Improved Electrical Conductivity of CFRP by Conductive Silver Nano-particles Coating for Lightning Strike Protection

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SUMMARY

The improvement of electrical conductivity of carbon-fiber reinforced plastics (CFRP) has been investigated by conductive silver nano-particles coating for the purpose of aircraft lightning protection. Silver nano-particles in colloid were sprayed on the surface of carbon fibers, which were then impregnated by epoxy resin to form a CFRP specimen. Electrical resistance was measured by contact resistance meter which utilize the principles of the AC 4-terminal method. Electrical resistance value was then converted to electrical conductivity. The coated silver nano-particles on the carbon fibers were verified by SEM and EDS. The electrical conductivity was increased by four times of the ordinary CFRP.

Keywords: Carbon-Fiber Reinforced Plastics, Electrical Conductivity, Conductive Nano-Particles, Lightning Strike Protection

INTRODUCTION

Recently, worldwide interest is being focused especially on the usage of carbon-fiber reinforced plastics(CFRP) after the advent of B787 aircraft which utilized it more than 50 wt% of its structural weight including the primary structures such as fuselage and main wings as well as the secondary structures. Also current oil price jumps facilitate the use of CFRP for making the light-weighted structures to increase their energy efficiencies in the transportation vehicles such as automobiles, aero vehicles as well as in the heavy blades of electric generating mega-watt wind turbines[1]. By adopting CFRP, many benefits due to materials such as high corrosion resistance, good thermal dimensional stability and excellent fatigue resistance as well as their high specific strength/stiffness can be utilized in their structural constructions in the diverse industrial sectors of transportation, construction, aerospace, marine, electronics, sporting and consumer goods. The application of CFRP to the primary structures of aircraft in the aerospace industry has necessitated the development of CFRP with improved electrical conduction properties to avoid or reduce the damage from lightning strikes of the CFRP structures due to their relatively lower electrical conductivity than the conventional aluminum alloy structures. To enhance the electrical conductivity of CFRP composites or make new electrically conducting CFRP materials, it is typical to add the electrically conducting materials such as carbon fibers, carbon black and carbon nano-tubes to the polymer base of the composites or to make graphite fiber itself with high electrical conductivity. Among the various efforts, the studies to make these CFRPs by increasing the electrical conductivity of graphite fibers have been dominant and active for a long time. However, they are for developing the electromagnetic shielding plate materials, the thermister, or the heat and current sensors, so improvement of the electrical conductivity is not suitable for the direct applications to the aircraft fuselage/wing structures [2-5].

Although the efforts to increase the electrical conductivity improved the concentration rate of the graphite reinforced conductive composite materials, but as a compromising result, mechanical strength would be less than expected and this becomes a disadvantage [6].

Studies to find the ways to maintain mechanical strengths of these CFRP's without degrading the electrical conductivity are under way in Korea. Heo et al. fabricated conductive composite materials by adding graphite particles to the carbon fibers and investigated the state of the fabrication conditions and changes in the electrical and mechanical characteristics of the composites through the microstructure observations and density measurements [7]. A study of the improvement of electrical characteristics of glass-fiber composite materials by adding multi-walled carbon nano-tubes is in progress. However, Lee et al. showed that the difficulty in making uniform distribution of multi-walled carbon nano-tubes in the resin matrix of the composite materials caused difficulty to increase the electric characteristics of the composites as expected [8]. Studies on nano-particles in the area of nanotechnology applications are also currently in progress. CFRP's are fabricated by adding silver nano-particles but are merely on the stage of specimen manufacturing, but the obtained volume fractions of carbon fibers did not meet the required amount for the commercial product applications [9].

In this study, carbon-fiber layers are coated by colloid spray method with silver nano-particles of various contents and well impregnated by conventional thermosetting epoxy resin. These pre-impregnated fiber layers with resin are cured to a laminate to have somewhat enhanced electrical conductivity. To evaluate the electrical and mechanical characteristics of the cured laminate, observations by the scanning electron microscope(SEM), validations by the energy dispersive spectroscopy(EDS), electrical conductivity measurements and tensile tests have been performed.

BACKGROUND AND MOTIVATION

It is well known that the average normal aircrafts in service flight are exposed to 1 or 2 times of lighting strikes every year. When aircrafts are struck by the lightning, the aircraft structures may have not only direct damages, such as local burnt area and fracture of structures by extremely high voltage spark propagation and local heat generation, but also indirect damages such as interference in the electronic systems caused by high electromagnetic field disorder. In view of safety for aircrafts, lightning induced damages have emerged as one of the important issues. Studies in the design have first begun to select pertinent materials for the aircraft fuselage and wings that best prevent damages from lightning strikes. The latest and most active works are performed on studying the proper use of fiber reinforced composite materials for the new civil aircrafts (B-787, A350, A380 aircraft, etc) to find whether those composite materials with various fibers could reduce the percentage of damage by lighting as expected.

Currently, most of the external surfaces of composite fuselages are covered with wire mesh, expanded foil of aluminum to prevent and/or reduce damages from lightning

strikes; however, it tends to increase the weight of fuselage by adding a thin metal layer in the CFRP fuselage and wings, and also it may induce galvanic corrosion that may become a concern after long service flights [10].
In this paper, silver nano-particles are used as coating materials for carbon-fiber layers by spray method to make cured laminate to enhance electrical conductivity of CFRP's, without increasing the weight of structures too much; and a way more improved and efficient than the other methods are proposed and verified through several experimental evaluation in terms of electrical conductivity.

EXPERIMENT

Materials and Production

A carbon/epoxy prepreg tape, UIN125C (SK Chemical, Korea), and a epoxy-based resin film (SK Chemical) which will be used for the resin impregnation for the carbon fiber layers obtained by extracting the resin from UIN125C prepreg by MEK (Methyl Ethyl Ketone) are used for the fabrication of the electric conductivity enhanced laminate. Also AGS-WP010 (Ag 10% colloid), AGS-WP005 (Ag 5% colloid), AGP-200 (Ag 24.5% powder) by Miji-tech Co. are used as coating conductive silver nano-particles to the carbon-fiber layers above mentioned.

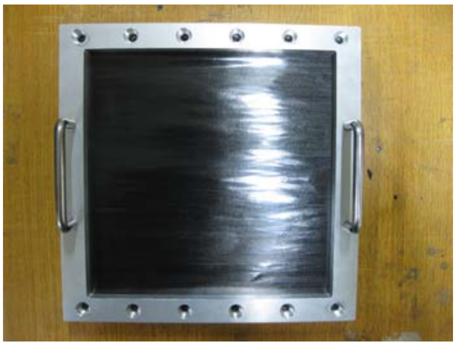


Fig. 1: Metal jig frame to dissolve resin from prepreg

The first step for making laminate is to cut the UIN125C prepreg into a piece of 30cm x 30cm and fixed it onto an aluminum jig frame which designed to keep original alignment of fibers in prepreg as shown in Fig. 1. Then, the resin from the prepreg in the aluminum jig frame is completely dissolved by MEK for about 50 seconds. After finishing the dissolution of resin and drying the carbon-fiber layer from wet prepreg with MEK, a spray gun containing colloid of silver nano-particles is used to coat the dried carbon-fiber layer. The amount of colloid from the spray gun actuated by compressor is adjusted to keep 15 ml per minute. After coating the colloid, the carbon-fiber layer is completely dried in the oven and two resin films are placed on both sides of the dried layer to make it having prepreg state by impregnating the resin again.

Then the resin-filled carbon-fiber layer is molded at a hot press heated to 90℃, and closing pressure of 7MPa is applied to the resin-filled carbon-fiber layer for 10 seconds. A prepreg is made to have the fiber volume fraction of about 70%, similar to the commercial prepregs [11]. Fig. 2 shows the dimension of the specimens for the tensile test to observe the strength changes related to the nano-particles coating amounts controlled by spraying time and colloid concentration types.

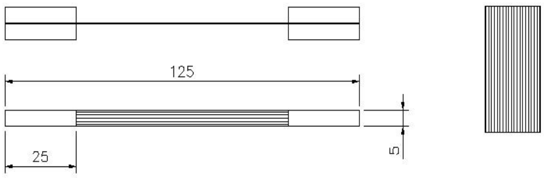


Fig. 2: Configuration of tensile test specimen

Condition and Measurement

Specimens coated with the conductive silver nano-particles were used to observe the coating status of the conductive nano-particles and the formation of the electrical network were estimated by using SEM and EDS. The electrical conductivity (σ) shown in Eqn. (1) is measured by the electric resistance meter (HIOKI 3506 AC mΩ Hitester, Hioki Co. Japan) which uses the 4-point probe method. Where A is the cross sectional area (m^2) of the specimen, its normal direction is parallel to the fibers, L is the distance (m) between the terminals contacted on the cross sectional surface, I is electric current (Ampere) and V is electric voltage (Volt). The unit of electrical conductivity, σ, is S/m, where S (Siemens) is the inverse of the electrical resistance. To reduce the change in the resistance caused by temperature changes, the temperature is maintained at 25 ℃ during the measurement. Also to reduce the measuring error due to contamination of specimens, the specimens are dried 3 days after fabrication and sealed well in a glove box in order to evaporate the alcohol used to clean the surface.

$$\sigma = \frac{I}{V} \times \frac{L}{A} \tag{1}$$

RESULTS AND DISCUSSION

Fabrication Status Analysis

The fiber volume fraction of the fabricated laminate was measured by cutting along the transverse direction to the fiber direction with a diamond saw, and the cross sectional view of the laminate is shown in Fig. 3. The cross sectional surface is observed with an SEM (S-4300, Hitachi, Japan) and the fiber volume fraction was calculated by area measuring method. As shown in Fig. 3, the distribution of fibers is almost uniform in the epoxy matrix; for the SEM picture showing the cross sectional view, the area of 24μm x 25μm is placed in the picture and the area occupied by fibers was measured to count the fiber volume fraction in the laminate. The result showed that the fiber volume fraction is approximately 70%, which is almost equivalent to the commercial prepregs.

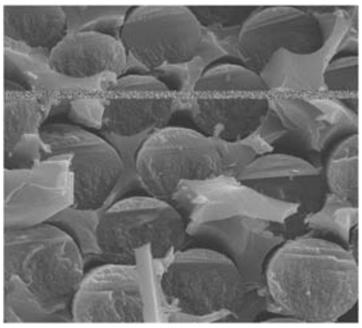
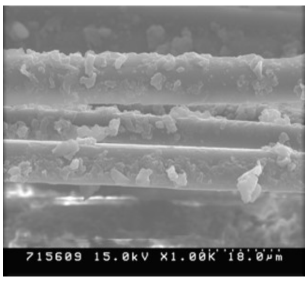
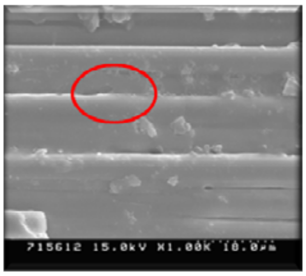


Fig. 3: Cross-sectional view of CFRP laminates

Fig. 4 shows the transverse shape of the impregnated laminate with the resin films and corresponding EDS result. Fig. 4(a) shows non-coated carbon fiber impregnated with the epoxy resin films and Fig. 4(b) is for a laminate with coated fibers with the 10% silver nano-particle colloid. On the non-coated carbon-fiber reinforced specimen as shown in Fig. 4(a), the pulverized particles of the hardened epoxy resin was observed on the space between fiber and fiber. However, in case of Fig. 4(b), many of the coated conductive nano-particles were observed with the hardened epoxy resin between fiber and fiber. In addition, the existence of the coated silver nano-particles on the surface of the carbon fiber was proven through the EDS analysis. Fig. 5 shows the results of EDS analysis for both uncoated and silver nano-particle coated fiber reinforced laminates. In Fig. 5(a) for the uncoated specimen, only C (carbon) and O (oxygen), the elements of carbon fiber and epoxy, were detected by the EDS analysis, while in Fig. 5(b), the EDS analysis shows not only C (carbon) and O (oxygen) but also Ag (silver) element existing on the surface of the 10% silver nano-particle coated fibers were detected by the EDS. Through these experimental results, the fact that the fiber surface was evenly coated by the nano-particles sprayed with the silver nano-particle distributed colloid is verified.

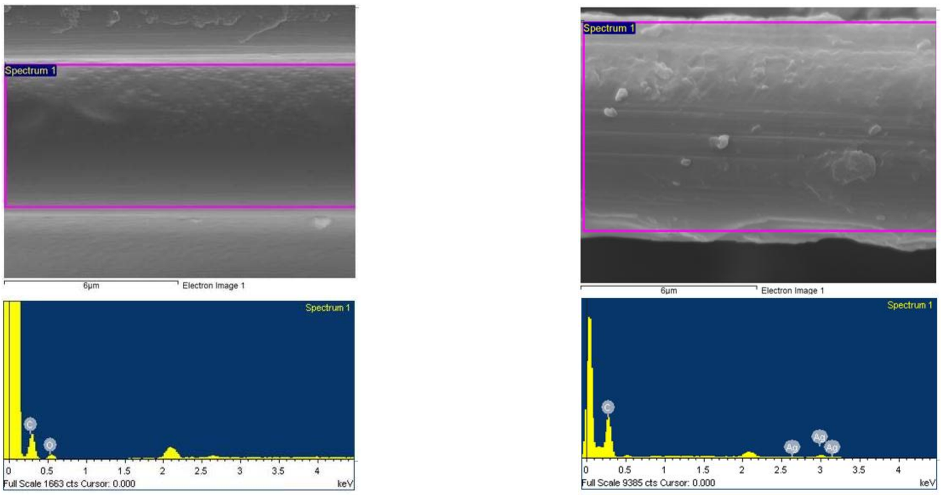


a) The non-coating CFRP



b) The 10% colloid coating CFRP

Fig. 4: The changes of the microstructure by conductive nano-particle colloid coating



a) The result of EDS from non-coating CFRP

b) The result of EDS from 10%colloid coating CFRP

Fig. 5: The result of EDS by conductive nano-particle colloid coating

Electrical conductivity

Electrical conductivity is closely connected with the concentration of nano-particles. Electrical conduction is made through the network between the metal particles, metal and carbon fiber, and carbon fibers. The electrical conductivity not only depends on the metal particle size, aspect ratio, and the physical and chemical properties, but also the content of metal particles, and their distributed status [12, 13].

The relationship between electrical resistance and the content of metal particles can be explained by the percolation theory. By adding the particles to the composite materials the initial electrical resistance was almost unchanged, but if a certain amount is added, the resistance decreases rapidly. The content of particles at this moment is called the critical content and even if the particle content is higher than the critical content, then the change of resistance is not overly high [14,15].

In this study, the change of the electrical conductivity depends on the spray concentration and the spray time and so these were observed, and the electrical conductivity obtained from this experiment and that of the commercial B-787 specimen were compared. First, we focused on the change of the electrical conductivity which dependent on the spray time of the nano-particles colloid. In this study, the facts that the change of the electrical conductivity depends on the colloid concentration and the spray time were observed. Also the electrical conductivity results obtained through the experiment and the electrical conductivity results measured for the same specimens prepared with the same materials used for the B-787 composite parts having aluminum foil mesh for lightning protection were compared. As shown in Fig. 6, as the injection time increases from 3 seconds to 5 seconds, the electrical conductivity for 5% concentration colloid increases to 7.5% compared to the uncoated case, while the electrical conductivity for 10% concentration colloid increases to 11%. When the spray time was fixed to 5 seconds, but there is a change in concentration from 5% to 10%, then it was observed that the corresponding electrical conductivity was changed by approximately 2 times. From these results, it was found that the changes in the spray time and the colloid concentration affected the increased percentage of the electrical conductivity. Also, for 5 seconds of injection, the electric conductivity for the coated specimen with 10% colloid increased about 4 times higher than the case of the uncoated specimen. The electrical conductivity of the coated CFRP laminate and the conventional CFRP laminate just manufactured with the aluminum mesh foil layer used for the lightning strike protection of B787 aircraft were compared.

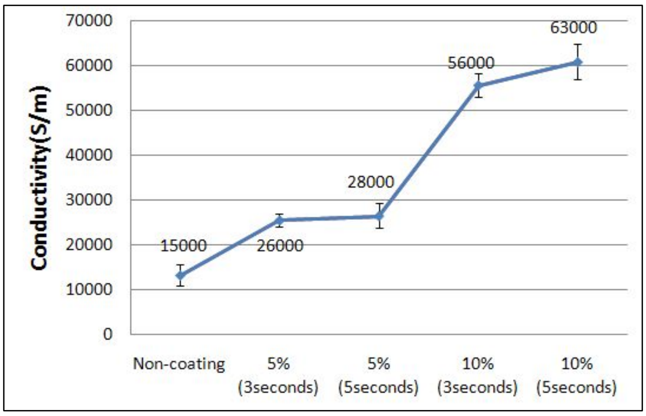


Fig. 6: The electrical conductivity in terms of concentration and the injection time of conductive nano-particles colloid coatin

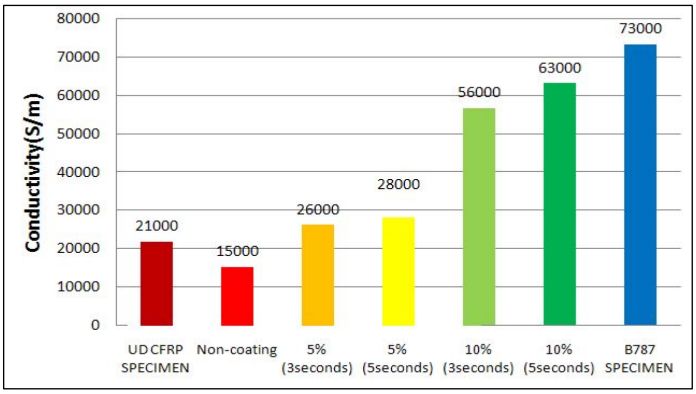


Fig. 7: The comparison of conductivity from B787 aircraft spaceman and the hybrid CFRP by conductive nano-particle colloid coating

As shown in Fig. 7, the electrical conductivity of the specimen made from the original UIN125C prepreg tape (SK Chemical, Korea) is approximately 21,000 S/m, while the specimen from the uncoated prepreg shows the electric conductivity of approximately 15,000 S/m. It appeared that there was no big difference between them. This means that the fabrication process for the coated CFRP laminate was reasonably prepared when it came to have the same fiber volume fraction with the laminate fabricated from the original prepregs. The difference of about 6,000 S/m in electrical conductivity of the two is considered due to the result from much more uniform fiber array/alignment of the original prepregs than the re-fabricated ones for nano-particles coating treatment. For the specimen made with 10% colloid spray for 5 seconds, the electrical conductivity has increased to the 86% of B787 aluminum mesh foiled CFRP specimen. This means that a higher level of electrical conductivity by using the silver nano-particles coating method can be obtained instead of using the aluminum mesh foil for composite aircraft. From the results, the lightning protected aircraft composite fuselage structures with the silver nano-particles coating treatment can provide an advantage over the conventional aluminum mesh foiled ones, in the viewpoint of structural weight savings. When it comes to the aircraft structure itself, the composite aircrafts may have a 20% better fuel economy than the aluminum alloy ones. For these reasons, it is very important to reduce the weight of the aircraft. For the specimen made with 10% colloid sprayed for 5 seconds, weight has increased by 10%, whereas it would increase 25% by the aircraft specimen with aluminum mesh foil. Therefore, it is anticipated that using the silver nano-particles coating method will help enhance the fuel economy more than the existing techniques to prevent lightning damage.

Tensile Strength

In order to observe the dependence of tensile strength on the contents of silver nano-particles coated on the fiber layers in the specimens shown in Fig. 2. The specimens with various contents of nano-particles were prepared for the material-testing machine (TIRA test 27025, TIRA, Germany). Those results are shown in Fig. 8 for various nano-particle coating treatment. The uncoated specimen has strength of 2712MPa whereas the 5% colloid coated specimen has strength of 2815MPa.

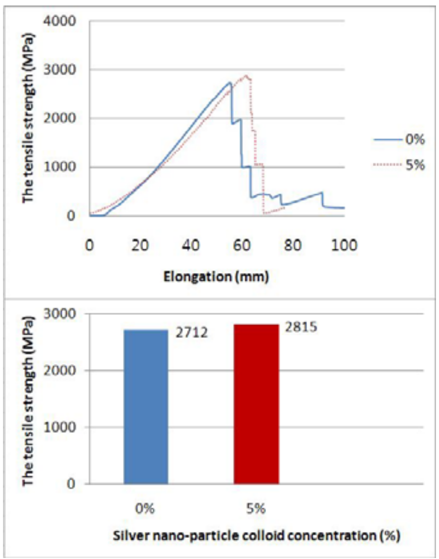


Fig. 8: The tensile strength from conductive nano-particle colloid concentration

This shows that the conductive nano-particle coating process does not affect the tensile strength in the fiber direction of the CFRP's very much. It also shows that by adding conductive nano-particles the electrical conductivity improves whereas the strength does not degrade as much.

CONCLUSIONS

In this study, the fabricating process for the silver nano-particles coated CFRP laminate has been developed to enhance the electrical conductivity of CFRP composites. Through the experiments, the changes in the electrical conductivity appeared to be dependent on the concentration of conductive nano-particles in colloid and spray time with basically no changes in the strength of CFRP's are observed. The conclusive results are summarized as follow.

1) When carbon fibers are coated by the conductive silver nano-particles and impregnated with the resin on the carbon-fiber surface, it significantly enhanced the electrical conductivity compared to the conventional CFRP's.

2) Increase in the electrical conductivity depends on the concentration of conductive nano-particles, which has very little risk to increase the weight of aircraft structures. This means that the coating process gives more benefits than the existing aluminum mesh foil method currently used for aircraft with composite fuselage structures.

3) The tensile strength of prototype specimens coated with conductive nano-particles and impregnated with epoxy resin film has not been degraded much when it is compared to the uncoated one

4) The conductive silver nano-particles coating process would have enough potential to be used as an alternative way for the lightning strike protection materials if it is possible to have some process modification and improvement for mass production.

ACKNOWLEDGEMENT

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