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THERMAL CONDUCTIVITY OF CARBON/BASAL FIBER REINFORCED EPOXY HYBRID COMPOSITES

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ABSTRACT

The purpose of this paper is to analyse the thermal conductivity of carbon/basalt fiber reinforced hybrid composite structures based on stacking sequences. The paper also investigates the thermal impedance of carbon fiber reinforced polymer (CFRP) and basalt fiber reinforced polymer (BFRP) with increased thickness. Research involved processing hybrid composite by using injection moulding. The weight ratios of fibers to polymers was 60%: 40%. Testing was conducted using the ASTM D 5470 standard test method. Results show that the stacking sequences of carbon/basalt fibers have a significant impact on thermal conductivity. Hybrid composite with the stacking sequence mode $C_3B_4C_3$ has the lowest thermal conductivity at 0.187 W/mK, and the highest thermal impedance of 0.0052 m^2K/W. The highest thermal impedance of BFRP is at 0.007 m^2K/W with 2.5 mm thickness. In CFRP, the highest thermal impedance is achieved by 3.4 mm thickness with 0.005 m^2K/W. Results therefore show that carbon/basalt/epoxy hybrid composites are good insulators, since thermal conductivity is less than 0.42 W/m^oK standard.

Keywords: Hybrid composite; Isolation; Stacking sequence; Thermal conductivity; Thermal impedance

1. INTRODUCTION

Over the last few decades, composites have been used widely in engineering products, owing to a wide range of beneficial properties, including low density, corrosion resistance, strength and durability, renewability, and low-cost production (Song et al., 2012). This study isolates several advantages of composites. Manufacturing of composites is currently carried out by combining two or more different fibers, reinforcing as a single matrix to maximise beneficial properties (Mingchao et al., 2009; Dehkordi et al., 2010). This material is subsequently known as a hybrid composite (Ashby & Brechet, 2003). Hybrid composites can significantly improve mechanical properties, including ultimate strain and impact (Pandya et al., 2011). Badie et al. (2011) study drive shafts made of a hybrid composite, basing their study on the angle of fiber orientation and stacking sequences. They examine the drive shaft's tensile stiffness, natural frequency, stress buckling, fatigue life, and failure mode. Zhang et al. (2012) study the lightweight bearing load of glass/carbon fibers reinforced hybrid composite laminate. Flexural properties of hybrid composite with reinforced glass/carbon fibers have been subsequently studied by Dong et al.

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(2012). Tensile strength and flexural strength of inter-ply carbon/basalt fibers reinforced hybrid composite has been studied by Subagia and Kim (2013) and Subagia and Kim (2014a), respectively. Subagia et al. (2014c) also study hybrid basalt fiber and tourmaline micro/nano particles. Such research shows that basalt fibers influence the flexural strength of composites up to 70% (Nurjaya et al., 2015). Additionally, the effect of stacking sequences on mechanical properties has been studied by Onal and Adanur, (2002), Mariatti et al. (2003), Agarwal et al. (2014), Lim et al. (2014), and Subagia et al. (2014b).

Thermal conductivity comprises the physical properties of materials that indicate the rate at which heat flows through a given material. Several studies have been carried out in the last decades with the aim of improving the thermal conductivity of composites. For example, Yamashita et al. (2008), investigate the thermal conductivity of plain weave fabrics and plain weave fabric/resin composites. Their study confirms that the anisotropic behaviour of the composite influences thermal conductivity. Research into the effects of filler size distribution on thermal conductivity of composites was conducted by Holotescu and Stoian (2009). An investigation of thermal conductivity with imperfect interfaces on composite materials was carried out by Marcos-Gomez et al. (2010). The thermal conductivity of composite material using wastes wood and expanded polystyrene was studied by Agoua et al. (2013). The effect of carbon nano-tubes (CNT) and carbon fiber reinforced composites on thermal conductivity was studied by Park et al. (2014). Agrawal and Satapathy, (2015) determined the thermal conductivity of polymer composites with hybrid filler using a mathematic model. The effect of stacking sequences on the effective thermal conductivity of unidirectional composite laminates has been studied by Yu et al. (2015). Despite all this research, until now there have not been many studies of the effect of stacking sequences on the thermal conductivity of composite hybrid laminate.

The main aim of the experiment detailed in this paper is to determine the thermal conductivity and thermal impedance of hybrid composites based on their stacking sequences. The study also investigates the influence of thickness on the thermal impedance of CFRP and BFRP.

2. EXPERIMENTAL

2.1. Materials

Carbon fibers and basalt fibers are used as reinforcement materials. Woven mat strands composed of carbon fiber (C120-3K) are produced by Hyundai Fiber Co Ltd (Korea). C120-3K has a density of 114 lb/ft^3 (1800 kg/m^3) and an elastic modulus of 240 GPa. Woven mat strands composed of basalt fiber (EcoB4-F210) are manufactured by Seco-Tech (Korea) (Subagia et al., 2014b). EcoB4-F210 has density of 2.7 g/cm^3 and an elastic modulus of 89 GPa. Basalt fiber is made from volcanic magma; rock is melted at 1300-1700°C and spun (Singha, 2012). Besides having good mechanical properties, basalt also has a high thermal stability, good electrical and sound insulating properties, and it a high chemical resistance. Basalt fiber is a new material for composite reinforcement that can replace glass fiber. The matrix is composed of epoxy resin (Modified BPA Epoxy Resin) produced by Jet Korea Industrial Corporation. The hardener used comprises modified Aliphatic Amine (Subagia & Kim, 2013). The epoxy resin is used owing to its low cost, good electrical and mechanical properties, and ease of handling (Murthy et al., 2012). The epoxy has a density and elastic modulus of 1350 kg/m^3 and 3.25 GPa, respectively.

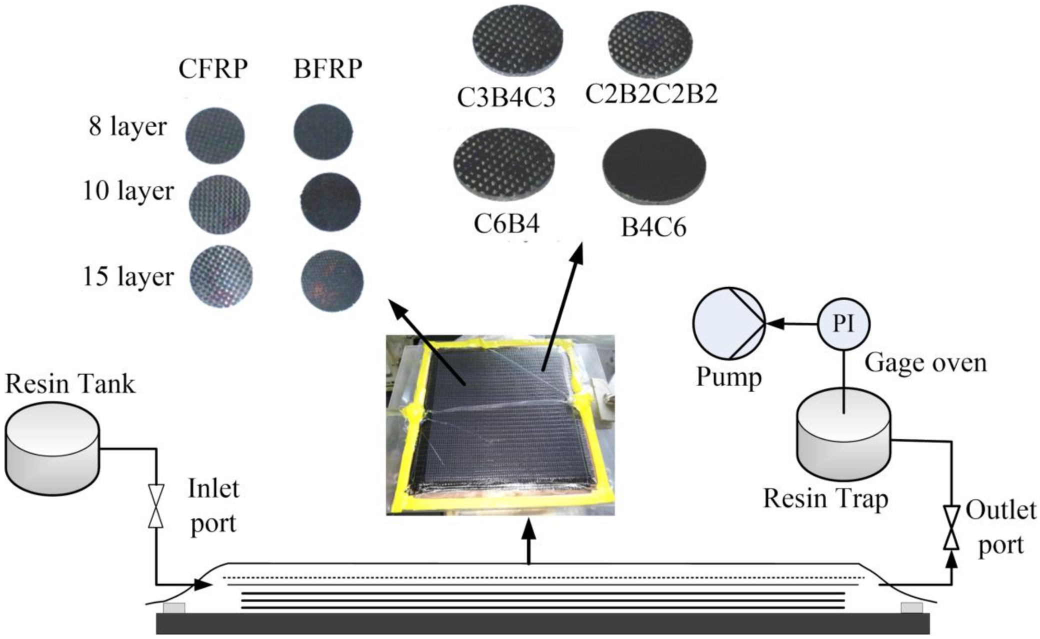

Figure 1 Injection procedure for hybrid composite manufacture

2.2. Manufacturing Procedure

Hybrid composite is fabricated using an injection molding procedure. The injection molding process is illustrated in Figure 1. It consist of five steps: fiber lamination and mold preparation, matrix preparation, injection process, curing, and specimen preparation. The sequence order is designed as [C_6/B_4]; [B_4/C_6]; [C_3/B_4/C_3]; and [C_2/B_2/C_2/B_2/C_2] as shown in Table 1 and Table 2. Capital letters [C] and [B] function as abbreviations of carbon fiber and basalt fibers, respectively. Suffix numbers are employed as code for the number of layers. The fiber orientation is 90/90 with 10 layers in total. Carbon fiber reinforced plastics (CFRP) and Basalt fiber reinforced plastics (BFRP) have been manufactured as controls. The difference in thickness between CFRP and BFRP was created using 8, 10 and 15 layers. For the test, each thickness was cut to a test specimen of 30 mm diameters.

Table 1 Thermal conductivity of hybrid composite

Composite Items	Code	Thickness (*m*)	Thermal Impedance [m^2K/W]	Thermal Conductivity [W/mK]
CFRP	CF-2	0.025	0.0043	0.276
BFRP	BF-2	0.019	0.0052	0.018
[$C_3B_4C_3$]$_{10}$	H_1	0.021	0.0052	0.187
[$C_2B_2C_2B_2C_2$]$_{10}$	H_2	0.020	0.0047	0.206
[C_6B_4]$_{10}$	H_3	0.021	0.0045	0.211
[B_4C_6]$_{10}$	H_4	0.020	0.0046	0.212

Table 2 Thermal conductivity of CFRP and BFRP

Composite Items	Code	Thickness [*m*]	Thermal Impedance [m^2K/W]
[CFRP]$_8$	CF-1	0.017	0.004
[CFRP]$_{10}$	CF-2	0.020	0.004
[CFRP]$_{15}$	CF-3	0.034	0.005
[BFRP]$_8$	BF-1	0.018	0.005
[BFRP]$_{10}$	BF-2	0.020	0.005
[BFRP]$_{15}$	BF-3	0.025	0.007

2.3. Data Analysis

The thermal conductivity of hybrid composites has been tested using the Guarded Heater Test Stack, based on the ASTM D5470 standard method. The schematic test is shown in Figure 2a. Three specimens of each variation of thickness and stacking sequence were tested at a temperature of 60±2^{o}C and at 20 kg applied loads. The specimens were tested using a consistent method for 60 minutes.

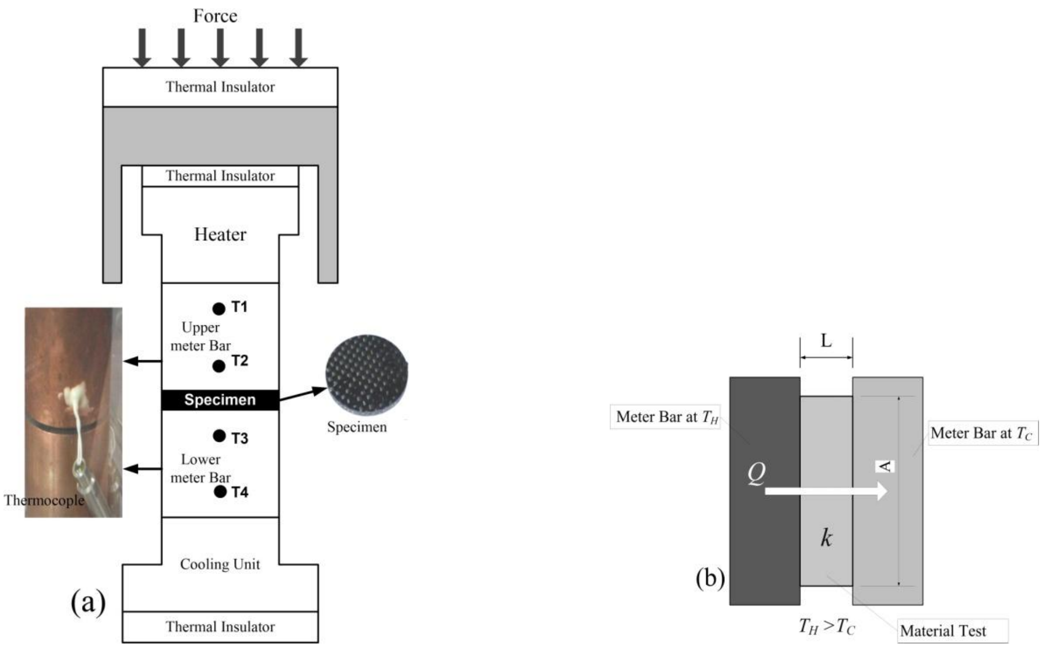

Figure 2 Schematic Test of Thermal Conductivity Set-Up by ASTM D5470 Standard

As illustrated in Figure 2b, there are two meter bars: a hot meter bar and a cold meter bar. The temperature of the hot meter bar surfaces that are in contact with the specimen can be calculated using the following equation;

$$T_H = T_2 - \frac{d_B}{d_A}[T_1 - T_2] \quad (1)$$

The side temperature of the specimen in contact with the surface of the cold meter bar can be calculated using the following equation;

$$T_C = T_3 - \frac{d_D}{d_C}[T_3 - T_4] \quad (2)$$

where T_H and T_C constitute the temperature of the hot meter bar and cold meter bar surfaces in contact with the specimen [K], respectively, T_1 and T_2 are the warmer and cooler temperatures of the hot meter bar [K], T_3 and T_4 are the warmer and cooler temperatures on the cold meter bar [K], d_A is the distance between T_1 and T_2 [m], d_B is the distance between the surface of the hot meter bar in contact with specimen to the T_2 (m), d_C is distance between T_3 and T_4 (m), d_D is the distance between the surface of the hot meter bar in contact with the specimen to the T_3 (m).

$$\theta = \frac{A}{Q}[T_H - T_C](\text{K.m}^2)/\text{W} \quad (3)$$

The thermal conductivity of the composite material according to proportional constants can be determined using the equation;

$$Q = \frac{KA(\Delta T)}{L} \tag{4}$$

$$K = \frac{L}{R}; R = \frac{(T_H - T_C)}{Q/A} \tag{5}$$

where Q is the heat flow rate of the isothermal surface [W], the area of the material test surface is A [m^2], and the specimen thickness or the gap of the meter bar is denoted as L (m), with R constituting the thermal resistance in surfaces.

3. RESULTS AND DISCUSSION

Theoretically, it is known that the properties of the composite materials are extremely dependent on the constituents used in the strengthening of the fiber and matrix. In order to improve the characteristics and the performance of FRP composites, hybridization is generally seen as a good solution. Yu et al. (2015) have looked into stacking sequences as one structural approach that can influence effective thermal conductivity (Yu et al., 2015). The thermal conductivity of carbon/basalt fiber hybrid composites with difference stacking sequences and specimen controls (CFRP and BFRP) are presented in Table 1. The results indicate that CFRP has the highest thermal conductivity at 0.276 [W/mK], 93% of BFRP at 0.018 [W/mK]. However, the thermal impedance of BFRP is highest with 0.0052 [m^2K/W]. CFRP has the lowest thermal impedance at 0.0043 [m^2K/W]. The thermal conductivity of hybrid composites is 0.187 to 0.212 [W/mK] depending on the stacking sequence. Thus hybridization is an effective way to modify thermal conductivity. Table 2 shows the thermal impedance of CFRP and BFRP, according to different numbers of layers and thicknesses. In both CFRP and BFRP, thermal impedance increases with higher numbers of layers. CFRP with 8 layers at 0.017 m thickness has the lowest thermal impedance: 0.004 m^2K/W. CFRP with 15 layers at 0.02 m thickness has the highest thermal impedance: 0.005 m^2K/W. BFRP with 8 layers at 0.018 m thickness has a thermal impedance of 0.005 m^2K/W. BFRP with 15 layers at 0.025 m thickness has a thermal impedance of 0.007 m^2K/W. It can be subsequently concluded that higher thickness produces higher thermal impedance. This can be effectively employed as a solution for thermal insulation and electrical devices.

Figure 3 shows the thermal impedance of hybrid composites with different carbon/basalt fibers stacking sequences for 10 layers in total. It shows that the thermal impedance of H1, H2, H3 and H4 decrease linearly from the thermal impedance of B_{10} (BFRP). The latter nonetheless has a higher thermal impedance than C_{10} (CFRP). It can be concluded that basalt fiber volumetric stability is maintained at a high temperature owing to basalt fibers nucleation at high temperatures (Borhan, 2013; Gori & Corasaniti, 2014). In these results, H1, with laminate orientation $C_3B_4C_3$, has a highest thermal impedance value compared with other stacking sequences models. At the same time, H2, H3 and H4 have similar thermal impedance values and an average difference in thermal impedance of stacking sequence hybrid composites compared to B_{10} of 9.7%. This shows that the stacking sequence is not a significant influence on thermal impedance.

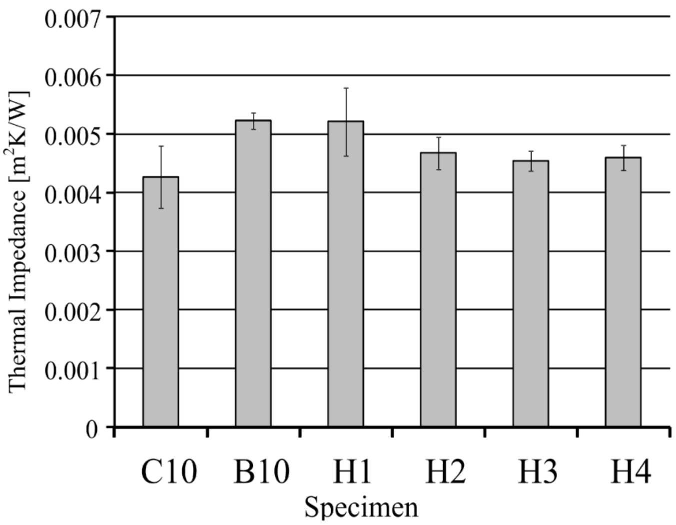

Figure 3 Thermal impedance hybrid composite of 10 layers

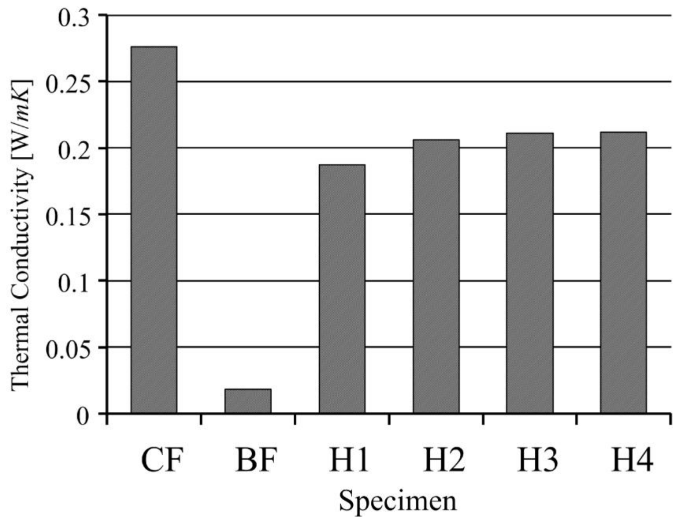

Figure 4 Thermal conductivity hybrid composite on 10 layers

Figure 4 shows the thermal conductivity of hybrid composites. Ten layers of reinforcement fibers (carbon fiber and basalt fiber) were stacked, based on the stacking sequence mode in the epoxy matrix. As is shown in Figure 4, thermal conductivity CFRP has a higher value than BFRP. Hybrid composites have a level of thermal conductivity between CFRP and BFRP. The comparison of thermal impedance as related to thickness of CFRP and BFRP is shown in Figure 5. Three of the thicknesses according to the number of layers CFRP and BFRP were tested: 8, 10 and 15 layers. Generally, for the same amount of fiber layers, BFRP exhibits a higher average thermal impedance of 20% compared with CFRP. However, BFRP with 8 layers at 0.018 m thickness has a thermal impedance of 0.005 m^2K/W, which is equal to CFRP with 15 layers at 0.034 m thickness. This suggests that basalt fiber has a higher temperature stability than carbon fiber. Result thus shows that basalt fiber is an excellent insulating material.

Figures 6a to 6c illustrate the internal condition of hybrid composites after the test. The internal condition of specimens are ascertained using a Scanning Electron Microscope (SEM) JEOL JSM 5900) at 10 kV with magnification of 20 µm, 100 µm, and 500 µm. As can be seen in Figure 6a, laminate basalt fibers in carbon fiber were carried out as stacking sequences.

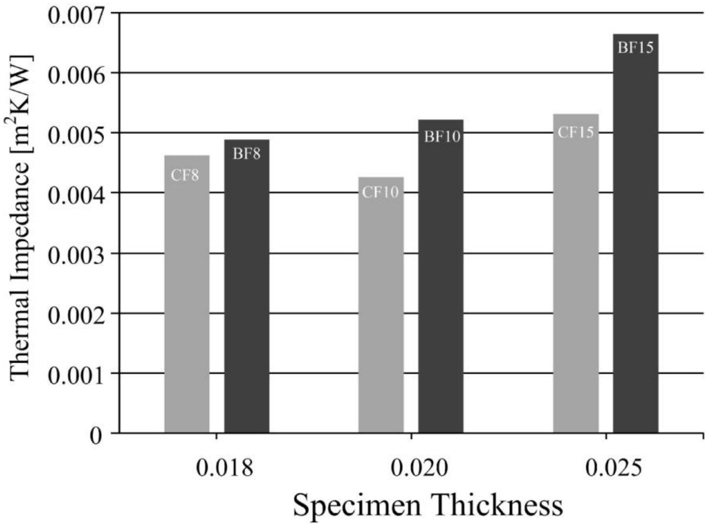

Figure 5 Thermal impedance of CFRP and BFRP based on composite thickness

Following heat transfer, no structural changes of the laminate between the carbon fiber and basalt fibers is detected, as the temperature of the test is lower than the melting temperatures of fibers. Temperatures are not high enough to alter material phases. Generally, damage occurs as a result of mechanical behaviors. Figure 6b shows the internal surfaces of BFRP after a heat transfer of 60^{o}C for as long as 60 minutes. Figure 6c shows the internal surfaces for CFRP during a similar process.

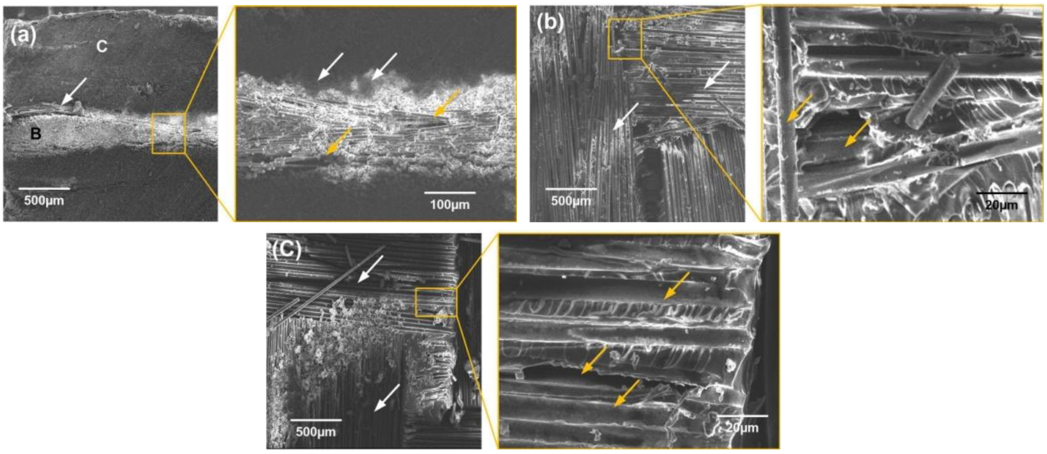

Figure 6 Internal condition of hybrid composites: (a) Carbon/basalt/epoxy hybrid composite laminate; (b) Internal surface of BFRP; and (c) Internal surfaces off CFRP

4. CONCLUSION

The results show that the stacking sequences of carbon/basalt fibers have a significant impact on thermal conductivity. Hybrid composites with the stacking sequence mode C3B4C3 exhibit the lowest thermal conductivity at 0.187 W/mK, and the highest thermal impedance at 0.0052 m^2K/W. The highest thermal impedance in BFRP is 0.007 m^2K / W with 2.5 mm thicknesses. In CFRP, the highest thermal impedance is achieved by 3.4 mm thicknesses with 0.005 m^2K/W. It is subsequently shown that carbon/basalt/epoxy hybrid composites operate as good insulators, because the thermal conductivity is smaller than the 0.42 W/m^{o}K standard. It can be concluded that stacking sequences in carbon/basalt/epoxy hybrid composite laminates is an effective way to modify the thermal conductivity of composite materials in engineering products. Moreover, basalt fiber has a higher temperature stability than carbon fiber. Basalt fiber is therefore an excellent insulating material. Furthemore, it can be concluded that temperature is an effective influence on material structure. However, material structures cannot change when temperatures are lower than melting temperatures.

5. ACKNOWLEDGEMENT

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