[Technical Paper]

Numerical Computation Technique to Examine Glass Fiber Mat and Cloth Reinforcement of Glass-Fiber-Reinforced Plastic

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Abstract: TDK is developing a wireless power transfer technology for electric vehicles (EV) that is based on two coils: one built into roads, parking spaces, or garages and the other fitted to the underbody of the car. One of these coils is the power transmission coil, and the other is the receiving coil. The receiving coil receives the magnetic field generated by the power transmission coil. Furthermore, the rectifier rectifies the alternating current to direct current. A coil case with magnetic and conductive properties produces an eddy current and decreases the power efficiency. Therefore, non-magnetic and non-conductive materials must be adopted in the design of the coil case. Furthermore, the coil case must protect the coil, ferrite cores, and the electronic component array. According to the Underwriters Laboratories Inc. (UL) standard, a vehicle overdrive test must be performed on the power transmission coil such that even if a vehicle rides on the power transmission coil case, it should not be damaged. In addition, a prototype of the power transmission coil case made of glass-fiber-reinforced plastic was created. During the glass-fiber-reinforced plastic molding process, the glass fiber bundle slipped and air gaps were formed. We decided to consider the scale of three patterns: micro, macro, and mesoscale. After considering the three scales, the experimental results and calculated results matched with high accuracy.

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1. Introduction

Recently, electric vehicles (EV) have attracted considerable attention because they can prevent global warming and save natural resources such as oil. They can also reduce carbon dioxide by using renewable energy, including solar and wind energy. The government predicts that the number of EV and plug-in hybrid EV (PHEV) will increase in the near future [1]. As the number of EV and PHEV vehicles increases, the number of chargers to be installed will also increase. The government has predicted the installation of 2 million normal chargers and 5 million quick chargers by 2020. TDK has developed a wireless power transfer technology (Figures 1 and 2) that can transfer 3 kW between two coils with an efficiency higher than 96.5%. The interval of the two coils is 100–160 mm, and the frequency of the AC power is 81–90 kHz. This technology will enable EV

users to charge the battery without connecting any cables. The technology is based on two coils: one coil built into roads, parking spaces, or garages and the other fitted to the underbody of the car. A coil case with magnetic and conductive properties produces an eddy current and decreases the power efficiency. Therefore, it is necessary to apply non-magnetic, non-conductive plastic or ceramic materials as the coil case material. However, their materials strength is generally low. Furthermore, the coil case must protect the coils, ferrite, and electric parts (Figure 3). According to the UL standard, a vehicle overdrive test must be performed on the power transmission coil such that even if a vehicle rides on the power transmission coil case, it should not be damaged. The load of the car tire was assumed to be about 5 kN. Glass-fiber-reinforced plastic was selected as the material of the coil case. It is very important to estimate the strength of a coil case made of the glass-

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fiber-reinforced plastic while designing. Consequently, the Young's moduli of the glass-fiber-reinforced plastics were estimated by applying the homogenization method to regular material composition and the value obtained by averaging the elastic modulus by laminating theory to irregular material composition. The prototype of a coil case made of the glass-fiber-reinforced plastic was designed and fabricated. In addition, the Young's moduli of the calculation and the prototype were compared. As a consideration, when the prototype was examined, air gaps were observed in the laminated part of the composite material. Therefore, the scales were defined for the analysis. First, the microscale was defined as a scale that can express the characteristics of glass fibers in micrometer order such as the irregularity of glass mat and the regularity of glass cloth. Next, the macroscale was defined as a scale that can express the characteristics of the composite material in millimeter order such as the regular placement of resin, glass mat, and glass cloth. Finally, the mesoscale was defined as a micrometer to millimeter order unit to measure the air gap in the laminated part of the matrix and the glass fiber. The material irregularity due to the material process could be expressed by mesoscale. A schematic of the defined model is shown in Figure 4. By comparing these three scales and the glass-fiber-reinforced plastic while considering regularity and

Fig. 1 Wireless Power Transfer System developed by TDK Corporation

Fig. 2 Components of the system

Fig. 3 Structure of the coil case

irregularity, the calculation result was compared with the experimental result.

2. Material

2.1 Composite material structure

Plastic materials strength is generally low. Glass-fiber-reinforced plastic was selected as the material of the coil case. In the glass-fiber-reinforced plastics, an unsaturated polyester resin was used as a matrix resin. Then, the simplest method called hand lay-up was used to fabricate the molding glass-fiber-reinforced plastic, which is a low-pressure molding method. The glass fiber mat and cloth were sequentially arranged in the mold. Unsaturated polyester resin was used as the gel coat and was applied to the mold using a spray, brush, and roller. The prototype (length: 600 mm; width: 600 mm; height: 55 mm; thickness: 6.88 mm) is shown in Figure 5. The fiber direction of the glass fiber mat is random (Figure 6), whereas the fiber direction of the glass fiber cloth extends in the cross direction (Figure 7). In this prototype structure, the glass fiber mat and glass fiber cloth are laminated in turn. The physical properties of the materials are shown in Tables 1 and 2, and the structure of the coil case was analyzed to

Fig. 4 Schematic of the defined model

estimate the strength. Table 3 shows the equipment and the condition used for structural analysis of the coil case. The laminate constitution of the test pieces was examined. Every laminated piece was separated with tweezers and observed. A microscope was then used to observe the laminated structure of the composite materials, and the weight ratio of the glass fibers in the glass-fiber-reinforced plastic was examined. The width, thickness, and interval of the glass fiber bundles were then measured. The purpose of measuring the interval of the glass fiber bundle is to obtain the periodic function of the glass fiber cloth. Thus, to apply the homogenization method to the glass fiber cloth, it is necessary to define its periodicity as a characteristic function. Hence, three samples were prepared and three places at random on each sample were measured. The values shown in Table 4 are average values, and the coil case was constructed in the order of $2M + C + M + C + M + C$

+ M (M: glass fiber mat, C: glass fiber cloth) (Figure 8).

Fig. 6 Glass fiber mat

Fig. 7 Glass fiber cloth

Fig. 5 Prototype coil case

Fig. 8 Glass fiber laminating structure of the coil

Table 1 The physical properties of the glass

Physical characteristics	Unit	
Density	g/cm ³	2.60
Tensile strength	GPa	3.20
Modulus of elasticity	GPa	75.00
Maximum elongation	%	4.80
Poisson's ratio		0.20

Table 2 The physical properties of the unsaturated polyester resin

Physical characteristics	Unit	
Density	g/cm ³	2.00
Tensile strength	MPa	55.90
Modulus of elasticity	GPa	3.90
Maximum elongation	%	1.20
Poisson's ratio		0.27

Table 3 The laminated constitution observation

Test device	Muffle furnace (FP-31, Yamato Scientific Co., Ltd.)
	Electronic force balance (PG1003-3, Mettler-Toledo International Inc.)
Processing condition	650°C for 2 h
Measurement apparatus	Digital microscope (DVM2500+VZ700C, Leica Microsystems Co., Ltd.)

Table 4 The measurement of the glass fiber bundle

	Glass fiber bundle (mm)		
	Interval	Thickness	Width
Average	3.54	0.35	3.68

2.2 Tensile test

A test sample was cut from the coil case to perform the tensile test. The size is Japanese Industrial Standards (JIS) standard 1 B series B form. JIS K 7164 is used as a test method, and Table 5 shows the tensile test conditions. The Young's moduli and the Poisson's ratios were calculated from the stress gradient of 0.05%–0.25% of the distortion section (Table 6).

Table 5 The tensile test conditions

Testing method	JIS K7164 conformity
Measuring item	Young's modulus, Poisson's ratio
Shape of the test piece	1B series B form (Parallel part width 25mm)
Test condition	Elastic stress rate 1mm/min
	A cross pair of strain gauges (KFG-5-120-D16-23, Kyowa electronic instruments Co., Ltd.)
	Number of samples 3 (Cutting direction 0°, 45°)
Test environment	Temperature 23 ± 2°C, Humidity 50% ± 5% RH
Measurement apparatus	Universal tester (55R-4206, Instron Corporation)
	Dynamic response characteristic of strain gauge (DPM-711B, Kyowa electronic instruments Co., Ltd.)

Table 6 The tensile test results

	Cutting direction	Young's modulus (GPa)	Poisson's ratio
Average	0°	15.41	0.21
	45°	10.02	0.42

3. Simulation method

3.1 The homogenization method [2]

The homogenization method was used for the glass fiber cloth, and the method can be applied to a region wherein the macro field is uniform and periodicity is satisfied. A displacement function is the sum of the disturbance displacement due to the uniform deformation and heterogeneity (Equation 1). The advantage is that the characteristic displacement can be numerically obtained by micro analysis and the homogenization constant in macroscopic analysis can be calculated. It is also possible to localize the deformation of the microscopic structure using the homogenization constants obtained by macroscopic analysis. However, the disadvantage is that it is difficult to predict the actual microscopic structure of the mechanical response of irregular composites.

$$u(y) = \varepsilon y + u^* \quad (1)$$

u : Displacement, y : Micro Scale, ε : Strain, u^* : Disturbance displacement

The macro mathematical homogenization Young's modulus E^H of the entire structure is

required. As unit macro strain $\varepsilon=1$, the issue of the boundary value for periodic response displacement $u^* = -\chi(y)$ is addressed as follows (Equation 2).

$$\begin{aligned} \frac{d\sigma(y)}{dy} &= 0, \text{ in } Y = (0,1), \sigma(y) = E(y)\varepsilon(y), \varepsilon(y) \\ &= \frac{du(y)}{dy} = 1 - \frac{d\chi(y)}{dy} \end{aligned} \quad (2)$$

Y : Macro scale

The macro mathematical homogenization Young's modulus E^H was calculated when we performed a volume average of Y about stress as follows (Equation 3).

$$E^H = \Sigma = \langle \sigma \rangle = \langle E\varepsilon \rangle = \langle E(y) \left(1 - \frac{d\chi(y)}{dy} \right) \rangle \quad (3)$$

Σ : Stress of macro scale

σ : Stress of micro scale

$\langle \rangle$ is the volume average when the length of the micro structure is assumed as $|Y|=1$.

3.2 The value obtained by averaging the elastic modulus by laminating theory [3]

The randomly reinforced plastics is uniformly distributed in a range of $\alpha = -\frac{\pi}{2}$ to $\frac{\pi}{2}$ (Figure 9), and assumes that unidirectional reinforcements in any direction are laminated under a uniform distribution function. We use the value obtained by averaging the elastic modulus by laminating theory as Young's modulus of randomly reinforced plastics in the glass mat (Equation 4).

$$E_{GM} = \frac{(E_L' + E_T' - 2E_L'v_T + 4G_{LT})(E_L' + E_T' + 2E_L'v_{GM})}{3(E_L' + E_T') + 2E_L'v_T + 4G_{LT}} \quad (4)$$

$$E_L' = \frac{E_L}{1 - v_Lv_T}, E_T' = \frac{E_T}{1 - v_Lv_T}$$

$$v_{GM} = \frac{E_L' + E_T' + 6E_L'v_T - 4G_{LT}}{3E_L' + 3E_T' + 2E_L'v_T + 4G_{LT}}$$

$$E_L = E_mV_m + E_fV_f$$

$$\frac{1}{E_T} = \frac{1.36(K_f - K_m)}{(K_f - K_m)^2 - (v_fK_f - v_mK_m)^2} + \frac{1 - 1.05\sqrt{V_f}}{E_m}$$

$$K_f = \frac{E_f}{(1 - v_f^2)}, K_m = \frac{E_m}{(1 - v_m^2)}$$

$$v_L = \frac{1.05\sqrt{V_f}(v_f - v_m)K_f}{K_f - K_m} + v_m$$

$$v_T = v_L \frac{E_T}{E_L}$$

$$\frac{1}{G_{LT}} = \frac{1.36}{G_f - G_m} + \frac{1 - 1.05\sqrt{V_f}}{G_m}$$

$$G_f = \frac{E_f}{2(1 + v_f)}, G_m = \frac{E_m}{2(1 + v_m)}$$

E_{GM} : Young's modulus of randomly reinforced plastics (Glass mat)

V_{GM} : Poisson's ratio of randomly reinforced plastics (Glass mat)

E_L : Young's modulus of fiber horizontal direction

E_T : Young's modulus of fiber vertical direction

E_f : Young's modulus of fiber

E_m : Young's modulus of matrix

V_f : Fiber content

V_m : Matrix content

K_f : Bulk modulus of fiber

K_m : Bulk modulus of matrix

V_f : Poisson's ratio of fiber

V_m : Poisson's ratio of matrix

V_L : Poisson's ratio of fiber horizontal direction

V_T : Poisson's ratio of fiber vertical direction

G_{LT} : Elastic shear modulus of fiber horizontal direction

G_f : Elastic shear modulus of fiber

G_m : Elastic shear modulus of matrix

Fig. 9 Laminate of randomly oriented layers

4. Simulation technique

The Young's modulus for the composite material was calculated using the homogenization method and the value obtained by averaging the elastic modulus by laminating theory. The coil case was composed of 2M + C + M + C + M + C + M (M: glass fiber mat, C: glass fiber cloth) using an unsaturated polyester resin as a matrix. In the estimation of Young's modulus in the fiber direction, the homogenization method was applied to the glass fiber cloth, the value obtained by averaging the elastic modulus by laminating theory was applied to glass fiber mat, and the homogenization method was applied to a laminate structure of the composite material. The explanation contents are shown in Figure 10 and 11. Furthermore, Multiscale.Sim made by Cybernet Systems Co., Ltd.

was used for the homogenization method. This software is a micro and macro scale analyzable simulation based on the homogenization method [4–7] when the composite material is periodic. In other words, it calculates the macroscale material constants by homogenizing the microscale material constants. In addition, it can perform micro scale detailed analysis by localizing the macroscale part, and the characteristic to be considered in the macroscale governing equation is the body force (The force proportional to the volume and mass of the substance). The characteristic to be considered in the microscale governing equations [8, 9] is the disturbance displacement. In this analysis, homogenization analysis was mainly performed as the numerical material test. The displacement of the micro structure is the sum of the uniform displacement and the periodic disturbance displacement due to nonhomogeneity. Lastly, the Young's modulus of the homogenized unit cell was obtained from the analysis result by integrating the stress of the unit cell and taking the volume average of the unit cell [10–12].

5. Discussion

A test sample (width: 40 mm; length: 40 mm; thickness: 6.8 mm) was cut from the coil case, and its cross-section was observed using a digital microscope (at $35\times$ magnification). Figure 12 shows a photograph of the section observation, and the matrix thickness of the outermost layer of the cut surface was about $200\text{ }\mu\text{m}$. As a result of this observation, some air gaps were found in the laminated structure of the glass mat, the glass cloth, and the matrix. The cause of

some air gaps were presumed to be the molding method. The simplest method called hand lay-up was used for molding the glass-fiber-reinforced plastic. This method is a low-pressure molding method, and some air gaps were formed in the laminated structure due to insufficient pressurization during heat curing. Moreover, some air gap size was measured with a digital microscope, and the volume ratio of some air gaps in the composite material was 30%. The mesoscale was defined as a micrometer to millimeter order unit such that the air gap in the laminated part of the matrix and the glass fiber, as well as the material irregularity, was expressed by the manufacturing process on this scale. Conventionally, some methods based on the equivalent inclusion method [13] and the Weibull probability distribution method [14] have been studied for calculating the physical properties of a composite material containing probabilistically certain material. However, as a result of this observation, some air gaps were confirmed to be scattered along the glass fiber lamination. Therefore, the experimental result was compared with the calculation result by using the rule of mixture for estimating the Young's modulus of the composite material in the fiber direction. The Young's modulus calculation procedure of the composite material is shown in Figure 13 based on the previous discussion.

6. Result

The Young's moduli in the direction of the glass fiber were compared in the experimental and the numerical material test. The experimental result was

Fig. 10 Calculation process 1 (Microscale)

Figure 1 illustrates the manufacturing process of the G2MCGCMGCGM^H composite material. The process begins with a 2M (two glass fiber mats) and C (glass fiber cloth) layer, which is laminated to form a C layer. This is then laminated with an M (glass fiber mat) layer to form an M layer. This process is repeated to form the final G2MCGCMGCGM^H structure. The diagram shows the sequence of layers and the lamination steps.

the average value of the number of samples $n = 3$. As shown in Table 5, the sample shape was a 1 B series B form shape according to JIS K 7164 test method. This shape was also imputed to the tensile test simulation, and the laminate structure of 2 M + C + M + C + M + C + M (M: glass fiber mat, C: glass fiber cloth) was inputted using the unsaturated polyester resin as a matrix. Furthermore, the numerical material testing function of Multiscale.sim was used to simulate the tensile test (Figure 14). Finally, the rule of mixture was applied to the numerical material simulation result to consider the volume ratio of some air gaps, and the difference between the experimental and simulation result was about 4% (Table 7).

- The homogenization method was applied to the glass fiber cloth, and the value obtained by averaging the elastic modulus by laminating theory

Fig. 13 Additional calculation process (Mesoscale)

- The homogenization method was applied to the laminate structure of the glass fiber cloth, the glass fiber mat, and the matrix resin on the macroscale.
- As a result of the prototype observation, some air gaps were scattered along the glass fiber lamination. Therefore, the volume ratios of the air gaps and the composite material were divided into the high and low glass fiber densities, and the Young's modulus of the composite material in the fiber direction was estimated using the rule of mixture.

Moreover, as a result of about 4% error, the following was considered: First, the cross-section observation image of the prototype in digital image was obtained. The acquired image was expressed in

Fig. 14 1B series B form of the composite material

Table 7 The results of tensile test in the experiment and simulation

X-Y direction Young's modulus (GPa)	Experiment (GPa)	Simulation (GPa)	Error (%)
0°	15.41	15.92	3.28
45°	10.02	10.39	3.74

density with 8 bit gradation. At this time, the gray level of the image was selected as black or white depending on the threshold value. Lastly, the image-volume ratio of the air gap in the composite material changed based on the threshold value. Therefore, it seems that about 4% error occurred in the calculation and the experiment result depending on how to decide the threshold value.

7. Conclusion

The material properties for the micro, macro, and mesoscale were evaluated to estimate the Young's moduli of the glass-fiber-reinforced plastics. The material irregularities by the manufacturing process were then measured. Consequently, the material irregularities and some air gaps in the mesoscale were modeled and highly precise analytical data were obtained. An effective method for trial verification was also obtained, and this method will be applied to prototype wireless power transmission coil cases for EVs in the future studies.

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