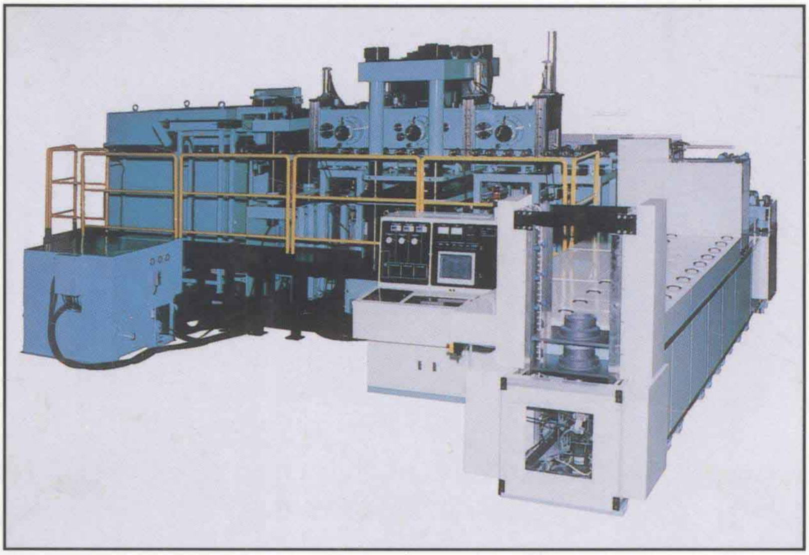
FUNCTIONALLY GRADED MATERIALS IN THE 21ST CENTURY

A Workshop on Trends and Forecasts



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Kiyoshi Ichikawa

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Kiyoshi Ichikawa
Mechanical Engineering Laboratory
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Japan

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FUNCTIONALLY GRADED MATERIALS IN THE 21ST CENTURY

A Workshop on Trends and Forecasts

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Preface

I am honored to chair this International Workshop on Functionally Graded Materials in the 21st Century: A Workshop on Trends and Forecasts, and would like to first express my sincere gratitude to everyone participating. The Mechanical Engineering Laboratory and the Japan International Science and Technology Exchange Center (JISTEC) have co-organized this workshop with the sponsorship of the Science and Technology Agency of Japan and the cooperation of the Association of Mechanical Technology. This workshop is an international conference to focus on functionally graded materials and the aim is to provide an overview of the present global technical trends and the future development of functionally graded materials over the next 10 years. I am very happy to see many researchers meeting together here — including seven researchers invited from abroad. During the three-day oral sessions, 36 research reports will be presented, and I'm sure I'm not the only one who is very anxious to hear and participate in the upcoming interesting discussions.

At present, the Mechanical Engineering Laboratory is conducting fundamental and ground-breaking research in such major areas as materials science and technology, bioengineering, information & system science, advanced machine technology, energy technology, manufacturing technology and robotics.

In particular, we consider research on materials science and technology to have the highest priority for the 21st century, and since 1996 have participated in the US-Japan joint research project, *Precompetitive Processing and Characterization of Functionally Graded Materials*.

The Mechanical Engineering Laboratory of Japan and the US National Institute of Standards have been carrying out this 4-year joint research project to produce and evaluate new functionally graded materials using spark plasma sintering. In Japan, Sumitomo Coal Mining Group, Izumi Technology, Co. Ltd. and Yanmar Diesel Engine Co. have joined the project. This joint research focuses on production of large-scale functionally graded material composites of a metal with high mechanical strength and a ceramic with high heat-resistance and high-wear resistance.

At present, international conferences related to functionally graded materials are being held all over the world, and many notable research achievements in processing and evaluation have been reported.

In light of the current development efforts on functionally graded materials at research institutes throughout the world, the objective of this workshop is to provide researchers an opportunity to present their respective accomplishments and exchange valuable information with their colleagues in the field.

I hope you all will benefit from the wide array of presentations scheduled for the workshop, including those on FGMs for modeling and simulation, coating, bulk processing, properties and characterization. I also hope you will discuss the value and necessity of continuing to hold workshops such as this one, and I hope this workshop will be the start of many more to come. I would like to conclude my address by once again thanking everyone here for your participation.

Dr. Naotake Ooyama
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Contents

Chapter 1

INTRODUCTION

1. STATE OF THE ART

1.1 Introduction

Direct bonding of metals and ceramics can generate thermal stresses in practical high-temperature applications which are due mainly to CTE mismatches. The thermal stress causes crack formation, debonding at hetero-interfaces and often results in delamination of the ceramic over-layer. A graded interlayer concept for metal/ceramic bonding was first proposed by Kawasaki and Watanabe [1], in which the thermal stress was effectively eliminated by a compositionally graded interlayer. Such graded materials possess simultaneously a super-heat-resistant property and sufficient toughness to arrest crack propagation. This concept was given the name of functionally gradient material (FGM) [2] and was originally applied to create the fuselage exterior and engine materials for space planes which would take off like airplanes, cruise at Mach 5 to 25 in the atmosphere subject to severe frictional heating from the airflow. Optimal response of material properties to conditions in an actual environment is the main requirement in the design of FGMs. To fulfill this requirement the composition and microstructure are varied throughout the structure, and this yields a property gradient within the combined materials. The FGM concept was also applied to improve the figure of merit of thermoelectric materials. In this case the carrier concentration is graded by finely control the doping element concentration, thus causing a wide temperature range with a high figure of merit [3]. The most remarkable difference between FGMs and conventional homogeneous materials lies in their needs-oriented materials design and non-homogeneous microstructural control. Such a concept is applicable to functional materials in various fields, wherein several functions are incorporated in a single material or new functions are expected to appear due to the compositionally graded structure [4]. Another significant advance in FGM research was brought about by the recently finished Physics and Chemistry of Functionally Graded Materials project (FY 1996-1998) supported by Japan's Ministry of Education. A great variety of processing approaches were proposed to manifest various material functions, and they included the sol-gel method, infiltration, polymerization, substitution reaction, eutectic phase reaction, electropholetic method, hydrothermal-electrochemical method, and molten salt reaction. Table 1.1 is a summary of the research topics in the project, which cover physical, chemical, agricultural and medical functions [5]. Not only composition as in conventional usage but also various microstructural features and electronic structures were graded, and the modifications of the material properties were investigated in detail.

Table 1.1. Research categories and number of topics in the Monbusho Project (1996-1998), Physics and Chemistry of Functionally Graded Materials.

Theme \ Year			1996	1997	1998
Physical function	Single function	Theory	3	3	2
		Mechanical	7	6	6
		Electrical	9	7	4
		Magnetic	5	6	3
		Optical	4	7	4
	Multi-function	Thermal - Electrical	5	5	5
		Electrical - Magnetic	1	1	1
		Magnetic - Optical	1	1	1
		Electrical - Optical	4	4	5
		Electrical - Strain	2	2	1
Chemical function		Chemical reaction	8	8	6
		Catalyst and sensor	4	4	1
		Separation film	3	1	1
		Corrosion resistance	1	4	2
		Battery	3	1	2
Agricultural function			3	3	2
Medical function			5	9	6

In this section several typical examples of successful applications of the FGM concept are briefly reviewed, and the results of research on the design and processing of FGMs from the recently completed Monbusho Project [5] are given, in which some selected topics with well-defined design concepts are described in further detail.

1.2 Practical Application Examples

1.2.1 Thermal Barrier/Anti-Oxidation Coatings

Refractory ceramics are coated on a metallic substrate by inserting a graded interlayer to assure good bonding between the two materials and to reduce the thermal stresses that would otherwise be generated due to large CTE mismatches at the interfaces. Zirconia coating on a nickel-chromium alloy substrate by plasma spraying [6] and SiC coating on C/C composites by CVD [7, 8] are typical examples of practically applied FGM coatings. The composition profiles of the graded interlayer are carefully controlled to optimum compositional profiles that will give the least stress generation. In these cases the requirements are fulfilled for the heat-resistant and oxidation-resistant properties, as well as for adequate mechanical toughness. The FGM coating will be used for gas turbine blades in power generators to improve combustion efficiency, and will surely be one of the most important technologies for saving energy in near future, thus helping to lower emissions into the environment. Long thermal fatigue life is presently an emerging subject to be investigated in these FGM coatings. The basic mechanism of crack formation and propagation leading to the delamination of the overlayer has been clarified by Kawasaki and Watanabe [9] through burner heating test results and by the fracture mechanical approach. The thermal fatigue properties of thermal barrier coatings have been extensively investigated worldwide [10-12].

1.2.2 Cutting Tools: Cemented Carbides

Sumitomo Electric Industries Ltd. developed FGM cemented carbide with improved wear resistance and long tool life [13]. In this example TiCN-WC-Co-Ni alloy is sintered in a controlled nitrogen atmosphere and at a controlled cooling rate to create a TiC-TiCN-WC graded microstructure with Co as a binder phase. The uppermost TiC Phase is a harder phase and has a good anti-wear property and the inner WC-rich phase has good toughness. The surface region itself contains no Co binder but the binder content increases from just beneath the TiC overlayer towards the inner region. This causes a CTE gradation in the surface region, generating compressive stress in the TiC overlayer that enhances fracture toughness and prolongs tool life.

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