Improvement of thermal radiation characteristic of AC servomotor using Al-CNT composite material

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Abstract. This study deals with a high thermal conductivity material of aluminum-carbon nanotube (CNT) composite with carbon fiber (CF) and the high radiation performance of AC servomotor using a stator made of nanotube composite material. The composite fabrication process was performed by melting a mixture of granular aluminum of less than 200 μm and CNT under conditions of pressed atmosphere at the same time. Two kinds of motors made using aluminum and the composite were evaluated to confirm the effect of thermal conductivity as the motor stator. A test rod of the composite with 14 wt% CF-7 wt% CNT-aluminum indicated the excellent thermal conductivity of 169 W/(mK) in the radial direction and 173 W/(mK) in the lengthwise direction. According to the obtained temperature radiation characteristic of the AC servomotor, the composite stator using CNT decreased the consumption energy to 16% compared to the conventional one. As a result, the highly efficient motor improved the radiation characteristic using the CNT composite stator.

1. Introduction
In recent years, nanotechnology has been hoped to impact industrial products in the future. Especially, nanocarbon material is becoming a central focus of public attention, and it has many structures with regard to form and crystallization, so there is a good possibility of its wide application in the industry as a material with easy manufacturing characteristic. A particularly important and topic material is carbon nanotube (CNT), which is useful with an excellent thermal conductivity of about 1000 W/(mK). CNT is a structure with a six-membered carbon ring, rolled and combined periodically; its perfect form consists of rolled multilayers that form a concentric circle structure. Its outside diameter is dependent on the number of layers and fabrication methods using physical vapor growth. The structure is classified as one layer of single-walled CNT (SWCNT), two layers of double-walled CNT (DWCNT), and a multi-walled CNT (MWCNT) [1]. Research and development have started from vapor growth carbon fiber (VGCF) 100 years ago. In the 1800s, it was found that VGCF with slender fiber form was made by thermal decomposition method from CH₄ or C₂H₂. In the 1990s, it was first made by Hyperion Catalysis Internal, Inc. and Showa Denko K.K. [2] using the industrial process. There are three kinds [3] of manufacturing processes, which are physical vapor deposition (PVD), chemical vapor deposition (PVD), and organic precursor route method. The fabrication methods are similar to that of the CF.
The results of CNT are applicable to the body constructive material of an airplane [4] as a composite with resin mixed CNT and a Li-ion electric battery [5] to store the energy.

This study was developed to determine (1) the high thermal conductivity of the Al-CNT material by adding the CF material and (2) the high radiation performance of the AC servomotor using the stator made by the Al-CNT composite.

The contents of this study are as follows:
- Evaluation of the thermal conductivity, mechanical strength, and thermal expansion,
- Thermal simulation of the AC servomotor using the Al-CNT stator, and
- Radiation evaluation of the AC servomotor using the Al-CNT composite to be applied in stator.

2. Fabrication and basic characteristic of the Al-CNT composite

2.1. Fabrication of the Al-CNT composite

The CNT made by Showa Denko was VGCF created using the CVD method, which at the same time created the carbonization and fiber formations, and the structure was SWCNT of approximately 200 nm in diameter and 200 μm in length. Figure 1(a) and 1(b) show a schematic CNT image and a SEM formed Al-CNT composite, respectively. The aspect ratio was about $10^4$, and the outward appearance was like a black cotton. It was found that there was no affinity between melted Al and CNT. The formation process included CF lattice sheet to obtain affinity characteristics. Additionally, it was a necessity to have an anisotropic thermal conductivity of the Al-CNT composite to obtain the high performance of thermal radiation, as CNT has high anisotropic thermal conductivity of about 1000 W/(mK) in length. A fabrication process was performed by melting a mixture of granular Al of 200 μm and CNT at pressed atmosphere at same time. A fabricating condition and a formed Al-CNT composite are shown in Table 1 and Figure 2, respectively.

2.2. Thermal and mechanical characteristics of the CNT composite

The fabricated CNT rod composites were measured and evaluated for thermal conductivity in radius $r$ and lengthwise $z$ directions and mechanical breaking stress. As listed in Table 2, the sum total of Al and CNT was set to about 27 wt%. The evaluating instruments are as follows: thermal conductivity using LFA457 (Netzsch) of sample size of about 10 mm in diameter and 3 mm in thickness, breaking stress using the Instron-type testing machine (Shimadzu Corporation), and coefficient of thermal expansion using Advance Riko, Inc. The test pieces were 5 mm in diameter and 20 mm in length.

A conventional Al using die casting for the motor stator has 92 W/(mK) thermal conductivity and 280 MPa breaking strength. However, the characteristic from the fabricated CNT composite was more than the conventional values. As shown in Table 2, the test piece of No. 2 indicated an excellent value of
169 W/(mK) in the radial direction and 173 W/(mK) in the lengthwise direction. Additionally, it was found that breaking strength increased in correspondence with increasing CF component. There is an attention point that the maximal thermal conductivity obtained 23 wt% CNT and other points have values less than it.

Table 1. Fabrication conditions of the Al-CNT composite.

| Material       | Al (ADC12) | Less than 0.2 (mm) |
|----------------|------------|--------------------|
| CNT (Showa Denko) | 200 nm diameter | 200 µm length |
| CF (TORAY)     |            |                    |
| Formed condition | Melting temperature | 680 °C |
|                | Formed pressure | 9.8×10⁴ N |

![Fabrication conditions of the Al-CNT composite.](image)

3. Thermal simulation of the motor

3.1. Analytical model and boundary condition

The thermal simulation of the AC servomotor with a square flange size of 100 mm used ANSYS thermal software (FEM) [6,7]. The analytical machine conditions and thermal conductivity of parts are shown in Table 3. An analysis model scale is selected in one-four size in the direction of circumference, and parts of the heating source are set to winding coils in a stator. The boundary condition assumed that the generated heat in coils radiated to the air through the stator and both blankets (front and back). The element of FEM used was a three-dimensional tetrahedron with 10 nodes.

The result of thermal conductivity under the condition of a half-symmetric structure about the motor that used Al (ADC12) frame is shown in Figure 3. It was set that a quantity of heat from the coils was 85 W/m³, the external temperature of stator flame was 15 °C, and the thermal conductivity of the
frame was 92 W/(mK). As a result of the steady-state analysis, the temperature of coils and surfaces of the stator frame was 122 °C and 60 °C, respectively. Therefore, it was considered that the coil temperature increased to 107 °C at the rated operating condition of motor with current of 5.7 A on AC 200 V and the temperature of the stator increased to 45 °C.

### Table 3. Thermal analysis condition of the FEM machine and thermal conductivity of parts.

| Item                          | Condition / Value               |
|-------------------------------|---------------------------------|
| Simulating machine           | Intel Celeron CPU, 600 (MHz)    |
| Time                          | 8 (min)                         |
| Solver                       | ICCG method, δ₄/₄<1.0e⁻⁷        |
| Number of node                | 122,073                         |
| Number of element (Tetrahedron with 10 nodes) | 85,197                         |
| Parts (Material)              | Thermal conductivity (W/ (mK))  |
| Rotor of motor (Fe)           | 83.6                            |
| Gap, Space (Air)              | 0.0241                          |
| Front/Rear blanket (Al)       | 92.0                            |
| Stator frame (Al)             | 92.0                            |
| Stator frame (Al-CNT)         | 36.0 - 232                      |
| Coil (Cu)                     | 403                             |
| Molding of stator (Epoxy)     | 0.95                            |

3.2. Simulation of thermal conductivity on the motor that used CNT composite

The conventional thermal conductivity using Al stator in the motor frame was 92 W/(mK). However, in this study, the thermal conductivity consisting of Al-CNT composite was 171 W/(mK). Therefore, the thermal conductivity simulation in the motor that applied the CNT composite was tested. Figure 4 shows the simulation results of temperature dependence on the thermal conductivity of stator and coil using the CNT composite. It was shown that the stator temperature increased but the coil temperature decreased with increasing estimated thermal conductivity of stator. This is the reason that coil temperature decreased as thermal conductivity increased in the stator. A caution feature result is that
temperature increase appears in the stator when thermal radiation reaches saturation. It was found that the temperature increase of stator is possible to decrease using that of the CNT composite. In other words, more than the rate current value. According to the FEM simulation result, the coil temperature is 114°C, which is less than 13 °C of the conventional Al stator using Al-CNT 14 wt% composite with thermal conductivity of 171 W/(mK).

![Graph showing temperature dependence on thermal conductivity of motor frame](image)

**Figure 4.** Temperature dependence on thermal conductivity of the frame using the FEM.

4. Fabrication and evaluation of the CNT motor

4.1. Basic characteristic and fabrication of the CNT motor

Two kinds of motors made using Al and CNT composite were evaluated to confirm the effect of thermal conductivity of stators. The common specifications of the two kinds of motors are shown in Table 4. Both motors have a square flange size of 100 mm, length of 120 mm, and weight of about 4.5 kg. As shown in Figure 3, the temperature of the motor was measured at point \( D_p \) using C-A thermocouple (B13-440). An AC servomotor made by the CNT composite stator is shown in Figure 5. As the surface of CNT composite stator had rough stripe patterns, the external surface obtained smooth surface using black color coating. Then, the measurement equipment of motor characteristics used was an optical encoder with rotary speed and acceleration at the opposite position of output power axis, and the motor controller used was a servomotor unit of TA8110 made by Tamagawa Seiki Co.

The dependence torque on rotary speed of both motors obtained linear characteristics between rotary speed of 0 to 4,510 rpm and torque of 10.2 Nm to 0, respectively. The dependence torque on the current of both motors obtained torque constants of 0.59 Nm/A under the condition of rate current of 5.6 A and torque of 3.3 Nm. The motor fabrication using the CNT composite led to the preparation of the radiation test.

| Item                | Value          |
|---------------------|----------------|
| Output power, \( P_o \) | 1.0 (kW) |
| Rated torque, \( T_r \) | 3.3 (Nm) |
| Peak torque, \( T_p \) | 9.9 (Nm) |
| Rated current, \( I_t \) | 5.7 (A) |
| Rated speed, \( S_r \) | 3,000 (rpm) |
| Max. speed, \( S_m \) | 4,500 (rpm) |
4.2. Radiation characteristic of the CNT composite motor

The temperature of the external atmosphere and the stator was measured at the same operating conditions for both motors. A change in temperature was observed until steady state at measurement points. An end time was decided by making sure it is less than 1.4 °C per 30 min of temperature decrease. Because direct temperature measurement of the coil would not be executed as coil was set at inner stator, the temperature was estimated by varied coil resistivity (i.e., the rise-of-resistance method) [8].

The increasing temperature dependence on the two kinds of motors at three points under the condition of rotational speed with 3,000 rpm and load torque with 3.3 Nm is shown in Table 5. The coil temperature was decreased to 19 °C at the same time as the stator frame temperature was increased to 5 °C in the case when the stator used the CNT composite. The result shows that the input current of the CNT motor can increase until it is equivalent to a value with coil temperature decrease. It fairly well confirmed the radiation effect of the applied CNT composite. The design and measurement values of the motor with CNT stator are shown in Table 6. The consisted material of CNT composite motor was the same as the conventional one without stator material. As a result, it was obtained that the CNT motor improved the decrease of coil temperature and radiation characteristics.

According to the obtained temperature characteristics, the composite motor using CNT decreased consumption energy by 16 % with respect to the conventional one. This fact means that it is possible to increase the rate current to 6.8 %. In other words, the rate current can be from 6.25 to 5.6 A and 3.7 to 3.5 Nm in the case of rate torque.

| Frame material | Measurement position | Detected temperature $T_a$ (°C) | Atmosphere temperature $T_a$ (°C) | Increasing temperature $T_a$ (°C) |
|----------------|----------------------|----------------------------------|-----------------------------------|----------------------------------|
| Al             | Frame surface        | 57.0                             | 15.6                              | 41.4                             |
|                | Coil                 | 122.8                            | 15.6                              | 107.2                            |
| Al-CNT         | Frame surface        | 62.0                             | 18.0                              | 44.0                             |
|                | Coil                 | 103.5                            | 18.0                              | 85.5                             |

*Figure 5. AC servomotor using the stator frame with the Al-CNT composite.*
4.3. Studies in the future
The development of the CNT composite and its application in motor were performed at the same time using thermal FEM. As a result, the highly efficient motor has improved the radiation characteristic using the Al-CNT composite stator. However, the future problems are as follows: (1) the cost of the CNT material, (2) confirmation of the influence on the human body, and (3) no good affinity of CNT for Al.

5. Conclusions
The nanotechnology applied in motors expects a bigger revolution in the future, which is why CNT using high thermal conductivity is particularly important. In this study, the making of the CNT composite and high thermal radiation motor was studied. The obtained results are as follows;

- Successful fabrication of Al 25 wt%-CNT composite; the CNT composite had twice thermal conductivity compared to Al (ADC12);
- A novel method of increasing the affinity between Al and CNT using CF; and
- Successful thermal radiation improvement of the motor stator, which then could increase to 6.8% motor current at the same size.

6. References
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