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Experimental and Numerical Investigation of Heat Transfer in Al-Tic Powder Metallurgy Composites

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Abstract—*In the project, Metal Matrix Composites are fabricated by powder metallurgy process, i.e., blending, compaction and Sintering by reinforcing micro-sized titanium carbide in the aluminium matrix. Thermal conductivity of these composites is measured by using an experimental setup.FEM is implemented to determine the effective thermal conductivity of particulate filled metal matrix composites and is validated by experimentation. A commercially available finite-element package ANSYS 13.0 is used for this numerical Analysis. Three-dimensional spheres-in-cube lattice array models are constructed to simulate the microstructure of composite materials for various filler concentrations ranging from about 5 to 15wt%. This study shows that the incorporation of titanium carbide results in a partial reduction of thermal conductivity. Still, it gives an improved strength and a decrease in the coefficient of thermal expansion which makes it applicable in the automobile industry.*

Keywords — *Metal Matrix Composite, Titanium Carbide Particulate, Thermal Conductivity, Finite-Element Analysis.*

I. INTRODUCTION

A. Composite Materials

A composite is a structural material which consists of combining two or more constituents. The constituents are combined at a microscopic level and are not soluble in each other. Other constituents are called reinforcing phase, and one in which it is embedded is called the matrix. The reinforcing material may in the form of the fibres, particles or flakes.

B. Uses of Metal Matrix Composites

- Extensively used in space technology and production of Aerospace components(tails, wings, fuselages, propellers).
- Used in the production of sports goods, e.g. racing car bodies and bicycle framesets.
- Used for general industrial and engineering structures for high-temperature applications.
- Used in high speed and fuel-efficient transport vehicles.
- Carbon composite is a key material in today's launch vehicles and spacecraft. It is widely used in solar panel substrates, antenna reflectors and yokes of spacecraft. It is also used in payload adapters, inter-stage structures and heat shields of launch vehicles.

C. Objective

To develop a new aluminium-titanium carbide metal matrix composites for different volume concentration of titanium carbide using powder metallurgy process(Blending of powders, Compaction process, Sintering). The experimental work is then carried out to find out the equivalent thermal conductivity of Al-TiC composites of varied titanium carbide concentrations. The variation of thermal conductivity of Al-TiC composites with varying temperatures also has to be found out. The simulation processes are then carried out for finding the thermal conductivity of the composites using ANSYS 13.0 to validate with the experimental results and then analyze the temperature distribution (i.e. conduction heat transfer) for the developed composites.

II. EXPERIMENTAL SET-UP

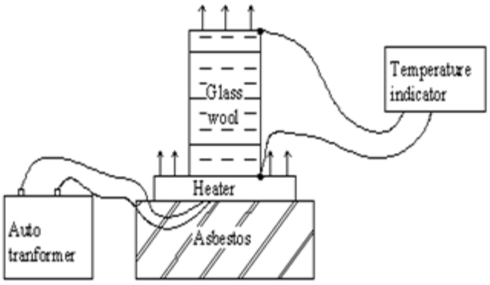

Figure 2.1 - Schematic diagram of the experimental setup

A. Specifications

- Heater dimensions: 40x40 mm.
- Composite dimensions: 20mm dia, 25mm length.
- Thermocouple used: Iron-Constantan.
  a) Matrix Material (Aluminum, Particle size 120 microns)
  b) Density 2707 kg/m^3
  c) Thermal conductivity 220 W/mK
- Filler (Titanium Carbide, Particle size 20-40 microns)
  a) Density 4940 kg/m^3
  b) Thermal conductivity 50 W/Mk

The experimental set up mainly consists of Al-TiC composite, heater, autotransformer and a digital temperature indicator. The composite is surrounded by glass wool to prevent the heat loss in the radial direction, and the asbestos blocks are provided below the heater to restrict the heat flow in a downward direction. Constant power is supplied to the heater element using the autotransformer, and the temperature rise of the composite, which is placed above the heater is measured at the bottom and the top position by an iron-constantan thermocouple. The thermal conductivity of the composite is then measured according to equation (1).

B. Heat Conduction Basis

Heat conducted through a cross-section is proportional to the temperature difference between hot and cold sides. The proportionally constant is called the thermal conductivity of the materials. The formula is as follows:

$$Q = \frac{KA}{L}(T_b - T_t) \text{------------------- (1)}$$

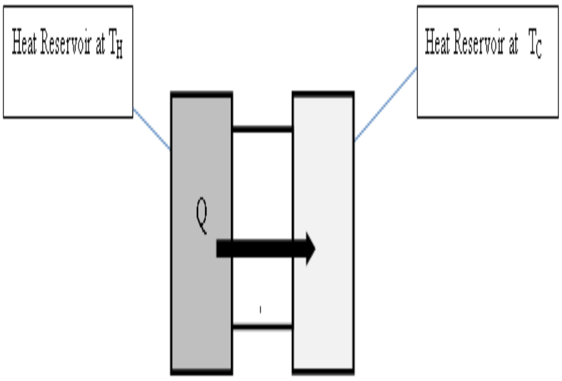

Figure2.2. - Heat conduction Phenomena

C. Theoretical Thermal Conductivity Models

The models have been applied solid-gas or solid-solid composite system. With few exceptions the models require:

1. Assumed particle geometry and particle distribution.
2. Complete interfacial contact between two solid phases.

The simplest cases to consider are the series and parallel models, for which the conductivity of the composite is given by:

For the series conduction model

$$\frac{1}{k_c} = \frac{\phi}{k_f} + \frac{1-\phi}{k_m} \quad \text{----- (2)}$$

For the parallel conduction model

$$k_c = (1-Ø)\, k_m + Ø\, k_f \quad \text{---- (3)}$$

For an infinitely dilute composite of spherical particles, the exact expression for the effective thermal conductivity is given as

$$k_c = k_m \frac{k_f + 2.k_m + 2.\phi.(k_f - k_m)}{k_f + 2.k_m - \phi.(k_f - k_m)} \quad \text{-------- (4)}$$

Equation 4 is the well-known Maxwell equation for dilute composites.

D. Preparation of Samples

The composites are made by compacting the metal powders in suitable dies and Sintering, that is, heating without melting. This process is called powder metallurgy. The preparation of the composites consists of the following operations in sequence

- Weighing of powders
- Blending
- Compaction
- Sintering

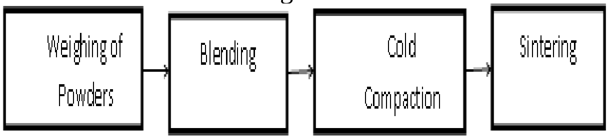

Fig.2.3 - Outline of processes involved in making powder metallurgy composites.

Weighing Of Powders

Using a digital weighing machine, Al and TiC (5%wt) powders that are required to produce one composite is weighed, and both are mixed for blending operation. The same process is being done for 10%wt and 15%wt of TiC**.**

Table 1 - Composition of Samples

	The weight percentage of TiC		
	5%	10%	15%
Mass of Al (gms)	24.792	24.0435	23.255
Mass of TiC (gms)	1.304	2.67	4.104

Table 2 - Sintering parameters

Composite	Temperature(°C)	Time(min)
Al-TiC	600	120

Table 3 - List of composites fabricated

Samples	Composition
1	Aluminum + 2.8 vol %(5wt %) Filler
2	Aluminum + 5.76 vol %(10wt %) Filler
3	Aluminum + 8.85 vol %(15wt %) Filler

Table 4 – Readings taken for 5%wt of TiC

V_{input}(Volts)	$T_{surface}$	T_1(at bottom)	T_2(top)
10	39	40	39
20	57	63	62
30	72	84	83
40	111	138	136
50	148	162	160
60	185	216	213
70	228	253	250
80	270	294	290

Table 5 – Readings taken for 10%wt of TiC

V_{input}(Volts)	$T_{surface}$	T_1(at the bottom)	T_2(top)
10	42	39	38
20	60	57	56
30	88	93	92
40	120	126	124
50	165	170	168
60	205	219	216
70	246	252	248
80	312	276	272

Table 6 – Readings taken for 15%wt of TiC

V_{input}(Volts)	$T_{surface}$	T_1(at the bottom)	T_2(top)
10	37	37	37
20	53	53	52
30	76	79	78
40	104	116	114
50	136	147	145
60	200	205	202
70	224	230	226
80	286	262	258

III. THERMAL ANALYSIS USING ANSYS

In this, thermal Analysis of particulate-reinforced composite materials will be conducted by using ANSYS 13.0 software. The main objective of applying thermal Analysis is to figure out the temperatures on each node generated by ANSYS 13.0 for a numerical solution in both the filler and matrix materials. By this way, obtained solutions will be used to calculate the thermal conductivities of composite materials numerically.

A. Model Development

The three-dimensional model has been developed for particulate-reinforced composites. For the 3-D model, the shape of the matrix material has been chosen as the cube, whereas the shape of the filler material (particle) has been chosen as a sphere. Geometric shapes of the particle-matrix combination have been given in Fig.4.1.

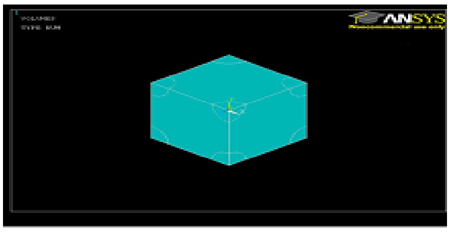

Fig. 4.1 - Three-dimensional geometric materials (Spheres in cube matrix)

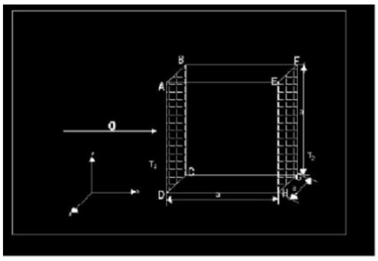

Fig. 4.2- 3-D geometry used in the assumptions model for particulate-reinforced composite

B. Thermal Analysis in 3D model

This part concerns the temperature distributions of 3-D models. For 3-D models, three different concentration ratios, Ø = 2.8%, 5.76%, 8.85%, have been taken to figure out how concentration ratio is effective in composite thermal conductivity.

In Fig.4.2, the geometry used in the 3-D model is shown. The temperatures on both the left (ABCD) and right (EFGH) surfaces are designated as $T_1$and T_2 respectively. Heat flow Q and its direction are shown, and dimensions of the cubic matrix are designated as 'a'. The left (ABCD) and right (EFGH) surfaces that are perpendicular to the heat flow were assumed to be isothermal. The remaining side surfaces of the cube (AEHD, ABFE, BCGF and CDHG) that are parallel to the heat flow were assumed to be adiabatic. The fillers were assumed to be not in contact with each other and to be uniformly distributed into the matrix material.

3-D thermal Analysis has been started initially with 2.8% concentration, and the sphere shape fillers have been individually investigated for various concentration ratios ($\emptyset$ = 5.76%, 8.85%). The temperature on the boundary surface, (ABCD) has been kept constant throughout the Analysis and given as T_1=300ºC. The surface (EFGH) has been given with convective heat transfer coefficient of ambient prescribed as 2.5W/m^{2}K at the ambient temperature of 27ºC. The mesh generated for $\emptyset$ =2.8% has been illustrated in Fig.4.3, 4.4, 4.5.

Boundary conditions have been given to the ANSYS 13.0 software after meshing process was completed. As a result of thermal Analysis, the following solutions have been obtained.

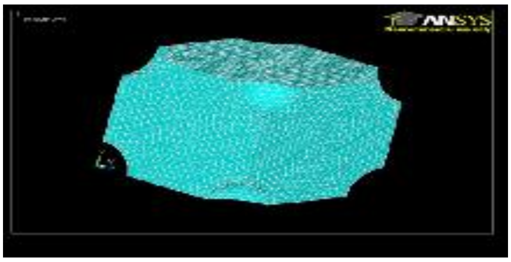
Fig.4.3- 3-D view of Meshed Matrix model.

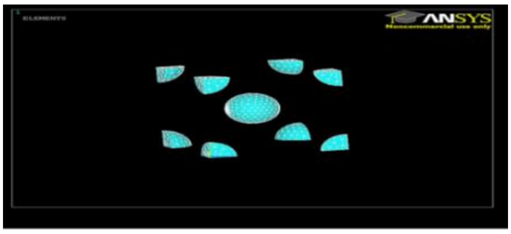
Fig.4.4 - 3-D view of Meshed Filler model.

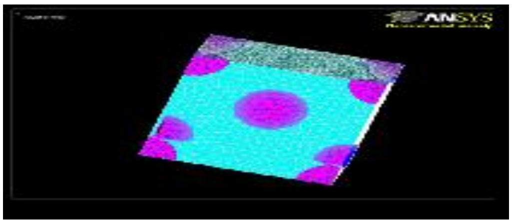
Fig.4.5 - 3-D view of meshed Metal matrix composite.

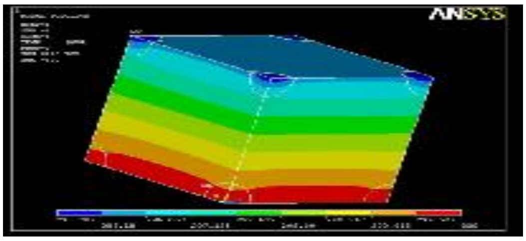
Fig.4.6- Temperature distribution over $\emptyset$=2.8%

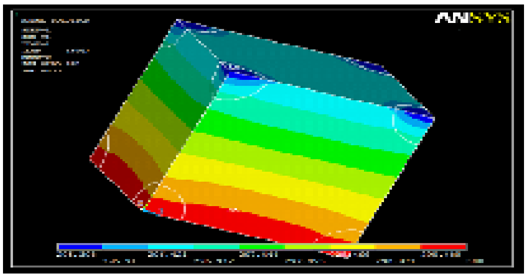
Fig. 4.7- Temperature distribution $\emptyset$ = 5.76%

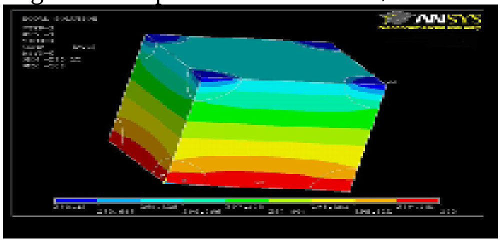
Fig. 4.8- Temperaturedistribution over $\emptyset$=8.85%

IV. 5. RESULTS AND DISCUSSIONS

A. *Model Analysis Results*

3-D model analysis is done on 3 different concentration ratios, $\emptyset$= 2.8%, 5.76%, 8.85%. The temperature distribution results for all the concentrations can be seen in Fig.4.6, 4.7 & 4.8. From the temperature distribution results, it can be analyzed that as the concentration of filler material increases, isotherms are getting deflecting rapidly towards the filler positions. At 8.85% volume concentration, deflection of isotherms towards filler positions is more when compared for other volume concentrations, i.e., 2.8% and 5.76%.

a) Calculation of Effective Thermal Conductivity

Firstly, for a given filler volume concentration, the temperature distribution of the composite is obtained. Now a model is constructed, with a known value of thermal conductivity, with the same dimensions as that of the composite. The temperature distribution of this model is found out. Now by keeping on changing the thermal conductivity of the model, the temperature distribution has to be brought as that of the composite. Now the thermal conductivity of the composite will be the same as that of the model since the temperature profiles of both are identical.

B. *Thermal Conductivity Values Obtained From Different Methods*

The values of effective thermal conductivities of the particulate filler metal matrix composites with varied proportions of titanium carbide obtained using Maxwell'scorrelation, Experimental and FEM analysis are given in Table 5.1.

Table 7 - Thermal conductivity obtained from different models

	The volume percentage of TiC		
	2.8%	5.76%	8.85%
Maxwell model	212.65	207.06	200.34
Experimental	181.75	179.1	175.1
Simulation	192.5	190	188.35

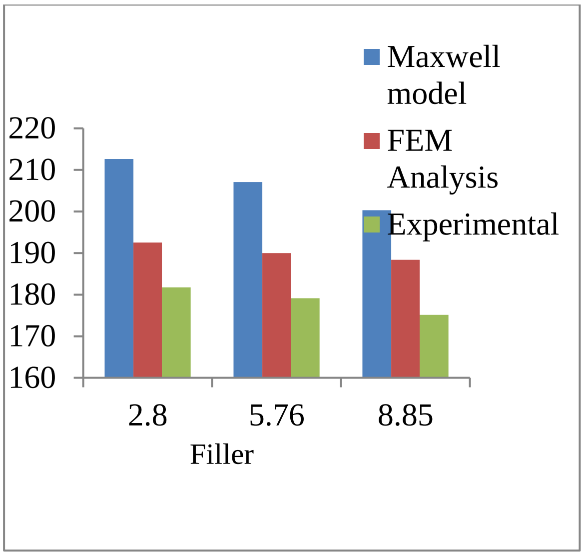

Figure 18 - Comparison of thermal conductivity values obtained from different methods

Fig.18 presents a comparison among the results obtained using these models concerning the values of effective conductivity obtained experimentally. It is noticed that the results obtained from the finite element analysis using ANSYS 13.0 are closer to the measured values of effective thermal conductivity for composites of different filler content.

On comparison, it is found that while the errors associated with the FEM values concerning the experimental ones lie in the range of 5.9 to 7.56 %, the same for results from Maxwell's correlation lies 14.41 to 17.55% respectively. The percentage of errors associated with each method for individual composites are given in Table 5.

Table 8 - Percentage errors concerning the measured value

	The volume percentage of TiC		
	2.8%	5.76%	8.85%
Maxwell model	212.65	207.06	200.34
Experimental	181.75	179.1	175.1
Simulation	192.5	190	188.35

It leads to a conclusion that for a particulate filled composite of this kind, the FEM model can very well be used for the predictive purpose in determining the effective thermal conductivity for a wide range of particle concentration. The difference between the calculated values and the measured value of conductivity for any particular composite sample may be attributed to the fact that some of the assumptions taken for the FEM analysis are not real. The shape of titanium carbide is assumed to be spherical, while in actual practice they are irregular shaped. Although the distribution of titanium carbide in the matrix body is assumed to be in an arranged manner, it is dispersed in the metal matrix almost randomly.

Table 9 - Variation of the coefficient of Thermal Expansion with the Volume content

	The volume percentage of TiC		
	2.8%	5.76%	8.85%
Maxwell model	212.65	207.06	200.34
Experimental	181.75	179.1	175.1
Simulation	192.5	190	188.35

Table 9 shows that as the filler volume concentration of titanium carbide increases, it results in a reduction of the coefficient of thermal expansion which makes it suitable in automobile and electronic applications for high-temperature applications.

C. Thermal Conductivity Temperature Plot

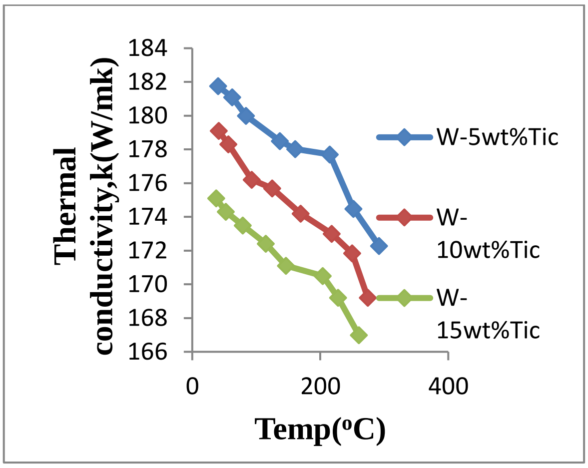

Figure 19 - Thermal conductivities for the composites with various titanium carbide particles as a function of temperature

From the Fig.19, it can be concluded that increasing the volume concentration of the filler makes the slight reduction in effective thermal conductivity value due to the decreasing thermal bridges along the path of the heat flow. Also, in case of pure aluminium, as temperature increases from 0 to 300ºC, there won't be any reduction in the thermal conductivity of the material. Still, here due to the addition of the titanium carbide particle to the matrix material (aluminium) there is a partial decrease in the thermal conductivity of the composite as the temperature of the composite increases.

V. CONCLUSION

FEM approach can be gainfully employed to determine the equivalent thermal conductivity of these composites with different amount of filler content. The value of equivalent thermal conductivity obtained for various composite models using FEM are in reasonable agreement with the experimental values for a range of filler contents from about 5 wt% to 15 wt%. The values of thermal conductivity obtained for FEM analysis are more accurate concerning the experimental values than the values calculated using Maxwell's correlation.

Incorporation of titanium carbide results in a slight reduction of thermal conductivity of metal matrix composite. Still, there was an improved mechanical strength due to the ceramics powders (titanium carbide) used as fillers and also a decrease in the coefficient of thermal expansion (for high-temperature applications). With the lightweight and improved strength titanium carbide filled metal matrix composite can be used for applications such as electronic packages, automobile industry for piston heads, aerospace applications etc.

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