HEFAT2014
10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
14 – 26 July 2014
Orlando, Florida

HEAT TRANSFER AND TEMPERATURE DISTRIBUTION OF LAMINATED FIBER COMPOSITE BLOCK CONSTRUCTED BY USING AUTOCLAVE MOLDING AND HOT PRESSING PROCESS

Kim K.B.*, Kim S. L and Seo H. S.
*Author for correspondence
Department of Mechanical Engineering,
Chungbuk National University,
410 Sungbong-ro Heungduk-gu Cheongju Chungbuk 361-763,
South Korea,
E-mail: kimkb11@chungbuk.ac.kr

ABSTRACT

Carbon Fiber Reinforced Plastics (CFRP) composite materials employed for the number of years in space shuttle program have also gained popularity in other variety of industrial components requiring to be lightweight, but strong enough to withstand harsh mechanical and thermal loading conditions. A rigid structure is necessary to manufacture any mechanical part using the composite materials. The sole goal of this study is to investigate heat transfer phenomena and temperature distribution of a carbon fiber block fabricated by laminating epoxy-bonded carbon fiber sheets (prepreg) during curing them to bind together into a solid block. Two different curing methods of the hot press and autoclave were applied to create the carbon fiber block. The heat transfer phenomena including conduction, convection, and radiation during the process must be better understood because inhomogeneous temperature distribution over the carbon fiber block that affects melting and solidifying of resin could cause serious defect of the block. In this study, simulation studies were carried out for evaluating the temperature distribution inside the CFRP composite block, and the simulation results were validated with experimental data.

INTRODUCTION

Carbon/epoxy composite structures having advantages of hardness, light weight, and non-corrosiveness are widely used in numerous industrial applications and are expected to replace lots of metallic structures. The composite structures are built of B-stage carbon/epoxy pre-pregs that indicates carbon fibers pre-impregnated with epoxy. Carbon fibers often take the form of weave, and the epoxy bonds fibers together during curing process. The epoxy, one of common matrix is characterized by good resistance to chemicals, low shrinkage, and outstanding adhesional and mechanical properties. It is partially cured for easy handling and usually stored in cooled areas to prevent complete polymerization. Therefore, a carbon block built of pre-pregs requires a high-pressure/temperature molded laminating processes such as hot-pressing and autoclaving to cure.

The epoxy resin slightly coated on the carbon fibers undergoes gelation and vitrification during the curing process. Degradation may occur at higher temperature than vitrification point of the epoxy that varies with ambient pressure. The degradation will lead to a reduction in thermo-mechanical properties of the epoxy, resulting in serious defect of the carbon block. To avoid this, curing temperature must be increased gradually up to vitrification point, and the post curing temperature must be set below the degradation point. In general, a differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA) and a rheometer were employed to evaluate the

NOMENCLATURE

A	[s^{-1}]	Pre-exponential coefficient
H	[J/g]	Exothermic enthalpy from resin curing process
E	[kJ/mol]	Activation energy
k	[W/mK]	Thermal conductivity
R	[Pam^3/molK]	Universal gas constant
T	[K]	Temperature
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction
z	[m]	Cartesian axis direction
Special characters		
α	[%]	Conversion degree
ρ	[kg/ m^3]	Density
Subscripts		
r		Epoxy resin
xx		x-direction
yy		y-direction
zz		z-direction

cure kinetics and rheological behavior of the carbon/epoxy pre-preg [1-4]. Nth order equation in combination with values of the kinetic parameters obtained from experiments was then used to determine the vitrification temperature and conversion degree of the carbon/epoxy prepreg. It is crucial to understand the cure behavior of a thermosetting system in the development and optimization of composite fabrication processes. With this in mind, a simulation study was carried out to investigate heat transfer phenomena from the perimeter to the core of the carbon/epoxy block. This paper focuses on conductive heat transfer through the block and aims to provide some information on temperature distribution over the block during the curing processes.

THEORY

Since the epoxy resin curing process involves in an exothermic reaction, a transient heat conduction equation should contain non-linear internal heat generation term as expressed in

$$\rho_r V_r H_r \frac{d\alpha}{dt} + k_{xx}\frac{\partial^2 T}{\partial x^2} + k_{yy}\frac{\partial^2 T}{\partial y^2} + k_{zz}\frac{\partial^2 T}{\partial z^2} = \rho C_p \frac{\partial T}{\partial t} \qquad (1)$$

where, ρ_r is the density of the resin, V_r is the volume fraction, and H_r is the exothermic enthalpy from resin curing process.

The carbon/epoxy plain-weave pre-preg laminate is anisotropic such that the thermal conductivity depends on the fiber orientation. Figure 1 shows the dimension of the carbon/epoxy block. In-plane thermal conductivity, k_{xx} and k_{zz} are 2-3.5 W/mk, while transverse thermal conductivity, k_{yy} is 0.5-0.8 W/mk [5]. The property could vary greatly due to carbon /epoxy volume fraction. Coupling these two materials can often lead to a laminate that has a through-thickness thermal conductivity of less than 1 W/m°C. The curing rate of the resin is given by

$$\frac{d\alpha}{dt} = A\exp\left[-\frac{\Delta E}{RT}\right](1-\alpha)^n \qquad (2)$$

where, A is the pre-exponential coefficients, and ΔE is activation energies. From equation (2), the degree of cure can be described below

$$\alpha = 1 - \left[1-(1-n)A\cdot t\cdot\exp(-\Delta E/RT)\right]^{(1/(1-n))} \qquad (3)$$

NUMERICAL METHOD

A simulation study was performed using finite element method (FEM) with commercial software package (ANSYS CFX V13). The change in the temperature distribution of the carbon block resulting mostly from conductive heat transfer was investigated. The number of grid was around 420,000 for the simulation. Figure 2 describes schematic sketch of carbon/epoxy block for curing processes by hot pressing and autoclaving methods along with proper boundary conditions applied for the simulation. Boundary conditions are different on the hot pressing and autoclaving process. Regarding the hot pressing method, two hot plates press the carbon/epoxy block at the bottom and up during the curing. The identical plates were made of SUS, and the temperature of plates was kept at 135°C. Therefore, constant temperature boundary conditions were applied to the block. Relatively larger plates could cause convective and radiative heat transfer through the side surfaces of the block. Curing is normally occurred in a vacuum chamber, the radiative heat transfer may dominate the convective heat transfer. Constant heat flux boundary conditions were applied to the side of the block. The heat flux on the front and rear sides was 71.76 $\mathrm{Wm^{-2}}$ while the right and left side was 46.13 $\mathrm{Wm^{-2}}$.

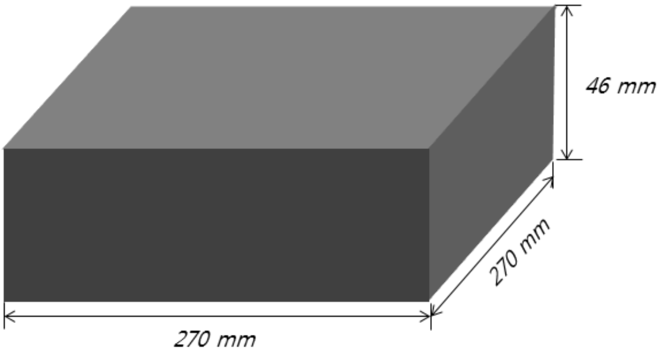
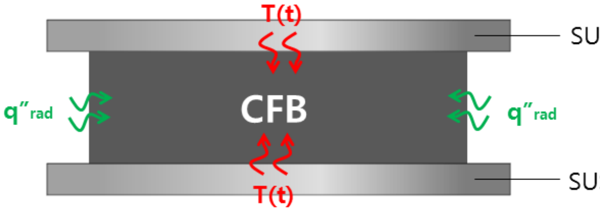
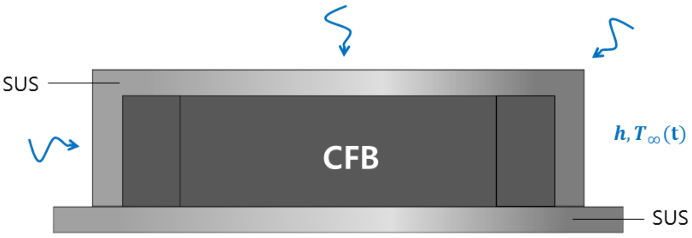


Figure 1 Dimension of a carbon/epoxy block used in this study

For the autoclaving process, small pieces of cured carbon blocks were placed at four sides of the uncured carbon/epoxy block to prevent of potential distortion during the process. The set of blocks were then placed on SUS pan with a sealed cover, and put it in the oven chamber. The temperature in the chamber was maintained at 135°C, so the convective heat transfer boundary condition was considered for preliminary study.



Hot pressing



Autoclaving

Figure 2 Two curing processes for the carbon/epoxy block along with boundary conditions

However, a constant high heat rate is normally avoided since large temperature deviation between the surface and the core of the carbon block is undesirable. It can cause incomplete cure of the core area, but the degradation of epoxy in the perimeter of the block. Therefore, a cure cycle constituted of several steps was employed. Steps are initially gradual temperature increase (heating rate of 2 ^{o}Cmim^{-1}) followed by two isothermal heating, and post cooling. As mentioned before, the degradation usually occurs at high temperature, so the post curing temperature must be set below the degradation temperature. Figure 3 shows the cure cycle used in this study.

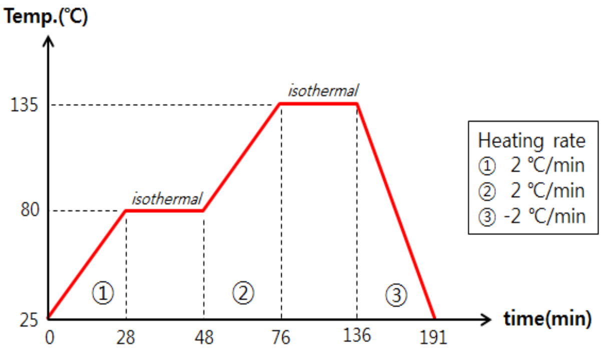


Figure 3 Temperature input profile for cure cycle comprised of two temperature ramps, two isothermal processes, and post cooling

RESULTS AND DISCUSSIONS

The conversion degree of epoxy resin was calculated using the kinetic equation (3) and experimental data [1]. Figure 4 shows the conversion degree as a function of temperature.

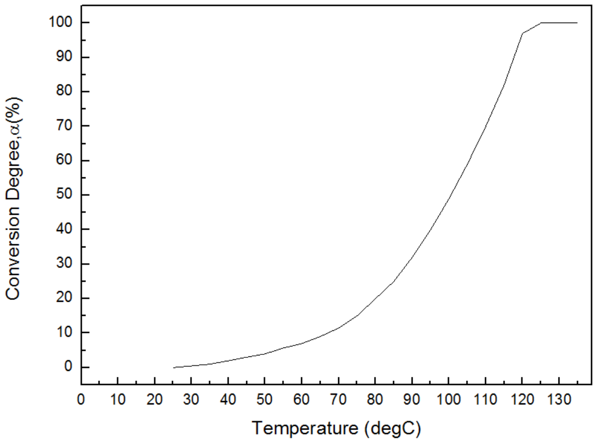


Figure 4 Degree of conversion for the carbon/epoxy prepreg as function of temperature

The gelation temperature was approximately 60^{o}C at which the epoxy resin starts the conversion. The conversion was completed when the temperature reached around 120^{o}C. To predict the temperature distribution inside the block, it is necessary to determine appropriate heat conduction coefficient that could be varied greatly. According to previous studies, the possible of the coefficient is in the range of 0.2 to 0.8 [W/mK]. The simulation was carried out with a constant heat conduction coefficient. Figure 5 shows the minimum temperature deviations between the core and surface for different conduction coefficients.

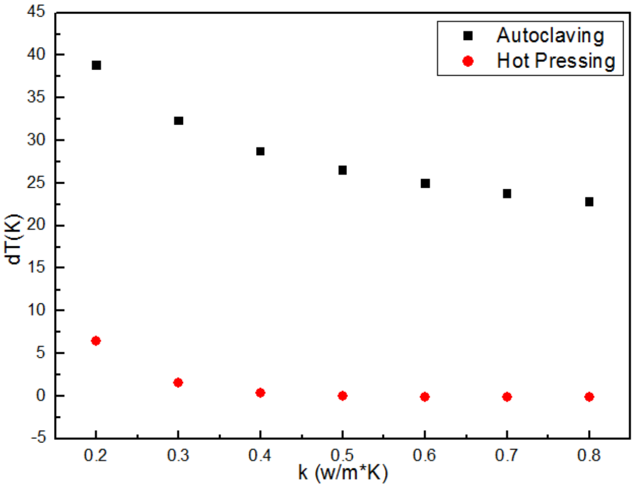


Figure 5 Temperature deviations between the core and surface for different conduction coefficients

The carbon/epoxy laminate is not homogeneous such that the heat transfer rate varies all over the block. As a result of the heat isolation, the temperature distribution is hardly predictable. Curing rate is also affected by the unpredictable heat transfer rate, which was described in terms of the heat conduction coefficient. The higher value represents the better heat transfer; hence, the temperature difference between the core and the surface (135 ^{o}C) is low. From the figure 4, the epoxy resin conversion degree was completed at 120^{o}C, so the overall conduction coefficient must be more than 0.8 [W/mK]. Figure 6 shows the temperature distribution of the block at 136 minutes of the cure cycle. The block was composed of tiny discrete blocks having different conductivity from 0.2 to 0.8 [W/mK]. The conductivity was assigned randomly to each block. It was observed that relatively lower temperature was observed at some areas where the epoxy polymerization might be incomplete.

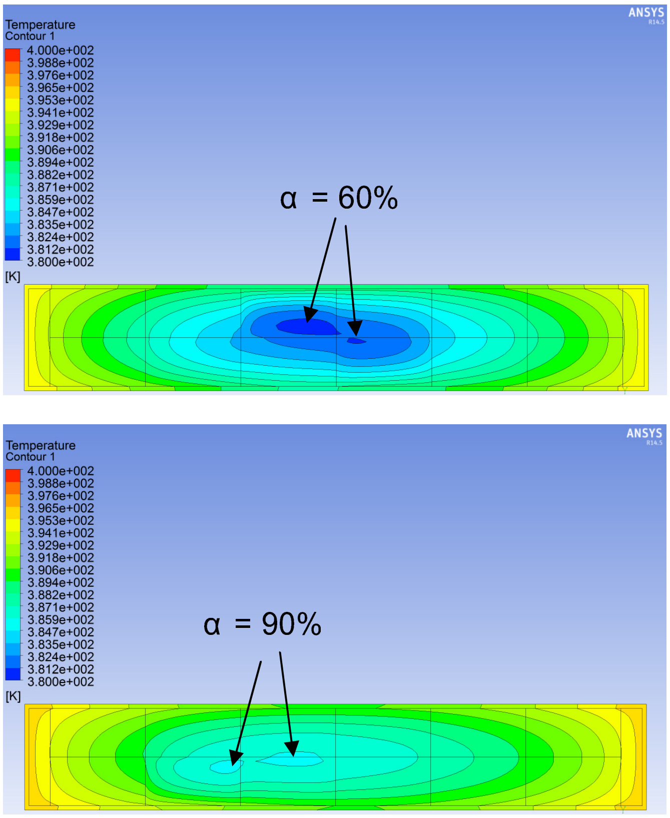


Figure 6 Temperature distribution of the cross section of the block

CONCLUSION

This is on-going study to provide the intuitive idea of the temperature distribution of the carbon/epoxy block using the heat conduction coefficient. A three dimensional FEM model was developed, and the heat conduction coefficients were randomly assigned in discrete volumes to simulate heat transfer characteristics affected by vitrification effect of the epoxy resin during curing reaction. Monte carlo simulation method in combination with C-scan data will be helpful to develop suitable model that can properly predict the temperature distribution comparable with experiment data.

REFERENCES

[1] Michelle L. C., Botelho E. C. de Paiva J. M. F., and Rezende M. C., Characterization of cure of carbon/epoxy prepreg used in aerospace field, *Materials Research*, Vol. 8, No. 3, 2005, pp.317-322

[2] Kim D. H., and Kim S. C., Vitrification effect on the curing reaction of epoxy resin, polymer Bulletin, Vol. 18, 1987, pp. 533-539

[3] Zhang J., Xu Y. C., and Huang P., Effect of cure cycle on curing process and hardness for epoxy resin, *Polymer Letter*, Vol. 3, No. 3, 2009, pp.534-541

[4] Shevtsov S., Zhilyaev I., Soloviev A., Parinov I., and Dubrov V., Optimization of the composite cure process on the basis of thermo-kinetic model, *18th International Conference on Composite Materials*

[5] Tian T., Anisotropic thermal property measurement of carbon-fiber/epoxy composite materials, Ph.D dissertation, *University of Nebraska - Lincoln*