PREDICTION OF THE THERMAL CONDUCTIVITIES OF 4-AXIAL NON-WOVEN COMPOSITES

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Introduction

Spatially reinforced composites (SRCs) potentially have better properties in the out-of plane direction than 2-dimensional laminated composites by reinforcing fibers(or rods) in that direction, even if the properties of SRCs are usually no more attractive than the 2-D laminate as far as the comparison is made in only planar direction. Moreover, the material properties of SRCs can be tailored by changing the volume fraction and structures of reinforcements in various directions and by using the reinforcements with different properties. Thus, the development of the prediction model for the material properties of SRCs provides a very useful means for the design and development of SRCs.

The mechanical and thermal properties of SRCs have been studied in a number of researches and the prediction models for the properties have been proposed and verified[1-2]. Our study considers the 4-axial non-woven composites(NWCs) which are reinforced in three directions, 0°, 60°, and 120°, in one plane and in the other direction perpendicular to the plane, as shown in Fig. 1. We have not been able to find the models of the non-woven composites and the nozzle throat of a kick motor under development consists of the NWC. Therefore, this paper proposes the prediction model for the thermal conductivity of 4-axial NWCs and compares the predicted results to measured ones.

We assume that the fibers (or rods) have transverse isotropy and the matrix have isotropy; we neglect the thermal resistance between the reinforcements and the matrix; and heat flux is parallel to the direction, when we induce the thermal conductivity in a direction.

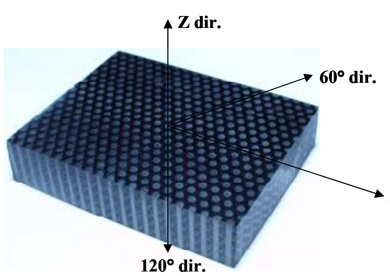

Fig. 1 4-axial NWC after curing and cutting

Thermal conductivity of 4-axial NWC using the concept of volume average

The volume average method employs existing micro-mechanical theories and conventional transformation rules to obtain constitutive relations for representative unit cells of the composites which are the smallest patterns with the same properties in the NWCs. We assume that this unit cell consists of *n* unidirectional composites aligned with each reinforced direction. We first obtain the thermal conductivity in local coordinate system, followed by the transformation of the thermal conductivity to the one in global coordinate system. And then, we average the thermal conductivity by weighing with the volume fraction in each direction. We acquire the thermal conductivities of unidirectional composites from the equation proposed by Hashin[3]. Fig. 2 shows the relationship between the local and global coordinate system. The effective thermal conductivities of the NWCs are

$$[K] = \sum_{i=1}^{4} \frac{V_{r_i}}{V_r} [T]_i^T [k'']_i [T]_i \qquad (1)$$

where, V_{r_i} is the volume fraction in each direction, and $V_r = \sum_{i=1}^{4} V_{r_i}$. $[T]_i$ is the transformation matrix from the local coordinate system ($1', 2', 3'$) to global on e($1'', 2'', 3''$) and matrix $[k'']_i$ means the thermal conductivities of *i*-th unidirectional composite in the local coordinate system. The $1'$-axis coincides with the axial direction of the reinforcements.

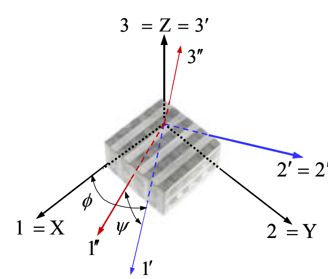

Fig. 2 Local and global coordinate system of a unit cell

Thermal conductivity of 4-axial NWC using the concept of thermal resistance

The thermal resistance method uses the analogy between the diffusion of heat and electrical charge. Defining resistance as the ratio of a driving potential to the corresponding transfer rate, it follows from Fourier's law for heat conduction that the thermal resistance for conduction is

$$R = \frac{T_1 - T_2}{q} = \frac{L}{kA} \tag{2}$$

Thermal resistance, as in the manner of electrical resistance, is divided into two classes: parallel and series. We divide the 4-axial NWCs into three laminae in order to apply thermal resistance concept, as shown in Fig. 3 and choose a hexahedron as the unit cell like Fig. 4. We obtain the thermal conductivity of this unit cell and presume the value as that of a lamina which is transformed from the local coordinate direction to the global one. Finally, the effective thermal conductivities of the NWCs are derived, after thermal resistance concept is applied in each direction. The coordinate transformation rule in this method is identical to the one in the former method.

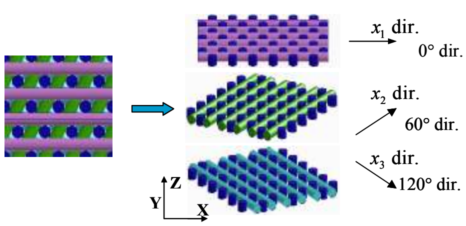

Fig. 3 A concept of the application of thermal resistance to 4-axial NWC

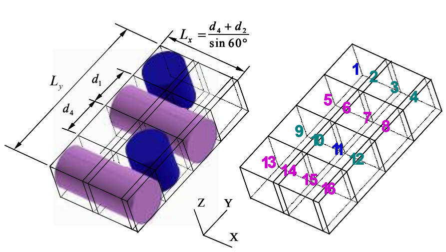

Fig. 4 A unit cell of a lamina of 4-axial NWC

Experiment for thermal conductivity of NWC

To verify the theoretical predictions, specimens are fabricated with pultruded carbon rods and epoxy, as shown in Fig. 1. Fig. 5 shows the comparison between the predictions and experimental results. The inputs for two predictions are shown in Table 1.

Table 1 Input for the predictions of k_{ZZ}

d_1 , d_2 , d_3	d_4	$k_{r,1}$	$k_{r,2}$	k_m
mm	mm	W/mK	W/mK	W/mK
0.67	1.33	5.675	0.338	0.189

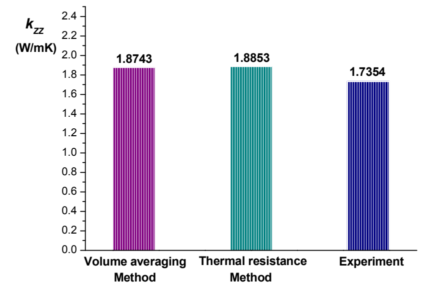

Fig. 5 The predicted and measured results

Conclusion

In this paper, we used the established volume-average method and proposed thermal resistance method to predict the thermal conductivity of 4-axial NWCs. The comparison of the numerical results with measured ones showed reasonable agreement.

In view of realities, the present model provides a means for predicting a reasonable upper bound for the thermal conductivity of the considered materials because of the assumptions mentioned above. 4-axial non-woven composites are usually fabricated with C/C composites as well as carbon/epoxy composites. It is difficult to predict the properties of C/C composites because of the high anisotropy and difficulties in the measurement of matrix properties. Our model, however, can be very useful guidelines for the design and the development of materials by enabling sensitivity studies to be conducted rapidly and easily.

References

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