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FGM activities in Japan

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The concept of functionally graded materials (FGMs) was proposed in 1984 by materials scientists in the Sendai area as a means of preparing thermal barrier materials. Continuous changes in the composition, microstructure, porosity, etc. of these materials results in gradients in such properties as mechanical strength and thermal conductivity. In 1987, a national project was initiated entitled 'Research on the Basic Technology for the Development of Functionally Gradient Materials for Relaxation of Thermal Stress'. In 1992 when the project was finished, samples of 300 mm square shell and 50 mm diameter hemispherical bowls for SiC–C FGM nose cones were prepared. The concept of FGMs is of interest not only in the practical design of super refractory materials, but also in the development of various functional materials. In 1993, the second national project was initiated for the research and development of FGMs as functional materials; 'Research on Energy Conversion Materials with Functionally Gradient Structure'. This program aims to apply functionally graded structure technology to the improvement of energy conversion efficiency. The project will continue until the fiscal year 1997. © 1997 Elsevier Science Limited. All rights reserved

(Keywords: Functionally gradient materials (FGMs); heat-shielding structural materials; space-planes; energy conversion materials; high-efficiency hybrid conversion system (HYDECS); FGM thermoelectric and thermionic materials)

INTRODUCTION

The concept of functionally gradient materials (FGMs) was proposed in 1984 by material scientists in the Sendai area in Japan as a means of preparing thermal barrier materials. Since then, an effort to develop high-performance heat-resistant materials using functionally gradient technology had been continued. In recent years, another attempt to apply the FGM concept to the enhancement of energy conversion efficiency has been initiated under the auspices of the Agency of Science and Technology (STA), Japanese Government. This paper provides an overview of these activities as well as some comments on future developments in this rapidly developing area of materials research.

NATIONAL PROJECT FOR R&D OF FGMs AS HIGH-TEMPERATURE STRUCTURAL MATERIALS (FGM Part I)

In the fiscal year 1987, a national project was initiated under the title 'Research on the Basic Technology for the Development of Functionally Gradient Materials for Relaxation of Thermal-Stress', commonly referred to as 'FGM Part I', under the auspices of STA. The aim of the project was to develop advanced heat-shielding structural materials for future space programs. Scientists from 17 governmental research institutes, universities, and companies have been engaged in this project.

In general, the highest temperature on the surface of space-planes is estimated to reach 2100 K. Hence, materials at the surface must withstand temperatures as high as 2100 K and temperature differences of 1600 K. Currently, no industrial materials are known that can withstand such severe thermomechanical loadings.

The unique idea of a FGM was proposed to prepare a new composite by using heat-resistant ceramics on the high-temperature side and tough metals with high thermal conductivity on the low-temperature side, with a gradual compositional variation from ceramic to metal. FGMs are therefore composite materials with a microscopically inhomogeneous character. Continuous changes in their microstructure distinguish FGMs from conventional composite materials. The continuous change in composition results in gradients in the properties of FGMs. The differences in microstructure and properties between FGMs and conventional composite materials are illustrated schematically in *Figure 1*[1].

The project activity has been conducted by three working groups: Materials design/data base, Processing, and Evaluation. By closely coordinating all activities,

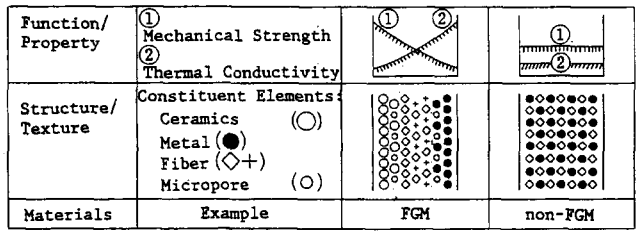


Figure 1 Characteristics of FGMs

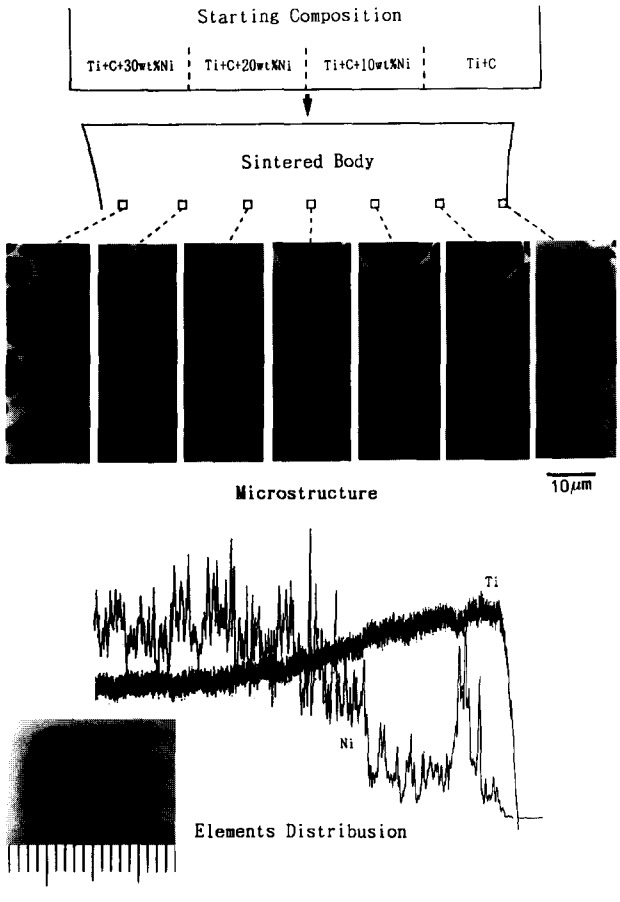


Figure 2 Microstructure and element distribution of TiC–Ni FGM with Ni composition between 0.10 and 30 wt%[7]

these groups have promoted research and development of FGMs.

Four methods such as CVD/PVD, powder metallurgy, plasma sprays, and self propagating combustion synthesis (SHS), have been employed to give the gradient in composition and structure.

Several representative FGMs obtained using these different methods in the earlier stage of Part I of the project were: SiC/C FGM (CVD)[2], PSZ/SUS 304 FGM (powder metallurgy)[3], Ni-base alloy/ZrO_2 FGM (plasma spraying)[4,5], and TiB_2/Cu and TiC/Ni FGMs (SHS)[6,7], *Figure 2* shows the microstructure and element distribution of this TiC–Ni FGM.

In this project the evaluation technologies for thermal shock, fatigue resistance and thermomechanical properties were developed. Material testing in the environment to which space-planes are exposed was also carried out to evaluate comprehensively the FGMs to be used as a super heat-resistant material.



Figure 3 300 mm square shell of SiC–C FGM prepared by Sumitomo Electric Industries

The goal of Part I of the FGM project (fiscal years 1987–91) was to fabricate larger FGM test pieces having complicated shapes. The production of FGMs, such as 300 mm square shells to be used for the base of the fuselage of space-planes and 50 mm diameter hemispherical bowls for nose-cones, etc. was undertaken with success. In *Figure 3*, a sample of 30 mm square shell of SiC–C FGM prepared by the CVD method is shown.

NEW PROJECT OF FGMs AS ENERGY CONVERSION MATERIALS (FGM Part II)

The concept of FGMs is of interest not only in the practical design of super refractory materials to be used for space-planes of the future, but also in the development of various functional materials, such as optic and/or electronic materials.

To extend the application of FGMs to different fields of industry, in 1990 the needs of FGM were surveyed among users of materials under the sponsorship of the FGM Forum, which was established among FGM scientists in 1988. Through this survey, about 200 possibilities for utilizing the FGM concept to improve conventional materials and to create new materials were proposed. The report summarizing these proposals was published in the spring of 1991[8].

On the basis of the report, FGM scientists investigated the various applications of the FGM concept to functional materials through a national project entitled 'Feasibility Study on the R&D of FGMs as Function Conversion Materials' under the auspices of STA during the fiscal year of 1992. About 30 scientists from different organizations including the Atomic Energy Laboratory, Hitachi and Sanyo have been engaged in this project.

The surveys were focused on the possibility of improving the efficiency of energy conversion materials by FGM technology. The results revealed that gradient technology would remarkably increase efficiency for photoelectric, thermoelectric, thermionic and nuclear energy conversions[9].

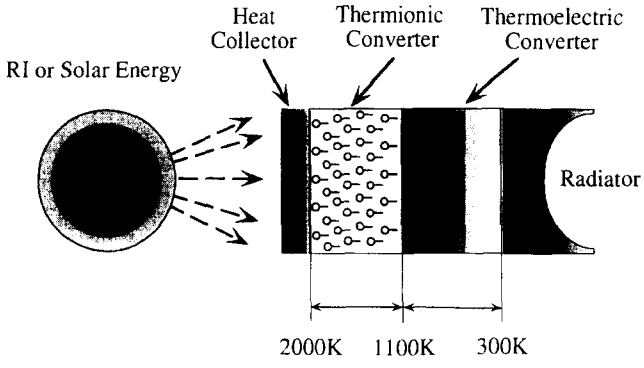


Figure 4 Energy-conversion forms covered by Part II of the FGM project[10]

Based on these results, a new national project entitled 'Research on Energy Conversion Materials with Functionally Gradient Structure', commonly referred to as 'FGM Part II', was initiated in fiscal year 1993, with the special coordination funds for promoting science and technology. More than 30 organizations—industrial, governmental and academic—joined forces.

Figure 4[10] shows the energy conversion forms covered by this research project. Solar and nuclear energies are considered as the sources of energy in view of the possible extensive application of the expected technological achievements. Radioactive isotope (RI) heat source is chosen as the nuclear energy, from the viewpoint of the ease of technical development involved.

As for the utilization of thermal energy, solar light and RI energy are converted to heat at the heat-collecting section, as shown in the right-hand section of *Figure 4*. As a final goal, this program will proceed to develop a high-efficiency hybrid conversion system (HYDECS) using different converters adopted for different temperature ranges: thermionic elements at a high temperature of 2000 K, thermoelectric elements at a lower temperature of 1400 K and a heat radiator at a temperature below around 300 K.

As an example of new FGM applications, let me introduce FGM thermoelectric materials. The efficiency of thermoelectric power generation is in proportion to the extent of temperature difference between hot- and cold-junctions. In the case of homogeneous materials, the figure of merit (Z) exhibits a curved distribution like the curves a, b, c, d and e shown in *Figure 5*[11]. Such a Z–T curve shifts with temperature as the carrier concentration varies. Therefore, if a thermoelectric material is supplied with a distribution of carrier concentration, it will become possible to obtain a high performance index over a wide temperature range, as shown by the dashed line in *Figure 5*.

Another approach to improve the thermoelectric conversion efficiency is to join different thermoelectric materials by FGM technique to extend the usable temperature range. Such composite thermoelectric materials are called FGM-segmented thermoelectric materials. *Figure 6* shows the total effect of both FGM-segmenting technique and carrier concentration FGM technique[10].

The FGM technique is expected to be useful for energy

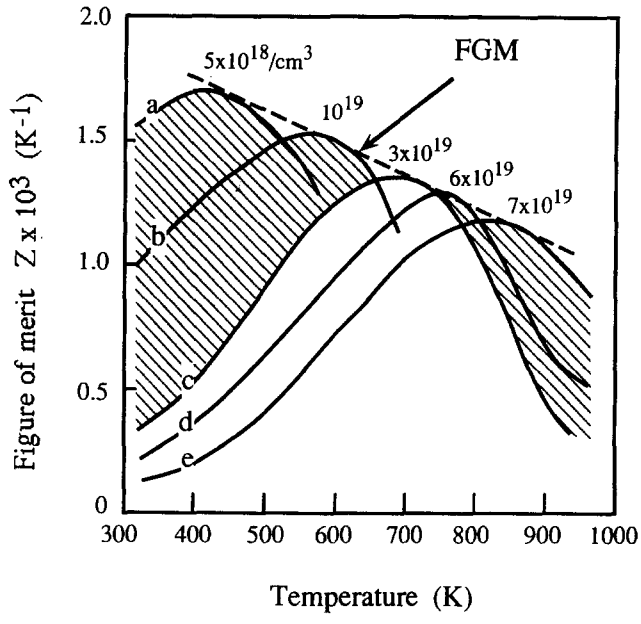


Figure 5 Figure of merit for n-type PbTe with various carrier concentration and the carrier controlled functionally gradient materials (FGM)[11]

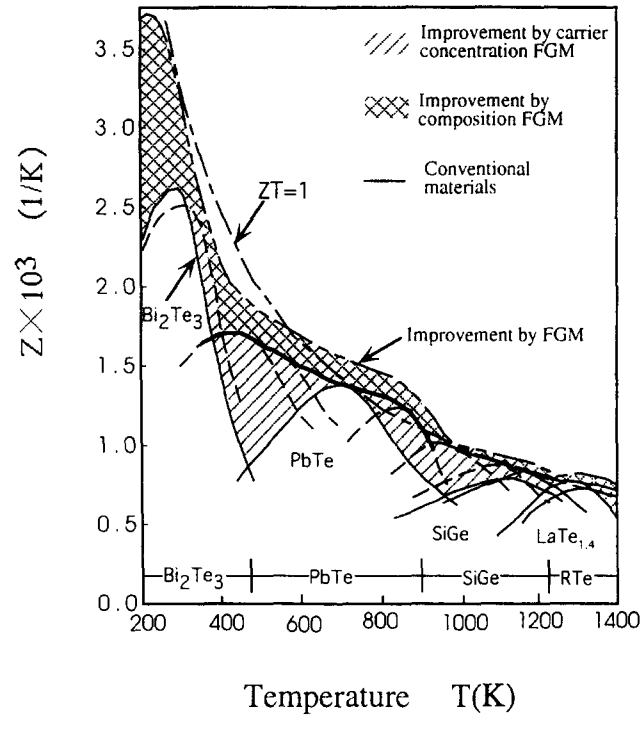


Figure 6 Theoretically estimated increment of figure of merit for thermo-electrics through the use of FGMs[10]

conversion materials. The FGM thermoelectric and thermionic materials are now being successfully fabricated. This program is to be completed in March, 1998.

FUTURE DEVELOPMENT OF FGMs

As mentioned before, the national project for R&D of FGMs as high-temperature structural materials, 'FGM Part I', was fruitfully completed in March, 1992. The

practical implementation of the results in aircraft and space vehicles is being attempted cooperatively by the National Aerospace Laboratory (NAL) and the National Space Development Agency of Japan (NASDA).

The hybrid conversion system to be developed in Part II will inevitably be exposed to the temperature difference of 1700 K. This figure exceeds what was set for the former FGMs project developed for the relaxation of thermal stresses, in which the goal was set at developing materials for the use in thermal environments at temperatures up to 2000 K and temperature difference as large as 1000 K. Part II of the FGM project, which focuses on the hybrid energy conversion system, calls for the provision of a gradient in 'function'. The materials for Part II are required to demonstrate full properties as 'functional' materials, in addition to the properties of 'structural' materials that can withstand the thermal stresses arising from large temperature differences. In this way, the fusing of function and structure in materials' R&D is expected to evolve into a new research area in the process of the promotion of the present FGMs project.

ACTIVITIES OF THE FGM FORUM AND IACFGM

The organizations engaged in the afore-mentioned national projects from both academic and industrial sectors were limited in number. Therefore, 'Functionally Gradient Materials Forum' was established in February 1988, in order to disseminate the activities of the national projects to the public and to conduct a survey of the possible application of FGMs in creating other structural and functional materials. The forum has continued to hold symposia and workshops, and to publish bulletins. Forum members include representatives from 49 companies and 86 individuals as of February, 1996.

The first international symposium on FGMs was held in Sendai in October 1990, under the sponsorship of the forum[12] followed by the 2nd in San Francisco, 1992, and the 3rd in Lausanne, 1994. The next will be held in Tsukuba Science City north of Tokyo in 1996.

During the Sendai symposium, the International Advisory Committee of FGM (IACFGM) was founded to promote R&D of FGMs on an international basis.

The progress of FGM research in Japan during the past ten years is summarized in *Table 1*.

Table 1 Progress of FGM research in Japan during the past ten years

Year	Progress of FGM research
1984	Original concept by Dr Niino and other material scientists in Sendai area, Japan
1986	Feasibility study on 'The basic technology for the development of functionally gradient materials for relaxation of thermal-stress' under the auspice of Science and Technology Agency (STA)
1987–89	National project 'Research on the basic technology for the development of functionally gradient materials for relaxation of thermal-stress', FGM PART I—Phase 1
1988	Functionally Gradient Materials Forum (FGMF). 1st FGM Symposium organized by FGMF
1989	Germany–Japan FGM Seminar in Köln, Germany
1990	1st International Symposium on FGM in Sendai, Japan. International Advisory Committee of FGM (IACFGM)
1990–91	FGM PART I—Phase 2
1992	Feasibility study on R & D of FGMs as functional materials under the auspice of STA. 2nd International Symposium on FGM and Japan–Germany–USA International Workshop in San Francisco, USA
1993	National project 'Research on energy conversion materials with functionally gradient structure' FGM PART II—Phase 1
1994	3rd International Symposium on FGM in Lausanne, Switzerland
1995	Japan–Russia–Ukraine Workshop on Energy Conversion Materials (ENECOM-95) in Sendai
1996	4th International Symposium on FGM in Tsukuba Science City, Japan

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