

DESIGN OF AN EFFICIENT ACTIVE COOLED MESO-SCALE HEAT EXCHANGER USING FUNCTIONALLY GRADIENT MATERIALS

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The cooling system explored in this project is the fluid flow through an array of parallel micro-channels. Among the advantages of this cooling method is the closeness of the micro-channels to the heat source and therefore the thermal resistance is reduced. Among the disadvantages is the non-uniform variation of heat flux throughout the body of the heat exchanger. This in turn causes uneven expansion which results in high induced thermal strains, warping and even cracks. We propose to use Functionally Gradient Materials to offset this effect of thermal gradient loading.

1. INTRODUCTION

Micro-textured or Functionally Gradient Material (FGM) can be processed by spatially modulating the compositional ratio between two powders. An FGM ideally has continuous gradiency. One can approximate such gradient properties by preparing subcomponents in the form of layers. Each layer is prepared by homogeneously mixing two powders in various ratios, which can be stacked to form the ‘discrete’ gradiency in thermo-mechanical properties. One area of micromechanics is concerned with calculating the effective or bulk physical properties of locally inhomogeneous, but statistically homogeneous, materials such as composite materials. Composite materials consist of at least two distinct phases – the matrix material and the reinforcing material, whose properties are known. Rather than microscopically modeling each inclusion in a composite medium, a given inhomogeneous material can be replaced by an equivalent “effective medium”. Structural and thermal properties of FGMs can be tailored by spatially varying the composition of the second-phase particles in the matrix material. This is achieved by modulating the concentration level of the second phase during fabrication. Therefore, the FGM fabrication processes should possess the ability to produce various distributions of particles to withstand assigned loading. For our finite element analysis, alumina and partially stabilized zirconia (PSZ) are chosen for their inherent interfacial strength and difference in their coefficient of thermal expansion (CTE) values. The Mori-Tanaka (1973) approach is used to solve for the properties of the FGM as a function of the volume fraction of the particles or fibers. Because of the almost similar sizes of the alumina and zirconia particles, the Mori-Tanaka mathematical model is solved twice, once for each of the two materials as the matrix. It is found that the properties of the intermediate discrete layers are almost similar by using either of the two models.

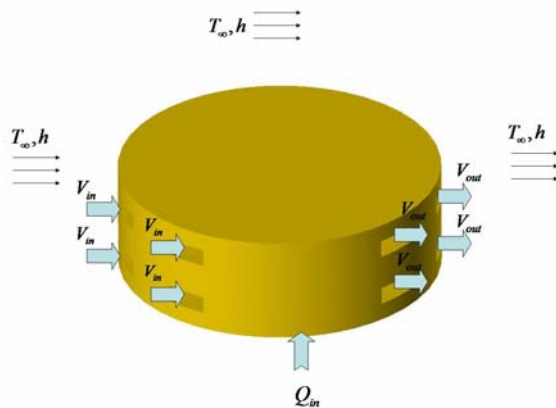


Fig 1: The Heat- Exchanger Model

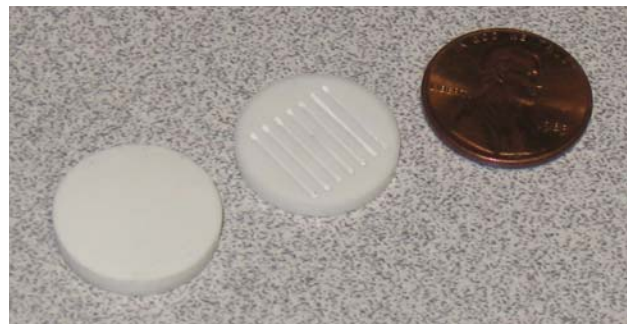


Fig 2: Photo of the micro-textured heat exchanger with internal and external micro-channels

2. DESCRIPTION OF DEVICE

The geometry of the proposed device (18mm diameter and 6mm thick) is as shown in Figure 1. This device is primarily designed to cool electronic chips or cutting tools. It is subjected to a high value of heat flux from its bottom surface as part of electronic package. The primary means of cooling this heat exchanger is through liquid coolants flowing through internal channels in the device. The device also loses heat to the ambient air through convection from its side walls and its top surface. A flux of 250,000 W/m² enters through its bottom surface. The coolant used is water and step-wise varying linear properties with temperature are assumed.

Water flows in all four channels with an inlet velocity of 0.5 m/s along the length of the channels. The water is discharged at the outlet to the ambient at atmospheric pressure. The ambient air is assumed to be at 25°C and its convective heat transfer coefficient is approximated to be 60 W/m²/K. The objective is to prevent the temperature of the solid media from raising over 50°C. At the same time we also want to minimize the induced thermal stress in the body. For this the material of the bottom layer and the one nearest to the heat source should have the least CTE value. An attempt is made to study the values of thermal stresses via finite element analysis (FEA) for different gradiancy in properties, which can be achieved by modulating thickness of each layer in the FGM. For the three layered model, the bottom layer (layer 1) is alumina, followed by a mixture of 50% alumina and 50% zirconia (layer 2), and finally a layer of partially stabilized zirconia (PSZ) (layer 3). The combination of layer thicknesses with the least induced thermal stress can then be chosen.

In addition, the FEA simulation is repeated for a six-layered FGM model with again the design objective being to choose the one with the least induced thermal stress. Again the six-layered model is built proportionately with the bottom layer being pure alumina, followed by the percentage of alumina in layer 2 being 80%, layer 3 with 60%, layer 4 with 40%, layer 5 with 20% and finally the top layer being pure zirconia. Table 1 lists the material properties of the composites with varying volume fractions computed using the Mori-Tanaka scheme [Mori and Tanaka, 1973 and Benveniste, 1987]. Because one cannot easily define which material is a matrix or reinforcement phase between alumina and PSZ, the mathematical model is solved twice, once taking alumina as the matrix phase and then taking PSZ as the matrix [Kwon et al., 1994 and Kwon and Dharan, 1995]. Thus, the average values are taken as the final material properties of the FGM.

Table 1: Properties of the FGM (from Mori-Tanaka scheme)

PSZ (%)	Alumina (%)	Young's Modulus (N/m ²)	Poisson's Ratio	CTE (/°C)	Thermal conductivity (W/m/K)
100	0	2.00000E+11	0.3	1.03E-05	3.00E+00
80	20	2.24150E+11	0.287085	9.77E-06	5.78E+00
60	40	2.50810E+11	0.273835	9.29E-06	8.82E+00
50	50	2.65127E+11	0.2672	9.07E-06	1.05E+01
40	60	2.80170E+11	0.26025	8.85E-06	1.22E+01
20	80	3.12796E+11	0.246085	8.46E-06	1.59E+01
0	100	3.50000E+11	0.23	8.10E-06	2.00E+01

3. FINITE ELEMENT MODEL

Our objectives here are two-fold:

- i. Solve the fluid-thermal interactions for temperature distributions in the FGM model as well as in the cooling fluid.
- ii. Solve the thermal-structure interactions in the solid part for induced thermal stresses.

Ansys Multiphysics is used to solve these coupled fluid-thermal-structure interactions. Extra care is taken to use only three-dimensional brick elements to mesh our models especially when computing flow through ducts. This is because it is important to align the grids along the direction of flow as they exert considerable influence on the flow and heat transfer.

For the fluid-thermal analysis, 3-D CFD flotrán elements are used. The segregated solver is used for flow and TDMA solver is used for the velocity calculations. Here the thermal properties of the non-fluid material are several orders of magnitude different from those of the fluid, and this is called an *ill-conditioned conjugate heat transfer problem*. In this situation, it is known that the TDMA method probably will not yield useful results no matter how many sweeps we specify. The most robust but most memory-intensive method for solving conjugate heat transfer problems, the Preconditioned Generalized Minimum Residual method, is used as the temperature solver. Preconditioned Conjugate Residual method is chosen as the pressure solver because of its robustness for solving ill-conditioned heat transfer problems. Appropriate boundary conditions are applied (Figure 1) and the model is solved till desired convergence is achieved. Now the 3-D CFD flotrán elements are replaced with 3-D structure elements in the solid regions, while null element is used in the fluid part. Then temperature boundary conditions are applied by importing the result file from the previous fluid-thermal analysis. Now the system is solved for thermal stresses only in the solid regions. The analyses are performed on all the three layered as well as six layered models.

4. RESULTS AND DISCUSSION

The results that are obtained from the finite element analysis are in agreement with our expected design objectives. First, the analysis is carried out on an alumina model and then the results are compared with the three layered and the six layered model.

4.1 Alumina model

Without the cooling channels, it is observed that the steady state temperatures are in the range of 250 °C to 280 °C. With the cooling channels we could bring down the steady state solid temperature range to 59 °C to 118 °C. After the thermal-fluid analysis, a structural analysis is performed to determine the maximum principal stresses in the model. It is observed that in the regions of high temperature gradients, the stress is the highest.

4.2 Comparing Results between – pure alumina, 3 layered FGM and 6 layered FGM

On comparing the results from the three models, it is found that the stress is least in the six layered FGM model, followed by the three layered model and it is maximum in the pure alumina model. Also for the models with the same number of layers, the ones with the smallest first layers produced the minimum stresses.

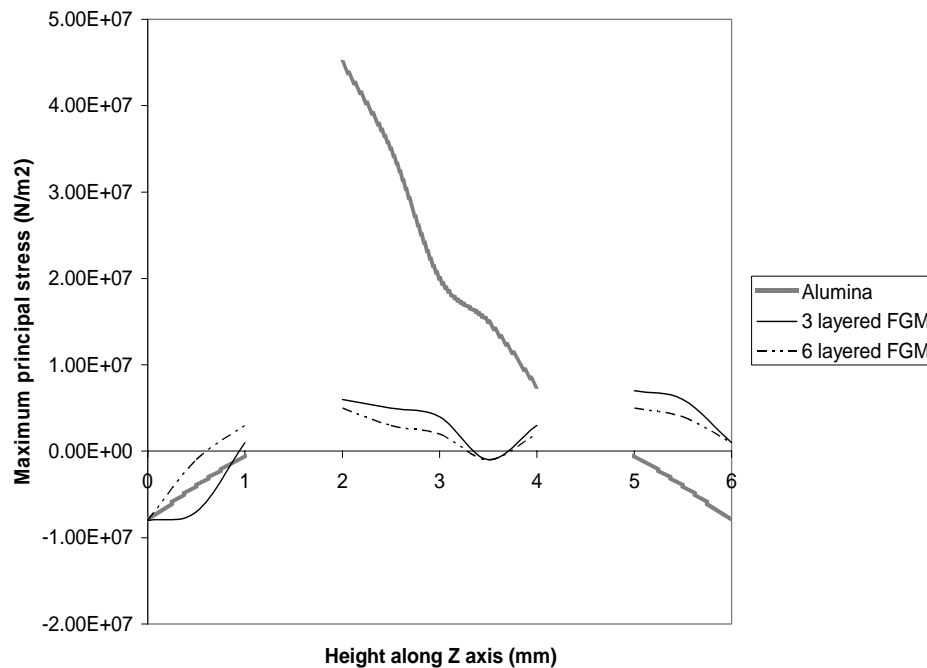


Fig 3: Maximum principal stresses- Section exactly through the centre of one set of cooling channels (x=0, y=3mm)

From the above results it is seen that we succeeded in reducing the tensile stresses significantly by building models using functionally gradient materials. Now, each of the two FGM models – the three layered and the six layered, are analyzed to see the effect in stresses by varying the thickness of each layer. The effect is not as pronounced as seen between an alumina model and a FGM model. However the effect is seen more in the case of the three layered FGM than the six layered FGM. For both the cases, the models with the thinnest bottom layers produced the minimum principal stresses. Perfect elastic behavior is assumed and the Rankine failure criterion is used in the models [Roeder and Sun, 2001a and b]. In all the cases, it is seen that the maximum principal stress in the models is well below the tensile limit.

5. VALIDATION

For validating our results, the finite difference approach is used. A simplified case of a two dimensional two layered FGM model of alumina and PSZ zirconia with only one cooling channel is considered. Starting from the simplified momentum and energy differential equations for fully developed (velocity and temperature profiles) flow in the two-dimensional parallel wall channel, the convective heat transfer coefficient is calculated when there is a constant flux through the lower wall but the upper wall is insulated. The finite difference equations are formed for each set of nodes corresponding to the boundary conditions and these are solved to obtain the nodal temperatures. Now, the model is assumed to be similar to a bimetallic strip and stress (tensile or compressive) on either material (alumina or PSZ) is calculated. These results are then compared with those obtained from a finite element model solved in *Ansys 7.0*. The results are within an error of 30%, which is considered reasonable considering the very rough estimate of the model.

6. CONCLUSIONS

Using eight parallel cooling channels is useful in bringing down the temperature in the operating range of the device. It is observed that the high thermal gradient created by the cooling channels results in high induced thermal stresses in the specimen. Hence to offset this effect, the concept of using a material with functionally gradient properties is used. From the results of the analysis, it can be inferred that the stresses in the FGM media are considerably less than the stresses in the alumina (homogeneous) media. Hence the incentive of using the FGM can be justified. The stresses in the six layered FGM model are further found to be lower than those in the three layered FGM model. Varying the thickness of the layers of the FGM also revealed interesting results. For both cases of three layered and six layered FGM models, it is found that the model with a thinner bottom layer had a lower value of stress than the other combinations. As far as future work on this topic is concerned, currently attempt is being made to powder process a three layered FGM model at MSU. Work can be done on finding what should be the optimum ratios of layer thicknesses with experimental validation of the heat exchanger being the final goal. Fugitive phases can be used and partially sintered ceramics are machined and joined after fully sintering for making the internal channels [Shin et al., 2000] and the heat exchanger can then be tested under actual conditions.

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