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Functionality development as a survival strategy for fine ceramics

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Abstract

More than twenty years have passed since the Japanese government first undertook R&D on fine ceramics in its National R&D Program. Stimulated by such efforts, fine ceramics have exhibited rapid development and diffusion through substitution in a broad range of functional and structural materials fields, including the electronics, optical, mechanical, chemical and biomedical fields. However, although gross production of fine ceramics steadily increased from 1 trillion yen (7.8 US$) in 1988 to 1.5 trillion yen (15.6 billion US$) in 1995, the orbits of innovation for functional and structural materials demonstrate a clear contrast. Applications for fine ceramics as functional materials have shown remarkable development while applications for fine ceramics as structural materials have shown little or no sign of advancement. This contrast can be attributed to differences in the functionality of the two types of materials. Thus, functionality development for fine ceramics used as structural materials has become crucial in terms of survival strategy.

This paper, by means of an empirical analysis of the development and diffusion orbit of innovation for fine ceramics in major use in Japan over the last two decades, attempts to identify factors contributing to the above contrast in functional and structural materials development.

Keywords: Fine ceramics; Functionality development; Functional materials; Structural materials; Diffusion orbit

1. Introduction

While ceramics have been used in various applications for many years and their characteristic properties, such as electrical-insulating and chemical durability, etc. were identified in the 19th century, the practical products with the expected characteristics could not be simply produced. Quality and the performance of the products produced by conventional manufacturing processes using natural raw materials were insufficient for practical use.

As electronic and magnetic properties of ceramics were elucidated in the 1930s, R&D on ceramics with peculiar electronic and magnetic properties was undertaken. In Japan, since the 1940s, R&D was intensively carried out for commercialization and those ceramics products were called the functional fine ceramics (functional materials).

Between the late 1950s and 1960s, many new electronics products made by functional materials were commercialized for electronic or magnetic components and devices used. After the late 1970s, with the remarkable development of electronics and information technology, the production of electronic appliance and equipment assembled components and devices made by functional materials exhibited a remarkable increase.

On the other hand, R&D on the structural fine ceramics (structural materials) was undertaken in the USA during the course of the cold war. Stimulated by the demand for the substitution materials for special steels containing rare earth materials, for which the USA had no resources, led to the development of the Cer-met (Composite materials of ceramics and metals). Triggered by the first oil crisis in 1973, significance of the improvement of thermal efficiency in turbine system urged the US government, successively Japanese government, to undertake R&D for applying advanced ceramics as structural materials to the parts of high-temperature gas-turbine system, etc. (Watanabe, 1999).

Supported by those R&D, R&D on the new type ceramics, named fine ceramics or advanced ceramics, with carefully controlled composition and microstructure

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using carefully refined and synthetic raw materials by specific manufacturing processes became active in the late 1970s leading the Japanese government to undertake R&D on fine ceramics in its National R&D Program Project (Watanabe et al., 1991).

Stimulated by such efforts, fine ceramics have exhibited rapid development and diffusion through substitution in a broad range of materials, both functional materials such as electronic and optical applications, and also structural materials including chemical, biomedical, thermal and mechanical fields. While their gross production exhibited a steady increase amounting to 1 trillion yen (7.8 billion US$) in 1988 and 1.5 trillion yen (15.6 billion US$) in 1995, orbits of respective innovation demonstrate clear contrast. While fine ceramics as functional materials have shown remarkable development, fine ceramics as structural materials have shown saturating trends. This contrast can be attributed to the differences of functionality between two materials. These observations suggest that a functionality development concept is essential for R&D strategy in fine ceramics.

To date, a number of studies have analyzed development paths and future prospects of fine ceramics and fine ceramics industry (e.g. MITI, 1984, 1990, 1998, Japan Fine Ceramics Association (1998, 2000).

In addition, recently, a number of studies have attempted to analyze innovation forecasting of fine ceramics as innovative goods (e.g. Watts and Porter (1997); Warren et al. (2000); Liang and Dutta (2001).

However, since these works focus on technological expectation, expected demand, and market prospect on possibility of substitution for existing materials, none have taken the concept of functionality development for analyzing development orbit of fine ceramics.

This paper, by means of the empirical analysis of the development and diffusion orbit of innovation of fine ceramics in major use in Japan over the last two decades, attempts to identify factors contrasting remarkable development and saturating trends between functional and structural materials. Analysis of the trends in functionality development of major fine ceramics, both functional and structural, is focused on by using logistic growth model within a dynamic carrying capacity (e.g. Meyer and Ausubel (1999).

Section 2 outlines analytical framework. Section 3 compares functionality development orbits between fine ceramics as functional materials and structural materials. Section 4 extracts implications with respect to the impacts of functionality development on sustainable growth orbit for fine ceramics. Section 5 briefly summarizes the key findings of the analysis and presents conclusions and points of future works.

2. Analytical framework

2.1. Functionality of innovative products in fine ceramics

Innovation of fine ceramics encompasses potentiality of variety of functionality and broad perspective of utilization. Table 1 summarizes classification of innovation of fine ceramics by function and perspective of utilization. Table 1 suggests that the innovation of fine ceramics with the following classification can be categorized based on the dimension with function and perspective of utilization as illustrated in Fig. 1: 1) electronic and optical materials, 2) chemical, biomedical and living materials, 3) thermal and nuclear materials, and 4) mechanical materials. In order to identify the perspective of future innovation and diffusion of respective innovation of fine ceramics, the diffusion process of typical fine ceramics innovation focusing on the functionality development in their diffusion process were analyzed by using logistic growth function within a dynamic carrying capacity.

2.2. Model synthesis

In order to identify the functionality development of major innovation of fine ceramics in their diffusion process, logistic growth function is used for the analysis.

First, general diffusion of innovative goods can be traced by the following simple logistic growth function:

$$f(t) = \frac{K}{1 + a\exp(-bt)} \tag{1}$$

where $f(t)$=number of adopters (cumulative consumption of fine ceramics); a and b=coefficients; K=carrying capacity (ceiling of the adoptions of innovative goods); and t=time trend.

The simple logistic growth function expressed by eq. (1) assumes that the level of carrying capacity (K in eq. (1)) is constant through the diffusion process of innovation. However, in particular innovations, the level of carrying capacity will be enhanced as their diffusion proceeds (Watanabe et al., 2001), and carrying capacity K in eq. (1) should be treated as the following function:

$$\frac{df(t)}{dt} = bf(t)\left(1-\frac{f(t)}{K(t)}\right) \tag{2}$$

where $K(t)$ is also an epidemic function enumerated by eq. (3).

$$K(t) = \frac{K_K}{1 + a_K\exp(-b_K t)} \tag{3}$$

where a_K and b_K=coefficients; and K_K indicates carrying capacity (the ultimate upper limit).

Table 1
Classification of innovation of fine ceramics by function and perspective of utilization

	Function	Typical fine ceramics components and devices
Electronic and Optical	Insulating	IC packages
		Battery electrodes
		Ceramic substrates
		Printed substrates
	Semiconductive	Sensors
	Conductive	Electrodes
		Ohmic heating elements
		Thermistors
		Varistors
	Magnetic	Ferrite magnetics
		Ferrite cores
		Ferrite magnetics for data-recording heads
		Memories
	Dielectric and piezoelectric	Ceramic capacitors
		Piezoelectrics actuators
		SAW filters
		Quartz crystal resonators
	Optical	Optical fibers
		Optical connectors
		Ferrules for fiber optics
		Electro-optic devices
Chemical, biomedical and living	Chemical	Sensors
		Catalysts and catalyst supports
		Ceramic filters
		Corrosion-resistant wares and jigs
	Biomedical	Biomedical implants
		Toiletry and cosmetics
	Living	Commodity and cultural goods
		Jewelry
Thermal	Heat resisting	Sparking plugs
		Engine components
		Ceramic components for IC production processes
	Heat insulating	Thermal insulators
Mechanical	Cutting and shaping	Tools for machines
	Wear-resistant	Mechanical seals
		Precision jigs
		Valves
		Bearings

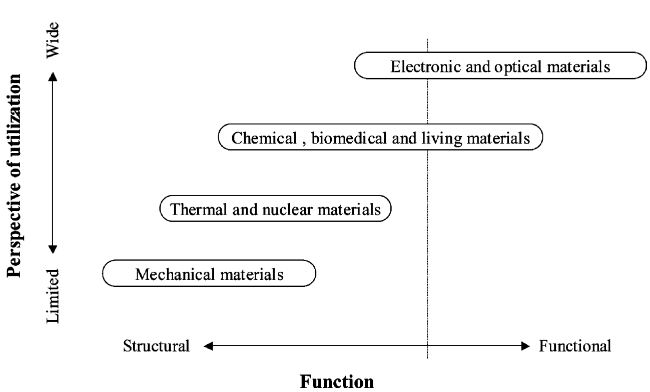

Fig. 1. Categorization of variety of fine ceramics innovation.

The solution of a differential eq. (2) under condition (3) can be obtained as eq. (4).[1]

$$f(t) = \frac{K_K}{1 + a\exp(-bt) + \dfrac{b \cdot a_K}{b - b_K}\exp(-b_K t)} \tag{4}$$

Eq. (4) encompasses eq. (1) as $a_K = 0$ leads to eq. (1).

2.3. Data construction and evaluation

Provided that the pregnancy period between production and commercialization in fine ceramics is short

[1] See Appendix for details of mathematical development.

enough to neglect[2] and depreciation rate can be treated as a reverse of the life time, cumulative consumption can be measured by the following equations:

$$S_t = C_t + (1-\rho)S_{t-1} \tag{5}$$

$$S_0 = \frac{C_1}{g + \rho} \tag{6}$$

$$\rho = \frac{1}{LT} \tag{7}$$

where S_t=cumulative domestic consumption at time t (1995 fixed prices); C_t=domestic consumption at time t (1995 fixed prices); g=increase rate of domestic consumption in the initial period; ρ=depreciation rate; and LT=life time (average years in use).

$$Cn_t = Pn_t - Ex_t + Im_t \tag{8}$$

$$C_t = Cn_t / WPI \tag{9}$$

where Cn_t=domestic consumption at time t (current prices); Pn_t=domestic production at time t (current prices); Ex_t=export at time t (current prices); Im_t=import at time t (current prices); WPI=domestic wholesale price index of ceramics industry (ceramic, stone and clay products industry).[3]

Life time of respective materials at the year 2000 (LT_{2000}) can be estimated as follows[4]

Electronic and optical materials:	3 years
Chemical, biomedical and living materials:	3.5 years
Thermal and nuclear materials:	4 years
Mechanical materials:	4.5 years

Provided that depreciation rate (ρ) is proportional to the rate of obsolescence of technology of ceramics industry, ρ at t can be measured by the following equation:

$$\rho_t = \frac{1 \quad \rho cr_t}{LT_{2000}\rho cr_{2000}} \tag{10}$$

where ρcr: rate of obsolescence of technology for ceramics industry.

Trends in domestic consumption of Japan's fine ceramics products over the period 1981–2000 classified by the above four materials and based on the above approach are summarized in Table 2 and illustrated in Fig. 2.

Looking at Table 2 and Fig. 2, we note that domestic consumption of electronic and optical materials shares more than half of Japan's whole consumption of fine ceramics and this share increases steadily (59.0% of whole consumption in 1981 to 68.1% in 2000) while shares of consumption of the other three materials continue to decrease: from 7.1% in 1981 to 7.0% in 2000 for chemical, biomedical and living materials, similarly from 8.3% to 6.0% for thermal and nuclear materials, and from 25.6% to 18.9% for mechanical materials. These trends suggest that the share of annual domestic consumption of fine ceramics products in Japan have been shifting from innovation for structural use to innovation for functional use.

In order to evaluate if the foregoing trends estimated by domestic consumption in money term represent trends in actual state of fine ceramics supply in the market, correlation analysis between estimated value (by 1995 fixed prices) and volume of domestic sales (by unit) was conducted taking typical products of electrical, thermal and mechanical applications over the period 1986–2000. The result proves strong statistical significance as follows which demonstrates the reliability of our estimation in Table 2 and Fig. 2:

$$\ln C = 1.878 \ln X \quad + 3.14 - 3.759D$$
$$(11.55) \qquad\qquad (7.07)(-2.54)$$

$adj.R^2$ DW D

0.913 1.58 1992 and 1993 = 1,

other years = 0.

where X=quantity of domestic sales (unit), C=value of domestic consumption (1995 fixed prices). Figures in parentheses indicate t-value, all significant at the 1 % level.

Using the above estimated domestic consumption, trends in cumulative domestic consumption of fine cer-

[2] This pregnancy period is estimated shorter than 1 year as fine ceramics R&D is generally conducted by manufacturers and users jointly, thereby commercialization starts immediately after the completion of R&D (MITI, 1990, 1998).

[3] Since values of export and import in 1981–1983 are inavailable, these values are estimated by using respective ratio with production.

[4] Since development process of fine ceramics can be considered similar to an R&D process of ceramics industry and its pace is faster than the pace of ceramics R&D, life time of fine ceramics as a whole is considered shorter than the life time of technology stock of ceramics industry which is 4.8 years (Watanabe, 1999, 2001). In addition, life time of cellular telephones, major utilization field of fine ceramics for electronic and optical materials which have the shortest life time among various use of fine ceramics, is estimated 2.1 years (Economic and Social Research Institute (2001). Furthermore, the length of life time is considered to be proportional to the limit of the perspective of utilization. Based on the above observations, life time of fine ceramics can be estimated 2.5–4.5 years, and the length of this life time is considered to be proportional to the limit of the perspective of utilization. With these suggestions, by means of questionnaires and interviews to member firms of the Japan Fine Ceramics Association (1998) the following life times are estimated: electronic and optical materials: 3 years; chemical, biomedical and living materials: 3.5 years; thermal and nuclear materials: 4 years; and mechanical materials: 4.5 years.

Table 2
Trends in domestic consumption of Japan's fine ceramics products (1981–2000): 100 mil yen at 1995 fixed prices

	Electronic and optical materials	Chemical, biomedical and living materials	Thermal and nuclear materials	Mechanical materials	Total
1981	1445	173	205[a]	628	2451
1982[b]	2630	245	428	520	3823
1983	3826	319	653	415	5213
1984	4146	520	524	1009	6199
1985	4635	620	478	740	6473
1986	4915	511	513	949	6888
1987	5497	507	587	1284	7874
1988	5768	528	679	1557	8531
1989	6521	544	634	1561	9260
1990	6654	701	643	1712	9710
1991	6686	669	625	1767	9747
1992	5771	547	531	2327	9176
1993	6680	440	452	2178	9750
1994	7328	458	488	2251	10525
1995	8529	667	714	2590	12499
1996	7697	642	901	2333	11573
1997	7785	773	1023	2896	12478
1998	7690	677	866	2736	11968
1999	9141	984[c]	839	2553[d]	13517
2000	10351	1067[c]	919	2866[d]	15203

[a] Statistics of sparking plug (which share approximately 70% of thermal and nuclear materials in 1981) are estimated by using their share in 1983.

[b] Statistics in 1982 for four products examined are based on the average of statistics in 1981 and 1983.

[c] Statistics of toiletry and anti-bacterial products (which share less than 5% of chemical, biomedical and living materials in 1999 and 2000) are estimated by using their share in 1998.

[d] Statistics of WC tools (which share approximately a third of mechanical materials in 1999 and 2000) are estimated by using their share in 1998.

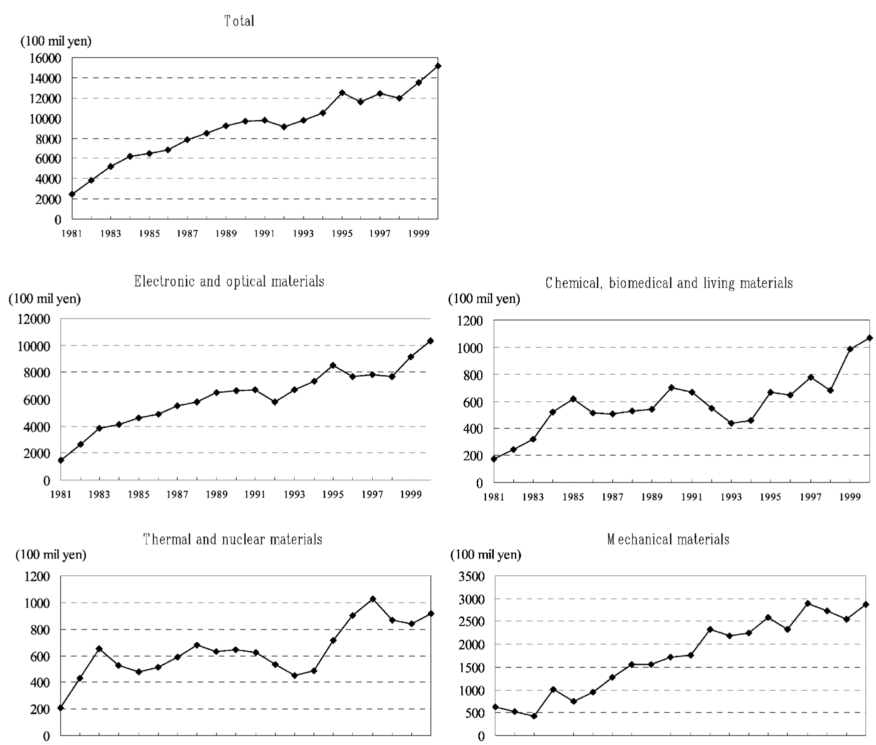

Fig. 2. Trends in domestic consumption of Japan's fine ceramics products (1981–2000): 100 mil yen at 1995 fixed prices.

Table 3
Trends in cumulative domestic consumption of fine ceramics in Japan (1981–2000): 100 mil yen at 1995 fixed prices

	Electronic and optical materials	Chemical, biomedical and living materials	Thermal and nuclear materials	Mechanical materials	Total
1981	2789	241	479	1565	5074
1982	4665	430	810	1803	7708
1983	7218	648	1297	1890	11053
1984	9374	1015	1553	2551	14493
1985	11400	1393	1706	2818	17318
1986	13081	1566	1856	3234	19737
1987	14799	1685	2041	3895	22419
1988	16252	1791	2274	4694	25011
1989	17948	1880	2401	5326	27555
1990	19178	2094	2500	5965	29737
1991	20018	2216	2553	6520	31307
1992	19581	2173	2490	7499	31744
1993	20084	2026	2353	8100	32563
1994	20970	1927	2275	8619	33791
1995	22718	2060	2437	9350	36565
1996	22939	2121	2736	9632	37428
1997	23078	2288	3076	10388	38829
1998	23075	2312	3172	10815	39374
1999	24524	2636	3218	10965	41342
2000	26701	2950	3332	11394	44377

amics in Japan over the period 1981–2000 are estimated as summarized in Table 3. Fig. 3 illustrates trends in this cumulative domestic consumption.

Looking at Table 3 and Fig. 3 we note that cumulative domestic consumption of electronic and optical materials shares more than half of Japan's whole cumulative domestic consumption and this share increases steadily from 55.0% in 1981 to 60.2% in 2000. Similar increase with respect to cumulative domestic consumption share can be observed also in chemical, biomedical and living materials (4.8% in 1981 to 6.6% in 2000). Contrary to these increases, shares of thermal and nuclear materials,

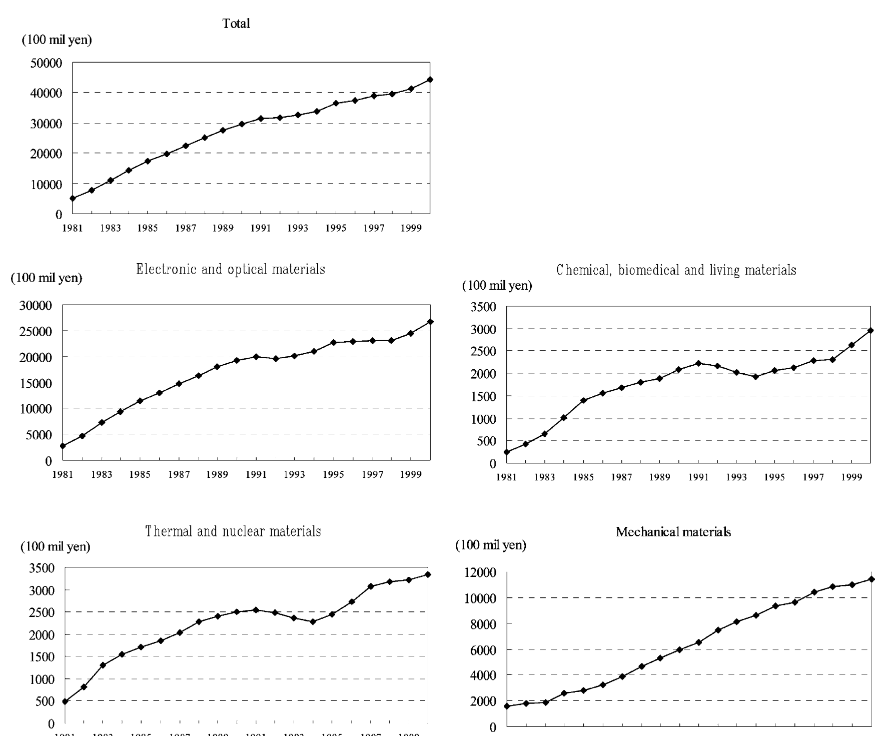

Fig. 3. Cumulative domestic consumption of fine ceramics in Japan (1981–2000).

as well as mechanical materials decreased from as 9.4% to 7.5% and 30.8% to 25.7%, respectively.

These trends suggest that the diffusion of fine ceramics in Japan has been shifting towards materials with more functional and wider perspective of utilization. This suggestion prompts us to the significance of functionality development in contrasting orbit of innovation for fine ceramics.

3. Analysis

Prompted by the foregoing observations, aiming at identifying the functionality development of fine ceramics in particular use in their diffusion process, a comparative analysis of diffusion orbits of four materials examined in the previous section is conducted.

Results of the analysis on the trends in the diffusion process of four innovations of fine ceramics over the period 1981–2000 by using logistic growth function within a dynamic carrying capacity as expressed by eq. (4)[5] in Section 2 is illustrated in Fig. 4(a–d).

Fig. 4(a–d) compare trends in number of adopters (cumulative domestic consumption) both actual (as illustrated in Fig. 3) and estimated (by eq. (4)), as well as carrying capacity measured by eq. (3) as a dynamic carrying capacity.

Looking at Fig. 4(a–d), we note the following noteworthy findings with respect to diffusion process and trends in carrying capacities of respective innovations.

3.1. Electronic and optical materials

Cumulative domestic consumption exhibited a dramatic increase in the 1980s and changed to slightly slow down, however it maintains sustainable increase over the period examined. Carrying capacity exhibits constant increase in parallel with increase in cumulative consumption.

3.2. Chemical, biomedical and living materials

While similar to the increasing trends of electronic and optical materials in the 1980s, cumulative consump-

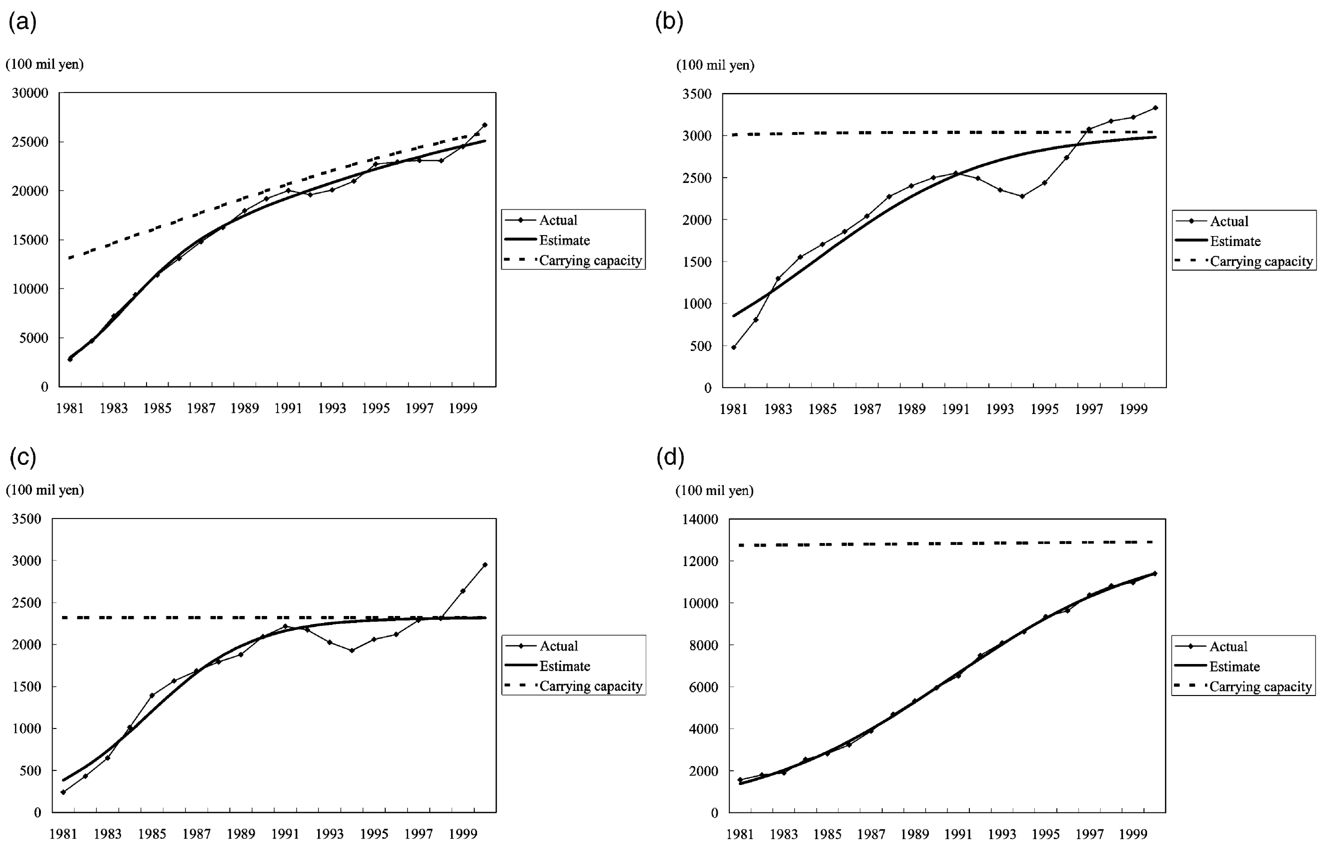

Fig. 4. (a) Trends in the diffusion process of fine ceramics for electronic and optical materials (1981–2000). (b) Trends in the Diffusion process of fine ceramics for chemical, biomedical and living materials (1981–2000). (c) Trends in the diffusion process of fine ceramics for thermal and nuclear materials (1981–2000). (d) Trends in the diffusion process of fine ceramics for mechanical materials (1981–2000).

[5] Non-linear regression analysis is conducted based on Quasi-Newton Method using numerical analysis software SHZAM (Version 9).

tion exhibited a dramatic increase in the 1980, its increasing trend changed to a stagnating trend in the 1990s leading to a saturating trend in the later half of the 1990s. This is primarily due to rise and fall the demand of oxygen sensors as well as catalysts and catalyst supports for automobiles exhaust gas purification.

Contrary to electronic and optical materials, carrying capacity displays the same level over the period examined.

3.3. Thermal and nuclear materials

Similar to the proceeding two materials, cumulative consumption exhibits a dramatic increase in the 1980s, this increase changed to decrease from the beginning of the 1990s. This decrease is considered due to the decrease in the demand of high energy efficiency and nuclear electric power. However, this decreasing trend changed to increase again from the middle 1990s reflecting the increasing demand of energy efficiency driven by increasing consciousness on the global warming. This increase was also induced by the increasing demand of ceramic components for IC production processes. Similar to chemical, biomedical and living materials, carrying capacity displays the same level over the period examined.

3.4. Mechanical materials

Contrary to the proceeding three materials, cumulative consumption increases with the same pace slightly with non-convex, and accessing to the ceiling of carrying capacity which is similar to the proceeding two materials, maintained the same level over the period examined. Slight stagnation with respect to increasing pace is observed in the latter 1990s. Allowance between the level of cumulative consumption and carrying capacity is bigger than the allowances of chemical, biomedical and living materials, as well as thermal and nuclear materials.

These observations suggest that only electronic and optical materials display dynamic charring capacity while remaining three materials display fixed carrying capacity.

4. Interpretation

Table 4 compares the fit of the logistic growth function within a dynamic carrying capacity for the diffusion process of four innovations of fine ceramics.

Looking at Table 4, we note the following findings with respect to diffusion process and trends in carrying capacities of respective innovations:

1. Table 4 demonstrates almost all indicators are statistically significant except for mechanical materials' b_K, thermal and nuclear materials' a and a_K, as well as chemical, biomedical and living materials' a and a_K.
2. The adjusted R^2 demonstrates that the logistic growth function within a dynamic carrying capacity represents the actual diffusion behavior of four innovations in the market place.
3. Parameters a_K for the later three innovations are extremely small values in comparison to the value for the first innovation (electronic and optical materials) which demonstrates that epidemic behaviors of these three innovations are similar to the behavior of simple logistic growth while an epidemic behavior of the first innovation, which demonstrates all parameters extreme fit, is similar to the behavior of logistic growth within a dynamic carrying capacity.
4. These statistics demonstrate that the epidemic behavior of the functional fine ceramics represented by the first innovation demonstrates to fit to logistic growth within a dynamic carrying capacity, while the epidemic behaviors of the structural fine ceramics represented by the later three innovation demonstrates to fit to simple logistic growth.
5. Given that logistic growth within a dynamic carrying capacity represents a diffusion process with functionality development in the diffusion process (Watanabe et al., 2001), functional ceramics demonstrate functionality development in their development and diffusion process, thereby construct self propagating orbit.

5. Conclusion

In light of the significance of the functionality development of fine ceramics as clearly demonstrated in the contrast of the development and diffusion orbit between fine ceramics in functional use and structural use, this paper analyzed diffusion orbit of four major fine ceramics in Japan over the last two decades.

On the basis of an empirical analysis using logistic growth function within a dynamic carrying capacity it was demonstrated that while a carrying capacity of the fine ceramics for functional use as electronic and optical materials has been increasing as their consumption increases, notwithstanding increase in their consumption, carrying capacities of fine ceramics for structural use as mechanical materials, thermal and nuclear materials, as well as chemical, biomedical and living materials have not increased. This contrast suggests the structural sources of prospecting development in functional fine ceramics and stagnation of structural fine ceramics.

As logistic growth function within a dynamic carrying capacity suggests, sustainable growth of electronic and optical materials can be attributed to a virtuous cycle between functionality development and demand

Table 4
Comparison of the fit of logistic growth function within a dynamic carrying capacity for the diffusion process of four innovations of fine ceramics (1981–2000)

K_K	a	b	a_K	b_K	adj. R^2	DW
Electronic and optical materials						
31450	14.927	0.637	1.543	0.099	0.993	1.16
(19.53)	(4.28)	(7.09)	(7.72)	(5.43)		
Chemical, biomedical and living materials						
2320	7.686	0.424	1.220E-05	0.422	0.910	0.43
(29.64)	(0.23)	(5.13)	(1.33E-04)	(1.98)		
Thermal and nuclear materials						
3041	1.614	0.254	0.014	0.252	0.899	0.37
(16.49)	(0.13)	(3.78)	(0.10)	(4.16)		
Mechanical materials						
13974	11.176	0.219	0.097	0.008	0.999	2.25
(183.35)	(24.98)	(33.39)	(1.54)	(0.26)		

increase. Dynamic carrying capacity increases together with increase of the level of cumulative consumption of fine ceramics as time goes by. Increase in carrying capacity induces further increases in cumulative consumption which in turn activates interactions with further qualified production leading to an increase in potential customers by increasing the value and function similar to network externalities typically observed in IT functionality development. This dynamism ultimately constructs a self propagating structure. Success of electronic and optical materials can be really attributed to this structure.

This success in functional fine ceramics prompts us to the strategic direction of structural fine ceramics towards break through of stagnating cycle by incorporating functionality development mechanism. One noteworthy observation can be obtained in a rapid development of ceramic components for IC production processes. Although these components are classified in thermal and nuclear materials, stimulated by a synergy between their original functions as heat resisting materials and additional function including chemical durability, a virtuous cycle has been constructed similar to electronic and optical materials. This suggests a key direction how to active potential functionality incorporated also in structural materials.

Further study is, therefore, expected to be focused on an in depth analysis aiming at identifying potential functionality, in each respective fine ceramics, and explore development strategy towards constructing self propagating structure identical to respective materials.

Appendix. Mathematical development of logistic growth function within a dynamic carrying capacity

Simple logistic growth function is expressed as follows:

$$\frac{df(t)}{dt} = bf(t)\left(1-\frac{f(t)}{K}\right) \tag{A1}$$

Given that innovation itself and the number of potential users change through the diffusion of innovation, logistic growth function within a dynamic carrying capacity is expressed by eq. (A2) where the number of potential users, carrying capacity (K) in the epidemic function is subject to a function of time t.

$$\frac{df(t)}{dt} = bf(t)\left(1-\frac{f(t)}{K(t)}\right) \tag{A2}$$

Eq. (A3) is obtained from eq. (A2):

$$\frac{df(t)}{dt} + (-b)f(t) = \left(-\frac{b}{K(t)}\right)\{f(t)\}^2 \tag{A3}$$

Eq. (A3) corresponds to the Bernoulli's differential equation expressed by eq. (A4):

$$\frac{dy}{dx} + V(x)y = W(x)y^n \tag{A4}$$

Accordingly, eq. (A3) can be transformed to the linear differential equation expressed by eq. (A5):

$$\frac{dz(t)}{dt} + bz(t) = \frac{b}{K(t)} \text{ where } z(t) = \frac{1}{f(t)} \tag{A5}$$

The solution for a linear differential eq. (A6) can be obtained as eq. (A7):

$$\frac{dy}{dx} + P(x)y = Q(x) \tag{A6}$$

$$y = \exp(-\int P(x)dx)\cdot\{\int(Q(x)\cdot\exp(\int P(x)dx))dx + c\} \tag{A7}$$

Accordingly, the solution for eq. (A5) can be expressed as follows:

$$\begin{aligned} z(t) &= \exp(-\int bdt)\cdot\left\{\int\left(\frac{b}{K(t)}\exp(\int bdt)\right)dt + c_1\right\} \\ &= \exp(-bt)\cdot\left\{b\int\left(\frac{1}{K(t)}\exp(bt)\right)dt + c_1\right\} \end{aligned} \tag{A8}$$

$$\frac{1}{f(t)} = \exp(-bt)\cdot\left\{b\int\left(\frac{\exp(bt)}{K(t)}\right)dt + c_1\right\} \tag{A9}$$

Assume that a carrying capacity $K(t)$increases sigmoidally, $K(t)$is expressed as follows:

$$K(t) = \frac{K_K}{1 + a_K\exp(-b_K t)} \tag{A10}$$

By substitution eq. (A10) for $K(t)$ in eq. (A9), eq. (A11) is obtained:

$$\frac{1}{f(t)} = \left\{b\int\left(\frac{\exp(bt)}{K_K/(1 + a_K\exp(-b_K t))}\right)dt + c_1\right\}\exp(-bt) \tag{A11}$$

where

$$\begin{aligned} &\int\left(\frac{\exp(bt)}{K_K/(1 + a_K\exp(-b_K t))}\right)dt \\ &= \frac{1}{K_K}\int\{\exp(bt) + a_K\exp((b-b_K)t)\}dt \\ &= \frac{1}{K_K}\{\int\exp(bt)dt + \int a_K\exp((b-b_K)t)dt\} \\ &= \frac{1}{K_K}\left\{\frac{1}{b}\exp(bt) + \frac{a_K}{b-b_K}\exp((b-b_K)t)\right\} + c_2 \end{aligned} \tag{A12}$$

Accordingly, $f(t)$ can be developed as follows:

$$\begin{aligned} \frac{1}{f(t)} &= b\left\{\frac{1}{K_K}\left\{\frac{1}{b}\exp(bt) + \frac{a_K}{b-b_K}\exp((b-b_K)t)\right\} + c_2 + c_1\right\}\cdot\exp(-bt) \\ \frac{1}{f(t)} &= \frac{1}{K_K}\left\{1 + \frac{b\cdot a_K}{b-b_K}\exp(-b_K t) + c_3\exp(-bt)\right\} \\ \frac{1}{f(t)} &= \frac{1}{K_K}\left\{1 + c_3\exp(-bt) + \frac{b\cdot a_K}{b-b_K}\exp(-b_K t)\right\} \end{aligned} \tag{A13}$$

$$f(t) = \frac{K_K}{1 + a\exp(-bt) + \frac{b\cdot a_K}{b-b_K}\exp(-b_K t)} \tag{A14}$$

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