Thermal Conductivity and Specific Heat Capacity of Different Compositions of Yttria Stabilized Zirconia-Nickel Mixtures

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Abstract. Ceramic-metal composites also known as functionally gradient materials (FGM) are composite materials which are fabricated in order to have a gradual variation of constituent materials’ thermal and mechanical properties so as to have a smooth variation of the material properties in order to improve the overall performance and reduce the thermal expansion mismatch between ceramic and metal. The objective of the study is to determine the thermal properties of various percentage composition of Yttria stabilized zirconia-Nickel mixtures for application as thermal barrier coating materials in automotive turbocharger turbine volute casing. Specific heat capacity of different percentage composition of ceramic-metal powder composite were determined using DSC822 differential scanning calorimeter (Mettle Tolodo, Switzerland) at temperature ranges between 303K to 873K. While the thermal conductivity of the different percentage composition of ceramic-metal composite structures were determined using P5687 Cussons thermal conductivity apparatus (Manchester, UK) which uses one-dimensional steady-state heat conduction principle. The results have indicated that the specific heat capacity of the FGM increases sharply with an increase in temperature while the thermal conductivity of the FGM decreases with an increase in temperature. These results strongly agree with the theoretical and experimental values as well as the rule of mixtures obtainable in literature, which indicated the suitability of these FGM materials for thermal barrier coating applications.

Introduction

In the contemporary industrial applications, almost all the selection of materials is done based on the mechanical and thermal properties of the material [1]. For the past three decades, thermal barrier coatings (TBC) played a key role in improving the efficiency, capability and durability of high temperature structural components such as those found in automotive and gas turbine engines [2, 3]. Functionally gradient materials (FGM) are improved composite thermal barrier coating material consisting of two quite different materials, one is engineering ceramics to withstand the extreme thermal loading from the severe temperature condition and the other is metal to reduce thermal expansion mismatch between the ceramic layer and the metal substrate as well as improve the structural rigidity [4]. Recently, these (FGM) materials had received considerable attention in the academic research and technical application due to the special characteristics of this material such as high stiffness, high strength and high thermal stability in severe condition of thermal loading [5-7]. The FGM thermal barrier system offered several advantages over its pure ceramic thermal barrier system counterpart due to the excellent ability of the former in thermal stresses reduction at higher temperatures than the latter [8]. Therefore vivid understanding of the thermal and mechanical properties of these excellent materials is a key step in evaluating their performance under real operation.
Thermal conductivity of material plays an important role in heat transfer process and thus has great influence in the choice material for thermal barrier coating \[9, 10\]. Although there had been several works on thermal conductivity and specific heat capacity of composite materials in literature, but hitherto, they have not covered all aspect of different materials and their compositions especially that of ceramic-metal composite. Hesselman and Johnson \[11\] obtained less accurate expression for thermal conductivity of fiber-matrix interfacial region as a result of the thermal expansion mismatch which exist between the fiber and the matrix. On the other hand, Gurtman et al \[12\] proposed a model which was based on random binary periodic anisotropic composite constituents. In addition, Hatta and Taya \[13\] also proposed a model which can be applied to a complex morphological reinforcement cases. Furthermore, Taya and Arsenault \[14\] studied both Taya and Hatta as well as Gurtman et al models and found that these models predict almost same values when the ration of the fiber to matrix conductivity is small. Also Cernuschi et al \[1\] used two and three phase composite materials for thermal conductivity modelling of thick porous zirconia based TBC and found that the porosity of the matrix has great influence on the thermal properties of the coating which all depends on the morphology and orientation of the pores within the matrix. On the other hand, Taylor \[2\] uses laser flash diffusivity technique to determined thermal conductivity of plasma-sprayed zirconia-alumina composite TBC and concluded that the thermal conductivity of composites decreases with an increase in temperature which agrees with Fourier’s law of steady state heat conduction as well as the prediction of the rule of mixtures. Furthermore, Mevrel et al \[15\] uses laser flash method for the determination of Yttria stabilized zirconia (YSZ) thermal conductivity and observed that the point defects present in the coating greatly influenced thermal conductivity at intermediate temperatures. The specific heat capacity of a substance is the amount of heat or thermal energy required to change a unit mass of the substance by one degree in temperature. However, unlike the thermal conductivity, experimental and theoretical analysis from various literatures had shown that this thermal property of a substance increases sharply as the temperature increases \[16-19\].

**Materials and testing methods**

Table 1 shows the details of the materials used and their dimensions for the thermal conductivity test specimens.

<table>
<thead>
<tr>
<th>S/No.</th>
<th>Sample type</th>
<th>YSZ (wt%)</th>
<th>Nickel (wt%)</th>
<th>Height (mm)</th>
<th>Diameter (mm)</th>
<th>Interface (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sample 1</td>
<td>75</td>
<td>25</td>
<td>14.00</td>
<td>19.50</td>
<td>5.00</td>
</tr>
<tr>
<td>2</td>
<td>Sample 2</td>
<td>50</td>
<td>50</td>
<td>14.00</td>
<td>19.50</td>
<td>8.00</td>
</tr>
<tr>
<td>3</td>
<td>Sample 3</td>
<td>25</td>
<td>75</td>
<td>16.00</td>
<td>19.50</td>
<td>7.00</td>
</tr>
</tbody>
</table>

**Thermal conductivity measurement.** A P5687 model of Cussons thermal conductivity apparatus (Manchester, UK) was used for the measurement of the thermal conductivity of the various percentage compositions of the composite materials. A one inch PVC water pipe was used as a mould for the casting of various cylindrical shapes of the specimens each having different percentage composition of the ceramic-metal mixtures (see table 1). It should be noted however, that a polyvinyl alcohol was used as a binder throughout the casting process of the specimens. In each test, the specimen was placed in between the electric heater and the copper plate (serving as heat sink) in the apparatus. Thermocouples were placed on the specimen as follows: (a) in between the top of the specimen and the electric heater which was used to record the temperature \(T_i\), (b) Two thermocouples were placed at an interval distance on the specimen (interface) with the thermocouple closer to the electric heater (near the top level of the specimen) was used to record
temperature $T_2$ while the one at the bottom (near the heat sink) was used to record the temperature $T_3$. (c) Another thermocouple was placed in between the bottom of the specimen and the heat sink and was used to record temperature $T_4$. (d) while another two thermocouples were used for recording the inlet and outlet temperatures of the water and designated $T_5$ and $T_6$ respectively. After checking that all thermocouples were in place, the apparatus was covered with the insulating jacket provided with the apparatus in order to minimized heat transfer across the environment to a negligible level. The thermocouples were then connected to temperature data logger software which is attached to a computer system for the record of various temperature readings from the apparatus. The cooling water supply (also attached with the apparatus) was turn on and set at the flow rate of 0.01 kgs$^{-1}$. The electric heater was switch-on to 0.3 Amps and waited until $T_1$ reaches 80 degC and then the electric current of the heater was reduced to 0.1 Amps. The apparatus was allowed until a steady-state conditions had been achieved through the monitoring the specimen and cooling water temperatures.

Heat transfer rate ($\dot{Q}$) was determined using Eq. 1

$$\dot{Q} = mC_p\Delta T$$

where $m$ is water mass flow rate (kgs$^{-1}$), $C_p$ is the specific heat capacity of water (kJ/kgK) and $\Delta T$ is the temperature change for the water inlet and outlet (degC).

The effective thermal conductivity ($k_e$) of the specimens were then determined using Eq. 2

$$k_e = \frac{q \times t}{T_s - T_b}$$

where $q$ is the heat transfer rate per unit area (heat flux) of the specimen, $t$ is the thickness of the specimen, $T_s$ is the top surface temperature of the specimen and $T_b$ is the bottom temperature of the specimen respectively.

Fig. 1 shows the plots of effective thermal conductivity against temperature for mixtures of 25wt% YSZ & 75wt% Nickel, 50wt% YSZ & 50wt% Nickel and 75wt% YSZ & 25wt% Nickel respectively.

**Specific heat capacity measurement.** A DSC822 model of the differential scanning calorimeter (Mettle Toledo, Switzerland) was used for the analysis using the heating rate of 10 degree per minute on the sample and mass of 6.4 mg for sample 1 (75wt% YSZ and 25%wt Nickel) and sample 3 (25wt% YSZ and 75wt% Nickel) as well as 6.1 mg for sample 2 (50wt% YSZ and 50wt% Nickel) respectively. The experiment was started at 30 degC ambient temperature up to 595.8 degC which is the highest temperature the testing model can attain. Readings were recorded using computer software attached to the testing machine.

The specific heat capacity (SHC) was calculated using Eq. 3

$$SHC = \frac{P}{m \times H_r}$$

where $P$ is the power (Watt), $m$ is the mass of the sample (kg) and $H_r$ is the heating rate (degCs$^{-1}$) respectively.
Fig. 2 shows the plots of specific heat capacity against temperature for mixtures of 75wt% YSZ & 25wt% Nickel, 50wt% YSZ & 50wt% Nickel and 25wt% YSZ & 75wt% Nickel respectively.

Results

Finally, Fig. 1 and 2 shows the plots of thermal conductivity and specific heat capacity against temperature respectively for the different percentage compositions of the YSZ-Nickel mixture for easy and convenient understanding and comparison of the behaviour of each composition mixture relative to one another.

Discussion

It can be seen clearly from figure 1 that the introduction of some percentage of Nickel (25%) has greatly shoot up the thermal conductivity of YSZ from 1.8W/mK to 3.9W/mK. As the percentage content of Nickel increases so also the effective thermal conductivity of the mixture kept increasing to a higher value. It can be clearly seen from the figure that due to 100% increase in the Nickel content (50wt% Ni; 50wt% YSZ), the thermal conductivity of the mixture sharply increased by over 40% from the level it was before the addition of the Nickel (ie 25wt% Ni; 75wt% YSZ mixture). Furthermore, additional 50% increase in Nickel on the 50wt% Ni & 50wt% YSZ mixture resulted in another shoot up of the thermal conductivity by over 45% increase from the level it was before the
addition (i.e., 50wt% Ni; 50wt% YSZ). These clearly demonstrated the high effect of Nickel content on the insulation properties of Yttria Stabilized Zirconia, and it is as a result of the fact that pure Nickel thermal conductivity at room temperature 50 times than that of Yttria Stabilized Zirconia. The results obtained have demonstrated a close similarity to the ones predicted by the rule of mixture [7, 20]. In all the cases the thermal conductivity decreases with an increase in temperature, this agrees with Fourier’s law steady-state heat conduction and other findings in literature [2, 3, 9, 15, 16]. On the other hand, the specific heat capacity results have indicated that addition of Nickel at whatever percentage has no much significant influence on the overall behaviour of the heat capacity of the ceramic-metal composite mixture. Furthermore, it can be understood from the results that their specific heat capacity in all the tested samples increases sharply with an increase in temperature and these are in strong agreement with several findings available in literature [16-20].

Conclusion

Thermal conductivity and specific heat capacity of various percentage compositions of Yttria stabilized zirconia (YSZ) and Nickel mixtures had been determined. The result strongly agrees with the theoretical and experimental values as well as the rule of mixtures obtainable in literature, which indicated the suitability of these FGM materials for thermal barrier coating applications.

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