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Development of a damage tolerant structure for nano-composite radar absorbing structures

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ABSTRACT

A radome structure, which is the protective cover for a radar antenna, is generally made of composite materials that have the high mechanical properties and low dielectric constants that are required for radome structures. Radar absorbing structures (RAS) are made of materials similar to radome structures, but include electro-conductive materials to enhance electromagnetic (EM) wave absorption characteristics.

Though composite structures have both excellent electromagnetic and mechanical properties, they are vulnerable to external impact loads. When the RAS is damaged by external impact loads during operation, damages such as cracks, delamination, and dents may be generated, which can change the EM wave reflection properties of the composite structure.

In this study, the surface of a RAS containing conductive nano-material was padded with ultra-high molecular weight polyethylene fabric to protect the composite structures against external impact loads. The impact characteristics of the RAS were investigated by drop weight impact tests with and without the pad, whose effect was measured by a compression test after impact (CAI). Additionally, the EM wave reflection characteristics of the padded RAS were investigated with a free space measurement. Finally, an optimum combination of UHMWPE fabric and glass composite face was suggested for the damage tolerant RAS structure.

1. Introduction

Radar, which stands for "Radio detection and ranging", designates a system using beamed and reflected radio frequency energy for detecting and locating objects, measuring distance or altitude, navigating, homing, bombing and other purposes [1]. Because radar technology has drastically improved, the development of the "Stealth" technologies for evading radar detection has become more important [2]. To enhance the stealth performance, radar cross section (RCS) should be minimized because the detectable distance by radar is proportional to RCS [3]. The RCS can be reduced by using the low observable design technique based on stealth shaping, radar absorbing material (RAM), and radar absorbing structures (RAS) [4,5]. However, stealth shaping design deteriorates the aerodynamic properties and is vulnerable to bi-static radars, and RAM has not only poor environmental endurance but also poor mechanical properties [6–8]. On the contrary, the RAS is the structure that has both the functions of load bearing and electromagnetic (EM) energy absorbing capability without interfering with the external profiles [9]. Because the EM properties of fiber reinforced polymeric (FRP) composites can be tailored effectively by simply adding electric-conductive powders, such as carbon black, ferrite, and carbonyl iron, to the matrix of composites [10], studies on RAS using FRP composite materials are becoming a popular research field [11].

Because a RAS is composed of FRP composite materials, it is vulnerable to impact damage [12]. Composite structures subjected to low velocity impacts have been the subjects of many experimental and analytical investigations [13,14] because low velocity impact loadings can occur when tools are dropped, and when debris, fragments, or projectiles impact the surfaces of composite structures [15]. If an impact starts a crack, the crack will grow until the stored energy is dissipated, which will result in crack growth in brittle composite materials [16]. The modes of induced impact damage range from matrix cracking and delamination to fiber failure and penetration [17]. Additionally, when the RAS is applied to the stealth vessel, it will be confronted with high humidity conditions where the crack growth rate can increase several times [18]. Therefore, preventing the impact damage to the RAS is important to maintain both the desired mechanical and EM wave reflection characteristics. Though the effect of the impact damage to the

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EM wave transmission characteristics of a composite radome was investigated [19], there is little research on the protection of the composite RAS from a low velocity impact while maintaining the required EM wave reflection characteristics.

In this study, a damage tolerant structure (DTS) composed of an E-glass/epoxy composite face and an ultra-high molecular weight polyethylene (UHMWPE) fabric pad for the RAS has been developed because the UHMWPE has excellent impact shielding capability [20]. The RAS is made of an E-glass/epoxy composite with dispersed nano-size carbon black to increase the dissipation of EM waves. The critical impact energy was investigated by a low velocity drop weight impact test, infrared thermo-scan imaging, and a compression test after impact (CAI) with respect to UHMWPE thickness. The critical impact energy is defined as the energy which degrades the mechanical performance of the RAS. The EM wave reflection loss characteristics of the RAS were measured with a free space measurement to determine whether the installation of the DTS in front of the RAS might deteriorate the EM wave reflection characteristics. From the measured impact and EM wave reflection characteristics, an optimum design of the padded RAS has been suggested.

2. Design of the nano-composite RAS

2.1. Electromagnetic wave absorption mechanism

Fig. 1 shows the schematic diagram of the RAS, which consists of a nano-composite and a perfect electrical conductor (PEC). The incident EM wave propagates through the nano-composite and is reflected by the PEC. When the incident EM wave and reflected EM wave have a half wave phase difference, destructive interference occurs and the reflected EM wave is canceled out. The destructive interference condition for the single face type RAS shown in Fig. 1 is expressed as follows [21].

$$L = \frac{1}{4}\lambda_{nano} \tag{1}$$

where L is the propagated length of the EM wave in the nano-composite, λ_{nano} is the wavelength of the EM wave in the nano-composite. Also from Maxwell's equations, wavelength λ_{nano} of the EM wave in the nano-composite can be expressed as follows.

$$\lambda_{nano} = \frac{\lambda_0}{\sqrt{\varepsilon_{nano}}} \tag{2}$$

where λ_0 is the wavelength of the EM wave in free space and ε_{nano} is the dielectric constant of the nano-composite. From Eqs. (1) and (2), the thickness of the nano-composite, which is equal to L, is expressed as follows.

$$L = \frac{1}{4}\frac{\lambda_0}{\sqrt{\varepsilon_{nano}}} \tag{3}$$

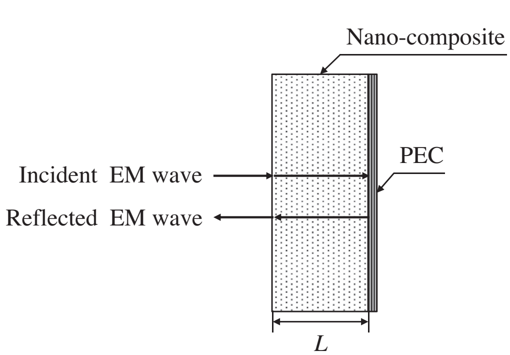

Fig. 1. Schematic diagram of the RAS.

Eq. (3) determines the thickness of the nano-composite that provides the destructive interference at the desired frequency.

2.2. Fabrication method

The RAS composed of the nano-composite and PEC was fabricated. For the nano-composite, plain weave E-glass fabric (1180, Muhan composite, Korea) was impregnated with the epoxy resin (YD114F, Kukdo chemical Co., Korea) containing 3% (by weight) nano-size carbon black (EC-300J, Ketjen Black International Co., Japan). The dielectric constant of the nano-composite was 7.3 and the required thickness of the nano-composite for the destructive interference at 10 GHz was 2.8 mm calculated by Eq. (4). For the PEC, one ply of plain weave carbon fabric (C-112, Muhan composite, Korea) was impregnated with the same epoxy resin containing 3% carbon black (CB). The fabrication process of the RAS is shown in Fig. 2(a). For uniform dispersion of the CB, the mixture of resin, hardener, and CB was stirred for 2 h with a magnetic stirrer at a rotating speed of 500 rpm under a vacuum to eliminate entrapped air and moisture. The mixture was pasted on the plain weave E-glass fabrics and carbon fabric by a hand lay-up method. Finally, the impregnated laminates were cured with an autoclave vacuum bag degassing method under the curing cycle shown in Fig. 2(b). The fiber volume fraction of the fabricated nano-composite was 57%. The specimens were cut to the size of 116 mm × 116 mm.

3. Impact characteristics of the RAS

3.1. Experimental procedure

3.1.1. Drop weight impact test

The guided drop weight impact tester was adopted for the low velocity impact test as shown in Fig. 3. The window size of the impact specimen was 100 mm × 100 mm, which was identical for the size of the CAI test and free space measurement. For the clamped boundary condition, the four edges were clamped by fixtures. The impactor mass was 5.8 kg, and the hemi-spherical tup radius was 17 mm based on ASTM D7136. The velocity and energy of the impactor was varied by changing the drop height of the impactor. Impact energies of 4 J, 8 J, 13 J, 18 J, 27 J, 35 J, 45 J, and 53 J were applied to the front side of the RAS specimens. The load during the impact test was measured using a piezo-electric type

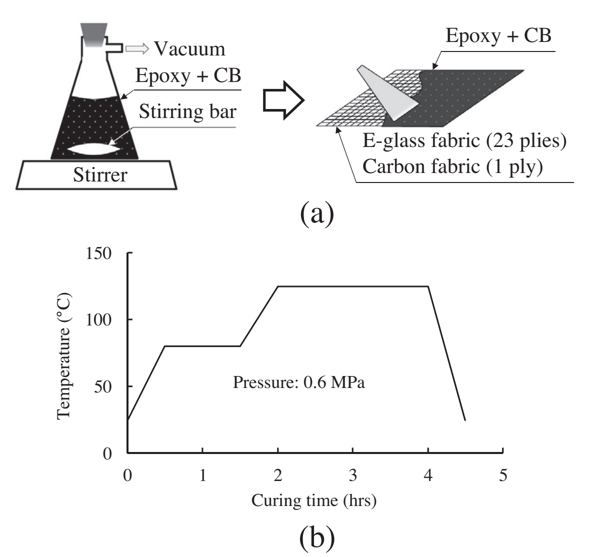

Fig. 2. Fabrication method for the RAS specimen: (a) fabrication process; (b) curing cycle.