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Evaluation of Thermophysical Properties of Functionally Graded Materials[1]

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In this work, by considering four-layered functionally graded material (FGM) specimens of Cu/Ni and PSZ/NiCrAlY, the transient characteristics and homogeneity of heat conduction media have been studied. The thermal diffusivities of the considered specimens have been measured by the laser flash method. As the temperature response curve of a FGM is very similar to that of a homogeneous material, it is difficult to distinguish a FGM from a homogeneous material by the shape of the temperature responses. Therefore, the thermal diffusivity obtained from the half-time method is usually taken as the corresponding value of the thermal diffusivity. The apparent thermal conductivity, obtained from the corresponding value of the thermal diffusivity and the average of the heat capacity of each layer, is different from the effective thermal conductivity, obtained from the sum of the heat resistances of each layer. As the values of the heat capacity of materials exist over a certain range, and the heat capacity distribution can be predicted when the materials in a FGM are known, the amount of error that will be caused when the effective thermal conductivity is replaced by the apparent value can be determined. Also, the heterogeneity of a FGM, based on an evaluation of thermophysical properties, has been discussed.

KEY WORDS: apparent thermal conductivity; effective thermal conductivity; functionally graded material (FGM); temperature response in a composite; thermal diffusivity.

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1. INTRODUCTION

Used as advanced heat-shielding/structural materials in space applications and the electronics industry, functionally graded materials (FGM) have attracted wide interest in the fields of material sciences as well as thermal and mechanical engineering. The evaluation of their mechanical and thermophysical properties has become essential in these fields. Generally, transient methods with pulse or stepwise heating are used for this work due to their simplicity and their advantages at high temperature. The present group has investigated the evaluation methods of thermophysical properties of FGMs since the beginning of the 1990s, especially using transient methods. A general solution for the temperature responses in multi-layered material [1] and a FGM [2, 3] was derived. Then, according to these solutions, a simplified method for estimating the property distribution inside a FGM was suggested [4]. The theoretical analysis has been compared with experimental results for FGM samples. Also, transient characteristics of heat conduction and homogeneity of dispersed composites were studied theoretically and experimentally [5, 6]. However, for FGMs, no further work has been found in the literature on the effect of their heterogeneity on the evaluation of thermophysical properties by transient methods.

The laser flash method [7] has been the most widely used transient method for measuring the thermal diffusivity. In this method, since the temperature response curve of a FGM is very similar to that of a homogeneous material, it is difficult to distinguish a FGM from a homogeneous material by the shape of the temperature responses [8]. Therefore, the thermal diffusivity obtained from this method is usually taken as the corresponding value of thermal diffusivity. The apparent thermal conductivity, obtained from the corresponding value of thermal diffusivity and the average of the heat capacity of each layer, takes a different value from the effective thermal conductivity obtained from the sum of the heat resistances of each layer. As the values of the heat capacity of materials exist over a certain range, and the heat capacity distribution can be predicted when the materials in a FGM are known, the amount of error resulting from the use of the effective thermal conductivity compared to the apparent value can be determined.

In this work, by considering four-layered FGM specimens of Cu/Ni and PSZ/NiCrAlY, the transient characteristics and homogeneity of heat conduction media have been studied. The thermal diffusivities of the considered specimens are measured by the laser flash method. The apparent thermal conductivities are obtained from the measured value of the thermal diffusivity and the averages of the heat capacity of each layer. The difference between this apparent value and the effective value obtained from the sum of heat resistances of each layer is paid special attention. And the error resulting from the use of the effective thermal conductivity instead of the apparent value is discussed. An evaluation method for the thermophysical properties of an FGM is suggested.

2. TEMPERATURE RESPONSES OF FGM BY THE LASER FLASH METHOD

2.1. Cu/Ni FGM Specimens

The temperature response of a Cu/Ni FGM specimen by the laser flash method is shown in Fig. 1. It can be seen that the temperature response curve of a FGM is very similar to that of a homogeneous material. Considering the FGM specimen as a homogenous material, its thermal diffusivity can be obtained by Parker's formula as $1.38 \times 10^{-5}\,m^2 \cdot s^{-1}$ [8]. The thermophysical properties of the layers of a four-layered material with their thicknesses are listed in Table I, which have been determined by considering each separate layer of a metal or alloy [8]. Using the measured properties of the layers, the temperature responses of the composites can be calculated by an analytical solution for multi-layered materials [1–3]. Then by using the half-time from this result and Parker's formula, the corresponding

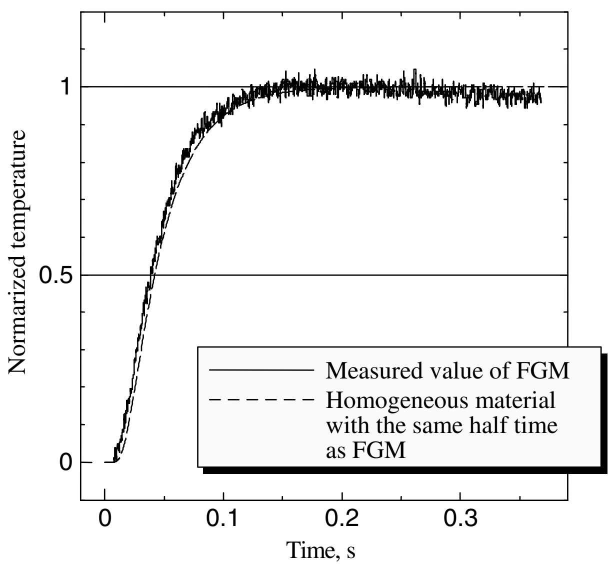

Fig. 1. Temperature response of FGM (Cu/Ni specimen, measured result).

Table I. Thermophysical Properties of Each Layer (Cu/Ni Specimen)

	Layer 1	Layer 2	Layer 3	Layer 4	
X	Cu100	Cu80-Ni20	Cu20-Ni80	Ni100	(mass %)
l	0.51	0.51	0.52	0.48	(mm)
ρ	8880	8884	8895	8899	(kg·m^{-3})
c	0.409	0.377	0.424	0.446	(kJ·kg^{-1}·K^{-1})
ρc	3635	3348	3774	3965	(kJ·m^{-3}·K^{-1})
a	6.58×10^{-5}	1.05×10^{-5}	8.84×10^{-6}	2.20×10^{-5}	(m^2·s^{-1})
λ	239.2	35	33.4	87.1	(W·m^{-1}·K^{-1})

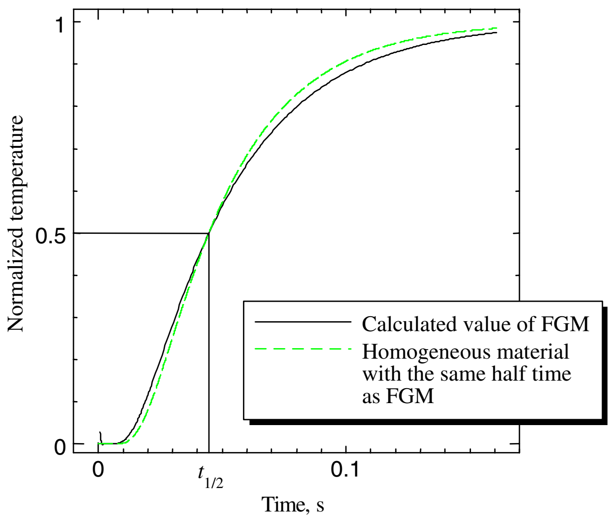

Fig. 2. Temperature response of FGM (Cu/Ni specimen, calculated result).

temperature response considering the specimen as a homogeneous material can be obtained. The calculated results are shown in Fig. 2. And the difference ΔV in the temperature responses of the four-layered FGM and its corresponding homogeneous material is shown in Fig. 3, which is obviously very small.

In Fig. 2, the two temperature responses are so close to each other that it is difficult to distinguish the FGM from the homogeneous material, especially considering the experimental noise in the measured result as shown in Fig. 1. Thus, it is significant that the thermal diffusivity of a FGM is obtained by the half-time method for a homogeneous material.

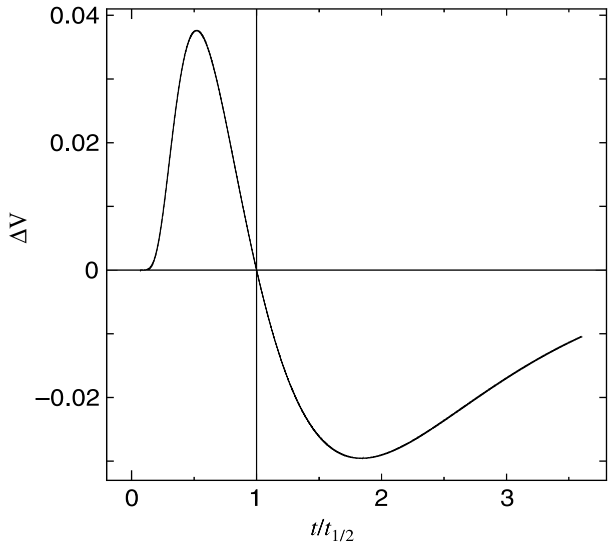

Fig. 3. Difference between two temperature responses (Cu/Ni specimen).

And this value is called the corresponding thermal diffusivity of an FGM, which is expressed by a_c.

2.2. PSZ/NiCrAlY FGM Specimens

The temperature response of a PSZ/NiCrAlY FGM specimen by the laser flash method is shown in Fig. 4. In this case, although the process is much slower then that shown in Fig. 2, the temperature response is still very similar to that of a homogeneous material. Then by the half-time method, the thermal diffusivity can be obtained as $1.67 \times 10^{-6}\ m^2{\cdot}s^{-1}$. The thermophysical properties in each layer of a four-layered material are listed in Table II along with the thicknesses of the layers. Using these properties, the temperature responses of the composites can be calculated by an analytical solution for multi-layered materials [1–3]. Then by using the half-time from this result and Parker's formula, the corresponding temperature response considering the specimen as a homogeneous material can be obtained. The calculated results are shown in Fig. 5. And the difference ΔV in the temperature responses of the four-layered FGM and its corresponding homogeneous material is shown in Fig. 6. It can be seen that the difference is smaller than that in Fig. 3 and the two temperature curves are almost the same.

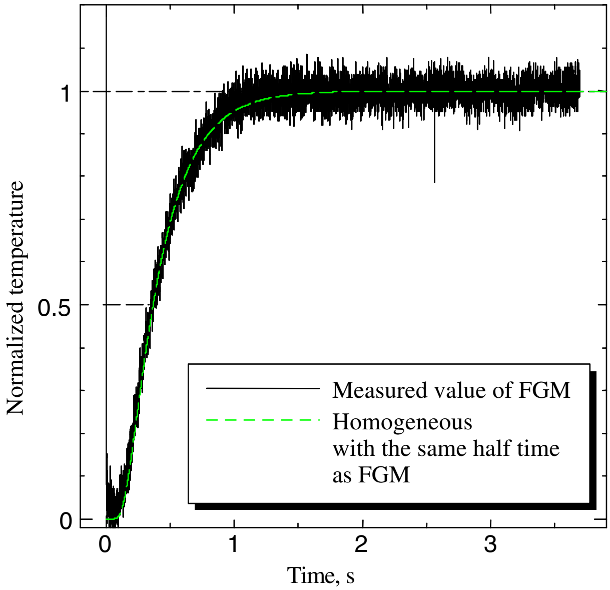

Fig. 4. Temperature response of FGM (PSZ/NiCrAlY specimen, measured result).

Table II. Thermophysical Properties of Each Layer (PSZ/NiCrAlY Specimen)

	Layer 1	Layer 2	Layer 3	Layer 4	
X	PSZ100	PSZ80-NiCrAlY20	PSZ20-NiCrAlY80	NiCrAlY100	(mass %)
l	0.52	0.52	0.52	0.52	(mm)
ρ	6016	6166	6797	7283	$(\mathrm{kg{\cdot}m^{-3}})$
c	0.460	0.494	0.460	0.458	$(\mathrm{kJ{\cdot}kg^{-1}{\cdot}K^{-1}})$
ρc	2768	3044	3128	3336	$(\mathrm{kJ{\cdot}m^{-3}{\cdot}K^{-1}})$
a	1.03×10^{-6}	1.17×10^{-6}	2.66×10^{-6}	3.93×10^{-6}	$(\mathrm{m^2{\cdot}s^{-1}})$
λ	2.86	3.56	8.31	13.11	$(\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}})$

3. EFFECTIVE AND APPARENT THERMAL CONDUCTIVITIES

3.1. Comparison of Experimental and Theoretical Results

For the two kinds of FGM specimens, the measured corresponding thermal diffusivities a_{c1} and calculated values a_{c2} by the solution of multilayered materials are listed in Table III. Two average heat capacities, the measured value $(\rho c)_{m1}$ and the calculated value $(\rho c)_{m2}$ by using the value of each layer, are also listed in the table. Then, from the

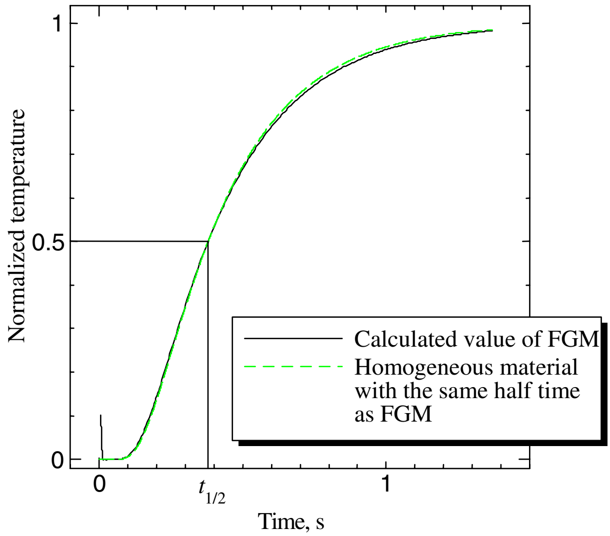

Fig. 5. Temperature response of FGM (PSZ/NiCrAlY specimen, calculated result).

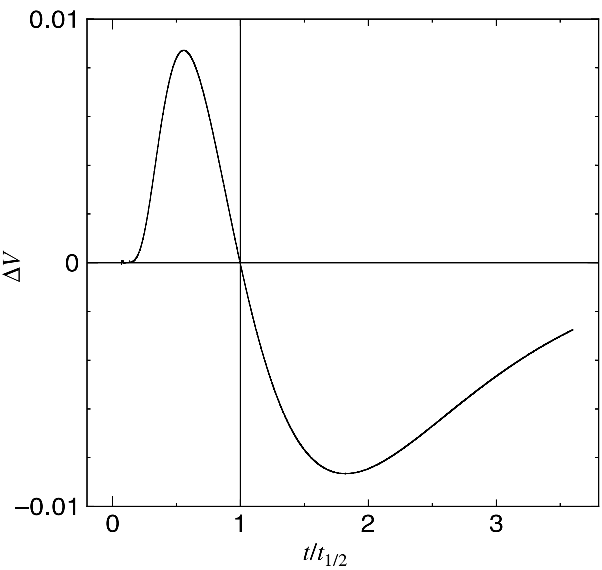

Fig. 6. Difference between two temperature responses (PSZ/NiCrAlY specimen).

Table III. Apparent and Effective Thermal Conductivity

	a_c ($m^2 \cdot s^{-1}$)	$(\rho c)_m$ ($kJ \cdot m^{-3} \cdot K^{-1}$)	λ ($W \cdot m^{-1} \cdot K^{-1}$)
Cu/Ni specimen			
Measured value	$a_{c1} = 1.38 \times 10^{-5}$	$(\rho c)_{m1} = 3281$	$\lambda_{a1} = 45.3$
Calculated value	$a_{c2} = 1.22 \times 10^{-5}$	$(\rho c)_{m2} = 3680$	$\lambda_{a2} = 44.9$
Calculated value			$\lambda_e = 53.5$
PSZ/NiCrAlY specimen			
Measured value	$a_{c1} = 1.67 \times 10^{-6}$	$(\rho c)_{m1} = 2964$	$\lambda_{a1} = 4.95$
Calculated value	$a_{c2} = 1.66 \times 10^{-6}$	$(\rho c)_{m2} = 3069$	$\lambda_{a2} = 5.09$
Calculated value			$\lambda_e = 4.86$

corresponding thermal diffusivities and the average heat capacities, the thermal conductivities can be obtained by the following equation:

$$\lambda_a = (\rho c)_m a_c \tag{1}$$

Because the material is not homogeneous, the thermal diffusivity is not defined physically, and the thermal conductivity obtained from this thermal diffusivity and average heat capacity also has no physical meaning. It is called the apparent thermal conductivity. The effective thermal conductivity is defined by the thermal resistance of each layer as

$$L/\lambda_e = \sum_{n=1}^{4} l_n/\lambda_n \tag{2}$$

which expresses the amount of complete heat transfer in a FGM.

In Table III, the measured values and calculated values of a_c show differences, which may be caused by the error in measured thicknesses and thermophysical properties of the layers and the noise in the measurements. The differences in heat capacities can be considered to have the same error sources. Therefore, the differences in thermal conductivities calculated by the two a_c, the average heat capacities $(\rho c)_m$, and Eq. (1) are also derived from the same error sources. It is, therefore, easy to understand the difference between the apparent and effective thermal conductivities. The former is calculated from the average heat capacity of the whole FGM while the latter is calculated by considering the heat capacity of each layer. It will be very convenient if the apparent value can be used as the effective one and it is important that when the apparent value is used in actual applications, there is an understanding of the difference between the two values.

3.2. Approach to General FGM

As the thermal conductivities for two kinds of FGMs have been obtained in the previous section, the evaluation methods can now be examined by application to another FGM with a heterogeneous property distribution. Generally, FGMs are composed of metals, alloys, and ceramics. The heat capacities of these three kinds of materials are concentrated over a certain narrow range of values; the differences are usually less than factors of a few. This means that, for the three compositions of FGM, the heat capacity can be represented by a typical value. However, the thermal diffusivities values are characterized over a wide range, and the differences are several orders of magnitude [2].

For a FGM composed of metal/ceramics, metal/alloy, and alloy/ceramics, the temperature responses, λ_a and λ_e, have been compared by giving typical values of thermophysical properties and their existing ranges. The results are shown in Fig. 7 and Table IV. The typical value of the properties in the calculations are $\rho c = 2200\,\mathrm{kJ\cdot m^{-3}\cdot K^{-1}}$, $a = 5.0 \times 10^{-5}\,\mathrm{m^2\cdot s^{-1}}$ for metals; $\rho c = 3800\,\mathrm{kJ\cdot m^{-3}\cdot K^{-1}}$, $a = 3.0 \times 10^{-5}\,\mathrm{m^2\cdot s^{-1}}$ for alloys; and $\rho c = 2400\,\mathrm{kJ\cdot m^{-3}\cdot K^{-1}}$, $a = 1.5 \times 10^{-5}\,\mathrm{m^{-2}\cdot s}$ for ceramics. The existing ranges are expressed by giving the maximum and minimum values in the table. The material is considered as four-layered with the same thicknesses. The thermophysical properties of each layer are calculated based on a linear variation.

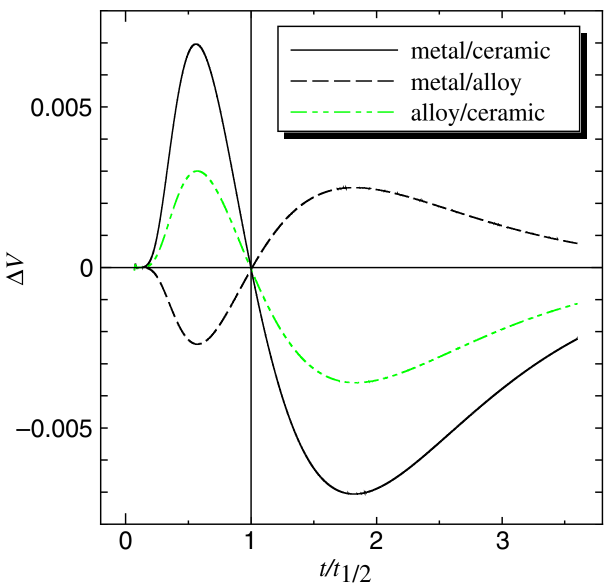

Fig. 7. Difference between two temperature responses of each FGM.

Table IV. Thermophysical Properties of FGM

	$\Delta\rho c$ ($kJ \cdot m^{-3} \cdot K^{-1}$)	Δa ($m^2 \cdot s^{-1}$)	a_c ($m^2 \cdot s^{-1}$)	$(\rho c)_m$ ($kJ \cdot m^{-3} K^{-1}$)	λ ($W \cdot m^{-1} \cdot K^{-1}$)	$(\lambda_a - \lambda_e)/\lambda_e \times 100$ (%)
metal/ ceramic	200	3.50×10^{-5}	2.34×10^{-5}	2300	$\lambda_a = 53.8$	−0.08
			–	–	$\lambda_e = 53.9$	–
metal/ alloy	1600	2.00×10^{-5}	3.84×10^{-5}	3000	$\lambda_a = 115.2$	2.73
			–	–	$\lambda_e = 112.1$	–
alloy/ ceramic	1400	1.50×10^{-5}	2.01×10^{-5}	3100	$\lambda_a = 62.2$	9.3
			–	–	$\lambda_e = 56.9$	–

Figure 7 shows the differences of temperature responses ΔV. It can be seen that the differences are very small, the largest one for metal/ceramics is only 4%, and the shapes of the temperature responses are almost the same as those of homogeneous materials. The difference caused by the thermal diffusivity difference is larger than that caused by the heat capacity difference. This means that the shape of the temperature response is affected by the distribution of thermal diffusivity inside the FGM. The difference of λ_a and λ_e in Table IV is smaller than that in Table III. It is shown that, even though the difference of the thermal diffusivity is larger, the metal/ceramics FGM with a small heat capacity difference shows the smallest difference of λ_a and λ_e. Generally, it is predicted that the distribution of heat capacity varies linearly. If a proper estimation of the heat capacity distribution is made and a typical value is used, the apparent thermal conductivity can be used instead of the effective one. However, it should be noted that this value can only be used as an estimate and the error caused by the heat capacity difference must be understood.

4. CONCLUSION

(a) Temperature responses of four-layered FGM specimens with known thermophysical properties of the layers have been measured and compared with those from theoretical calculations by using the FGM model and homogeneous model.

(b) It has been found that the thermal diffusivity obtained from the half-time method can act as the corresponding value of the effective thermal diffusivity.

(c) If a proper estimation of the heat capacity distribution is made and a typical value is adopted, the apparent thermal conductivity can be used instead of the effective value.

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