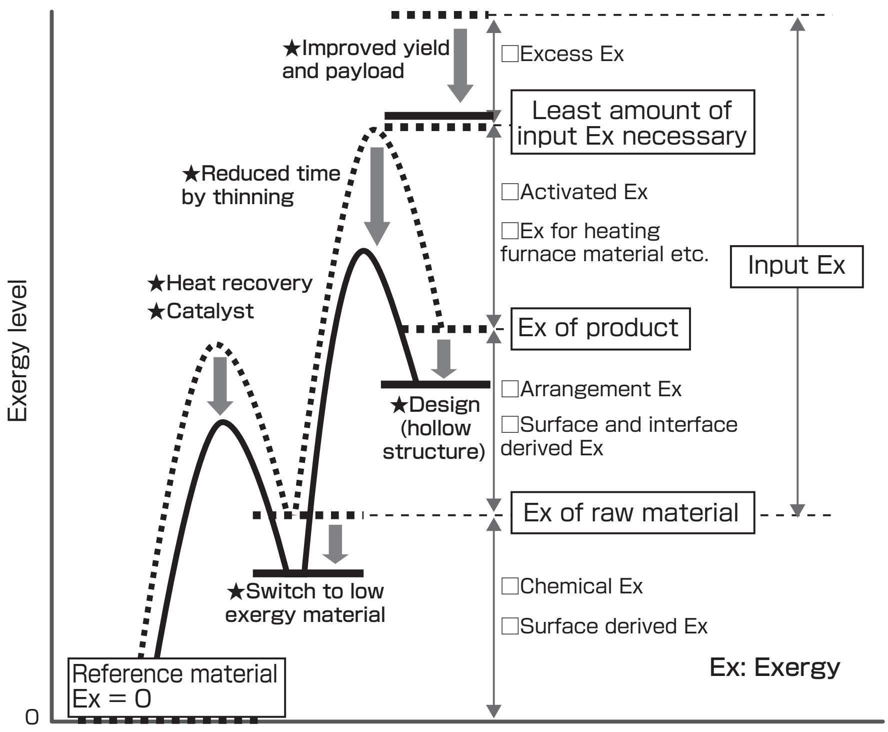

Fig. 11 Rationalization of ceramics process.

4 Summary

4.1 Evaluation of manufacture

Exergy analysis was done in case where members were manufactured with ceramics and steel, used as production member for 7 years in casting line for aluminum engine, and then disposed.

①Exergy input per product was 4175 MJ for ceramics and 621 MJ for steel, and significantly higher exergy was consumed for ceramics compared to steel.
②Exergy fixed in ceramics was 229 MJ, or 5.5 % of exergy input, and most are emitted outside the system.
③By operation, granulation and sintering consumed 80 % of total input.
④As result of high exergy input, ceramics have high conservation. When it is used in molten aluminum using this characteristic and used for 7 years, exergy consumption is reduced 362 GJ compared to steel.

4.2 Rationalization consideration

Assuming current system, guidelines for rationalization when ceramics or steel members were used and technologies needed for rationalization of casting system as a whole were summarized.

①**Steel**
・Development of material and coating technology that is not readily corroded by molten aluminum.

②**Ceramics**
To improve manufacturing efficiency of ceramics, rationalization of granulation and sintering operations that have significantly high consumption is mandatory.
・Optimization of water content while considering effect on preliminary and following operations, such as selection of deflocculant and adjustment of granularity.
・Catalyst that allows nitrification at low temperature using rough silicon particle, or combination of nitrification and sintering processes.
・Hollow structure design. Reduced amount of raw material and shortened sintering time.
・Technological development for exchange and repair of parts to use ceramics member manufactured with large exergy input.

③**Casting system**
・To increase efficiency of delivery system of molten metal, development of transportation container that is lightweight and has excellent insulation is the key.
・System for delivering the metal as solid and melting only necessary amount to be used for product. Several issues must be solved including heating source that allows instant melting, large ceramics tube and container with high insulation and without adhesion of molten metal, engine design with higher disassembly, and diffusion of recovery system of waste engine in the society.

5 Future prospect

Based on above considerations, we summarized the efficacy and issues of exergy analysis.

5.1 Efficacy of exergy analysis

①Normally, environmental impact assessment is conducted at manufacture phase and the content is already determined in the general plan, so options as measures for impact reduction are limited. It is necessary to forecast resource consumption and environmental impact of systems across wide-ranging level such as planning, R&D, and design, and the result should be fed back to technology and manufacturing. Exergy that links matter and energy is index appropriate for preliminary evaluation due to its characteristic, and effective use is desired.

②Cycling system is the outer shell of sustainability. To reduce input of resource and energy from outside needed to drive the cycling system, rationalization of system using exergy must be done swiftly.

③Although case of ceramics and metal was discussed in this paper, exergy is not limited to certain field or subject. Final goal is to link manufacturing (micro factor) to global level sustainability (macro result). It is possible, in principle, to calculate consumption speed of exergy using macro input and output data at national level for emission. This may become index for shift to sustainability.

5.2 Issues that must be improved

①Powder particle and sinted body made from that material were evaluated using same chemical exergy. In the future, it is necessary to have index that shows difference in condition such as surface and interface energy.

②Exergy is not appropriate for evaluating rarity or hazard, and it is necessary to conduct multifaceted evaluation by combining with other indices.

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Terminology

Term 1. Exergy: Effective energy that can be converted to other energy.

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Discussion with Reviewers

1 Importance of linkage between technology and index

Question & comment (Norimitsu Murayama)

Figure 2 shows the importance of evaluation index in synthesiological approach to research, and it is the heart of message of this paper. Between technological development and new evaluation index, what is made in “manufacture”? Also, isn’t the arrow from index to technological development “measure”? On contrary, isn’t the arrow from new evaluation index to technological development “advancement”?

Answer (Hideki Kita)

The object “manufactured” is product or process obtained in the process of technological development. Evaluation index and technological development are joined with double-headed arrow to indicate that improvement and progress take place by mutually reflecting their results. Index becomes “advanced” and the technological development improves in “competitiveness” as result of action of turning the cycle of “concept,” “development,” and “evaluation,” and these were placed outside the triangle.

2 Manufacturing efficiency

Question & comment (Norimitsu Murayama)

Assuming, for example, a sintering process with 100 % alumina, exergy is zero because alumina is a reference material and the exergy fixed in the sintered compact is zero. Therefore, even if there the total exergy input is varied, “manufacturing efficiency” will always be zero, and the differences in process will not be expressed. Rather than using the expression “manufacturing efficiency,” I think it is more appropriate to use the term, for example, “fix ratio of exergy in components.” Also, I think overall performance of the manufacture process can be expressed accurately by showing the values of both “fix ratio of exergy in components” and total exergy input.

Answer (Hideki Kita)

Exergy is a concept that originated in thermodynamics and applied to matter. In applying exergy to matter, as exemplified by the point that exergies for powder and ingot that have different bonding condition are same, as far as I can understand, systematization is insufficient from physical perspective in addressing surface and interface energy. It is one issue as a manufacturing index, and I mentioned this point in Section 5 of the text.

3 Performance evaluation of manufacture process taking in consideration the durability of components

Question & comment (Norimitsu Murayama)

Total exergy input indicates how distant it is from stable condition in nature, and it can be considered scientific expression of cost. The paper discusses the durability of ceramics components, but wouldn't the value of total exergy input/durable years be index that expresses the performance of entire manufacture process?

Answer (Hideki Kita)

I think the value of total exergy input/durable years is one of indices that express performance. On the other hand, considering environmental load, durable year (durability) itself is important guide. For example if the values of total exergy input/durable years are same, disposed amount of product with longer durability become less.

4 Future direction of evaluation method using exergy

Question & comment (Koichi Mizuno)

Based on the present comparison between the two kinds of heater tubes made from ceramics and iron (steel??), do you consider future research directions?

There are two ways. One is to widen out to operations other than heater tube (horizontal spread), on which the Reviewer do not have advice.

Another is deeper consideration of heater tube (vertical consideration). For example, to increase exergy efficiency further, technology to increase efficiency by recycling iron, or iron alloy technology to prevent dissolving in molten aluminum can be considered. Additionally, in ceramics, energy conservation may be considered in granulation and sintering operations that consume large energy in the manufacture process. For latter, "soft solution process" has been developed for manufacturing ceramics to avoid high-temperature sintering.

Answer (Hideki Kita)

Considering your comment, in Section 3.5, we showed guideline for rationalization of cases where ceramics or iron members were used, assuming current system, and then we summarized the current status and the direction of rationalization of casting system. 5 Future prospect is a mere summary.

For direction, we added guideline of rationalization of iron and ceramics in Section 3.5. Particularly for ceramics, we described the technological prospects for further energy conservation of granulation and sintering processes that consumes high amount of energy in the manufacturing process, along with Figure 11. Although soft solution process is an effective method for small, lightweight members or thin film, it is not process appropriate for large silicon nitride sintering compact addressed in this paper. Therefore we did not include it in our consideration.