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Hong-Kyu Jang [a] , Jae-Hwan Shin [b] , Chun-Gon Kim [c] , Sang-Hun Shin [d] & Jin-Bong Kim [e]

[a] School of Mechanical, Aerospace and Systems Engineering, Department of Aerospace Engineering, KAIST, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea

[b] School of Mechanical, Aerospace and Systems Engineering, Department of Aerospace Engineering, KAIST, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea

[c] School of Mechanical, Aerospace and Systems Engineering, Department of Aerospace Engineering, KAIST, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea;, Email: cgkim@kaist.ac.kr

[d] The 1st R&D Institute-3, Agency for Defense Development, 111 Sunam-dong, Yuseong-gu, Daejeon 305-152, Republic of Korea

[e] Composite Materials Laboratory, Korea Institute of Machinery and Materials, 66 Sangnam-dong, Changwon 641-010, Republic of Korea

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[a] School of Mechanical, Aerospace and Systems Engineering, Department of Aerospace Engineering, KAIST, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea

[b] The 1st R&D Institute-3, Agency for Defense Development, 111 Sunam-dong, Yuseong-gu, Daejeon 305-152, Republic of Korea

[c] Composite Materials Laboratory, Korea Institute of Machinery and Materials, 66 Sangnam-dong, Changwon 641-010, Republic of Korea

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Abstract

This paper presents a low observable structure with curved surfaces made by fiber-reinforced composites, conducting polymers and shows the possibility of developing stealth platforms for military applications. We propose radar absorbing structures (RAS) based on a circuit analog absorber in order to reduce the radar cross-section (RCS) of an object with curved surfaces. First, semi-cylindrical RAS with a periodic square patterned layer using a conducting polymer was designed and simulated by a commercial 3-D electromagnetic field analysis program. The designed semi-cylindrical structure with low RCS was then fabricated using fiber-reinforced composites and conducting polymer materials. Finally, the radar cross-section was measured in order to evaluate the radar absorbing performance of the fabricated RAS at a compact range facility. The measured radar absorption of the fabricated RAS showed that the target's RCS declined in a range of 65% to 94% within the X-band relative to a non-radar absorbing specimen.

Keywords

Fiber-reinforced composites, radar absorbing structures, conducting polymer, circuit analog absorber, radar cross-section

1. Introduction

Stealth technology is defined as a comprehensive technique to reduce the detection probability of weapon systems, such as those of friendly aircraft and warships, by

* To whom correspondence should be addressed. E-mail: cgkim@kaist.ac.kr

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the enemy's potentially diverse radar capabilities. Above all, the radar cross-section (RCS) reduction technique, whereby the electromagnetic (EM) wave transmitted from the detecting radar is absorbed and scattered, is the core of low observable technology. The low observable characteristic is regarded as a critical feature in warfare, as it can increase the survivability of aircrafts or warships and enhance the capability of mission completion in hostile territory.

Today, most military aircrafts are required to exhibit a low radar cross-section in order to avoid detection by radar systems, as a larger RCS indicates that an object is more easily detected by the enemy. The radar cross-section (σ) is the measure of a target's ability to reflect radar signals in the direction of the radar receiver. It is a measure of the ratio of backscatter power per unit solid angle in the radar's direction to the power density that is intercepted by the target. The RCS is expressed by Knott *et al.* [1] as:

$$\sigma = \lim_{r\to\infty} 4\pi r^2 \frac{|E^{\mathrm{scat}}|^2}{|E^{\mathrm{inc}}|^2}, \tag{1}$$

where r indicates the distance from the radar, E^{scat} is the scattered electric field, and E^{inc} is the incident electric field at the target.

Generally, the RCS of fighters can be effectively reduced by using low observable design techniques based on stealth shaping and radar absorbing materials or structures (RAM/RAS). Fourth and fifth-generation jet fighters, such as the F-15 Eagle and the F-22 Raptor, have low radar cross-sections, ranging from 1.0 m^2 to 0.01 m^2 at the front of the radar's incident direction.

However, if the incident angle of the detection radar changes to the side or back of the fighter and bistatic radar is used for detection instead of monostatic radar, the curved or dihedral parts of the fuselage and the airfoil provide good reflectors to the enemy's radar system. Consequently, curved surfaces increase the RCS and the detection probability of the fighters is increased [2]. In the monostatic radar, the conventionally used radar system, the transmitter and receiver are located on the same platform and frequently share the same antenna. On the other hand, the bistatic radar consists of a separately located radar transmitter and receiver when viewed from the target [3].

In this paper, we designed and fabricated a load-bearing radar absorbing structure with a curved surface by using fiber-reinforced composites and conducting polymers. We then measured the radar cross-section of the fabricated semi-cylindrical RAS in order to evaluate the radar absorbing performance. The purpose of this study is to present a low observable structure with curved parts and to demonstrate the feasibility of stealth platforms for military applications.

2. Design of Semi-cylindrical RAS

2.1. Circuit Analog Absorber

Conventional radar absorbing structures (RASs) to absorb electromagnetic waves consist of fiber-reinforced composites and lossy materials in the matrix. The fiber-reinforced composites, such as glass fiber/epoxy and carbon fiber/epoxy composites, act as the load-bearing part of the structures. The lossy materials like dielectric fillers and magnetic fillers, provide the necessary loss for the radar absorber, which dissipate EM energy as heat [4]. The nano powders, however, used for the lossy materials have some disadvantages, such as increment of the structural weight and degradation of the mechanical properties. In addition, it is difficult to control the electrical properties of the composites, such as permittivity and permeability, according to the nano-filler content. To overcome these problems, we studied a radar absorbing structure with a circuit analog sheet using conducting polymer materials with a view to consideration of applicability and efficiency.

In this study, the basic principle of a circuit analog (CA) absorber was applied to a semi-cylindrical structure with curved surfaces in order to achieve radar absorbing characteristics. The CA absorber consists of a resistive sheet, a dielectric substrate, and metallic ground, as depicted in the left-hand side of Fig. 1. The resistive sheet with periodic patterns is made of lossy materials and is placed above a metallic ground plane that is separated by a dielectric layer. This absorber can improve the bandwidth and attenuation of the resonant absorbers, such as the Salisbury screen and the Jaumann absorber [5]. The radar absorbing characteristic of the CA absorber is accomplished by the resistive sheet made of lossy materials. In addition, various patterns, such as a square patch, circular patch, and cross dipole, can be applied to the design in a periodic arrangement.

According to Munk [6], a resistive sheet with a periodic pattern can be described by an equivalent circuit that contains elements of resistance (R), capacitance (C) and inductance (L) according to the incident EM waves, as shown in the right-hand

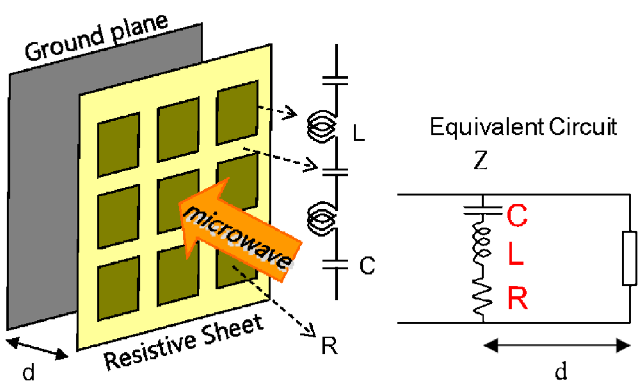

Figure 1. Circuit analog absorber and equivalent circuit. This figure is published in color on http://www.brill.nl/acm

side of Fig. 1. The impedance of the CA absorber is a function of R, L and C. By varying each variable ($R/L/C$), the impedance of the radar absorber can be adjusted to that of free space impedance ($Z_0 \approx 377\ \Omega$). Theoretically, the condition of minimum reflectivity is met when the impedance of the absorber is equal to the free space impedance Z_0. Therefore, good radar absorbing performance can be achieved by impedance control, which can be given by the combination between R, L and C [7]:

$$Z = R + jwL + \frac{1}{jwC}, \tag{2}$$

where the resistance component is controlled by the electrical conductivity (σ) and the coating thickness of the lossy materials. The capacitance and inductance are closely connected with the shape of the periodic patterns, such as the straight parts of elements and the gaps between elements. Consequently, the values of L and C can be tuned by the design of the circuit analog sheet with various patterns.

Conducting polymer materials are promising candidates for commercial devices and microwave absorber, offering advantages such as control of electrical conductivity, fabrication of various pattern shapes, and effective surface coating [8]. As such, they are good lossy materials for application as a resistive sheet in a CA absorber.

2.2. Design and Simulation of Periodic Pattern Layer

In this study, simple flat-plate RASs with a circuit analog layer arranged in periodic square patterns were designed. The radar absorbing performance of the designed flat-plate RASs was simulated and compared with each other. Upon consideration of radar absorbing efficiency, the final design of the resistive sheet was then selected for application in a semi-cylindrical RAS.

In order to effectively design the RAS, the pattern shape was limited to a square patch and the target frequency of the radar absorber was decided as 10.0 GHz within the X-band. The X-band (8.2–12.4 GHz) has been widely used for military detection radar systems. The combination of design variables with optimal radar absorption was determined by a parametric study of using CST-MWS at the target frequency. CST-MWS is a commercial 3-D electromagnetic field analysis program. The design variables of the RAS were pattern size, pattern gap, coating thickness, and substrate thickness. The complex permittivity of the substrate and the electrical conductivity of the conducting polymer paste used in the RAS design were measured in a prior study and are listed in Table 1.

Figure 2 shows the detailed design of the flat-plate RAS with a resistive sheet comprising periodic square patterns. The geometry of the designed RAS was 174 mm × 210 mm. The size of the square pattern was 4 mm × 4 mm × 0.008 mm and the gap between patterns was 2 mm. The height of the substrate made of glass fabric/epoxy composites was 2.7 mm except for the ground plane. The thickness of the ground plane used as total reflection layer, which was made of carbon fabric/epoxy composites, was also 0.5 mm. Notably, the ground thickness of the radar

Table 1.
Design parameters and properties of radar absorber

Glass fiber/epoxy	$\varepsilon' = 4.3/\varepsilon'' = 0.03$	Ground thickness	0.5 mm
Carbon fiber/epoxy	$\sigma = 60\,000$ S/m	Conducting polymer	$\sigma = 1300$ S/m
Substrate thickness	2.7 mm	CP thickness	8 µm

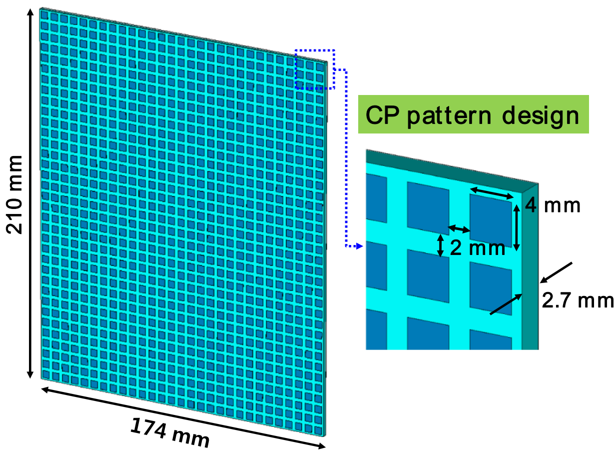

Figure 2. Detailed design of flat-plate RAS. This figure is published in color on http://www.brill.nl/acm

absorber must be larger than the skin depth (δ) in order to reflect all incident EM waves. δ can be expressed by the following equation [9]:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}, \tag{3}$$

where f is the target frequency of the radar absorber and σ is the electrical conductivity of the conductor. The target frequency of the RAS is 10.0 GHz and the conductivity of the carbon fabric/epoxy composites is about 60 000 S/m. Also, μ is the permeability of the conductor and it is generally equal to that of the free space, $4\pi \times 10^{-7}$ H/m. According to the value calculated by the equation, the skin depth is about 20 µm at 10.0 GHz. Therefore, the designed thickness of the carbon fabric/epoxy composites satisfies the condition of a perfect electric conductor. The detailed configuration and design values of the periodic square patterns layer are shown in Fig. 2 and listed in Table 1.

In this paper, reflection loss (RL) and radar cross-section (RCS) of the designed flat-plate RAS were simulated in order to evaluate its radar absorbing performance. According to the simulation results presented in Fig. 3, the designed RAS had a maximum reflection loss of −30 dB at 10.0 GHz, meaning that 99.9% of incident EM energy was absorbed. The bandwidth of 90% (−10 dB) radar absorption

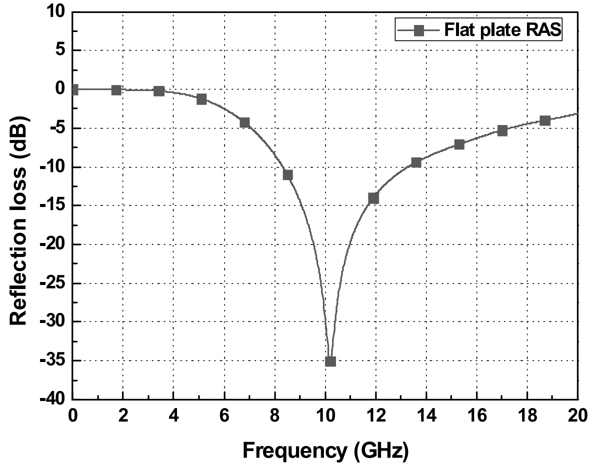

Figure 3. RL simulation of flat plate RAS.

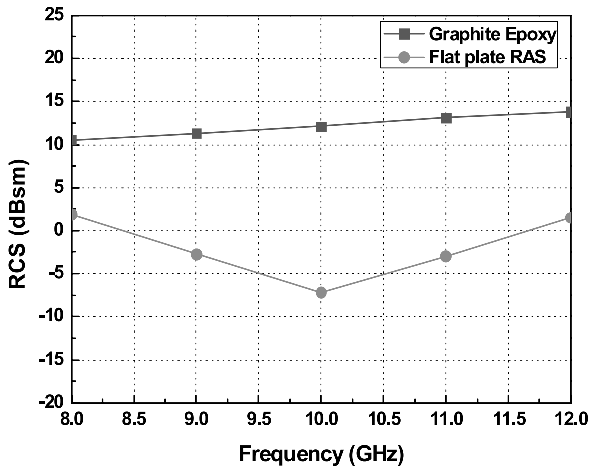

Figure 4. RCS simulation of flat plate RAS.

was almost 5.0 GHz from 8.3 to 13.3 GHz, covering the entire the X-band (8.2–12.4 GHz), as shown in Fig. 3.

Figure 4 compares the simulated RCS of the flat-plate RAS and graphite epoxy. The graphite epoxy sample has the same geometric shape as the flat-plate RAS, but is a non-radar absorber made of carbon fabric/epoxy composite. According to the results, the RCS of the flat-plate RAS (−7.2 dBsm) declined by nearly 98.8% relative to that of the non-radar absorber (12.1 dBsm) at the target frequency of 10.0 GHz. The RCS also fell at least approximately 86.2% (8.0 GHz) and at most 98.8% (10.0 GHz) within the X-band, as listed in Table 2, relative to the graphite epoxy. The RCS of a target can be expressed as a comparison of the strength of the

Table 2.
RCS simulation of flat plate RAS in X-band

Frequency	Graphite epoxy	Flat plate RAS	Absorption
8.0 GHz	10.5 dBsm ($11.22\ m^2$)	1.9 dBsm ($1.55\ m^2$)	86.2%
9.0 GHz	11.3 dBsm ($13.49\ m^2$)	−2.7 dBsm ($0.54\ m^2$)	96.0%
10.0 GHz	12.1 dBsm ($16.22\ m^2$)	−7.2 dBsm ($0.19\ m^2$)	98.8%
11.0 GHz	13.1 dBsm ($20.42\ m^2$)	−3.0 dBsm ($0.50\ m^2$)	97.5%
12.0 GHz	13.8 dBsm ($23.99\ m^2$)	1.5 dBsm ($1.41\ m^2$)	94.1%

reflected signal from the target to the reflected signal from a perfectly smooth sphere having a cross-sectional area of 1 m^2, as delineated in the following equation [1]:

$$\sigma_{\mathrm{dBsm}} = 10 \cdot \log_{10}\left(\frac{\sigma_{\mathrm{m}^2}}{\sigma_{\mathrm{ref}}}\right) = 10 \cdot \log_{10}\left(\frac{\sigma_{\mathrm{m}^2}}{1}\right). \qquad (4)$$

2.3. Design and Simulation of Semi-cylindrical RAS

A semi-cylindrical structure with a low observable characteristic was designed using a layer of periodic square patterns, designed and verified in Section 2.2. The EM wave absorption of the designed semi-cylindrical RAS was simulated and evaluated using CST-MWS program. The height and diameter of the designed RAS was 210 mm and 170 mm. The size of the square pattern was 4 mm $\times$ 4 mm $\times$ 0.008 mm, and the gap between patterns was 2 mm. The thickness of the substrate was 2.7 mm excluding the total reflection layer of 0.5 mm. The detailed shape and design values are shown in Fig. 5 and listed in Table 1.

In this paper, the RCS of the designed semi-cylindrical RAS was simulated in order to confirm its radar absorbing performance. Figure 6 compares the simulated RCS of the semi-cylindrical RAS and a non-radar absorber, graphite epoxy, having the same geometric shape as the RAS. According to the graph, the RCS of the semi-cylindrical structure was reduced by nearly 98.4% from −2.9 dBsm to −20.8 dBsm compared to the graphite epoxy at 10.0 GHz. The RCS also reduced by at least approximately 87.7% (12.0 GHz) and at most 98.4% (10.0 GHz) within the X-band. All derived results are summarized in Table 3.

From the simulation results, we found that the designed semi-cylindrical radar absorbing structure with a layer of periodic square patterns can effectively absorb the incident radar signal and successfully reduce the radar cross-section of the structure at the target frequency.

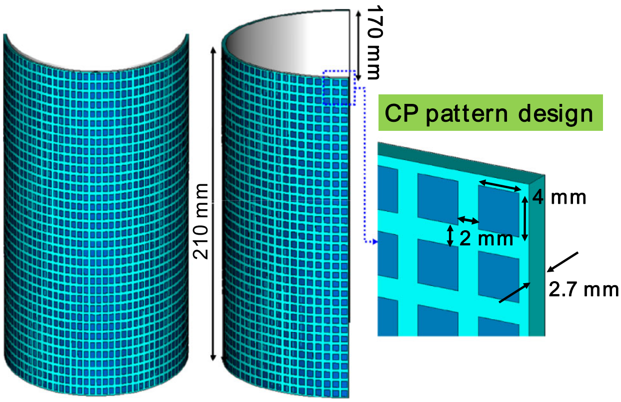

Figure 5. Detailed design of semi-cylindrical RAS. This figure is published in color on http://www.brill.nl/acm

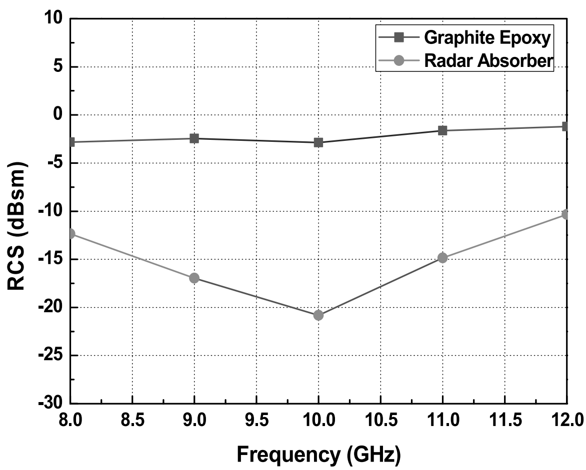

Figure 6. RCS simulation of semi-cylindrical RAS.

3. Fabrication of Semi-cylindrical RAS

3.1. Fabrication of Semi-cylindrical Structure using Composites

Fiber-reinforced composites were used in order to fabricate a semi-cylindrical structure. Composite materials are widely used in various industries due to their superior mechanical and electrical properties. However, for more accurate fabrication of a structure using composites, it is necessary to study the compaction phenomenon of fiber-reinforced composites. This refers to when the number of plies of a composite prepreg is linearly increased, and the total thickness of the cured composite laminates nonlinearly increases due to layer compaction and the matrix distribution under conditions of high temperature and high pressure [10]. Therefore, the thickness per ply (TPP) of the composite prepreg was determined through prelim-

Table 3.
RCS simulation of semi-cylindrical RAS in X-band

Frequency	Graphite epoxy	Radar absorber	Absorption
8.0 GHz	−2.8 dBsm ($0.52\ m^2$)	−12.4 dBsm ($0.06\ m^2$)	89.0%
9.0 GHz	−2.4 dBsm ($0.58\ m^2$)	−17.0 dBsm ($0.02\ m^2$)	96.5%
10.0 GHz	−2.9 dBsm ($0.51\ m^2$)	−20.8 dBsm ($0.008\ m^2$)	98.4%
11.0 GHz	−1.6 dBsm ($0.69\ m^2$)	−14.8 dBsm ($0.03\ m^2$)	95.2%
12.0 GHz	−1.2 dBsm ($0.76\ m^2$)	−10.3 dBsm ($0.09\ m^2$)	87.7%

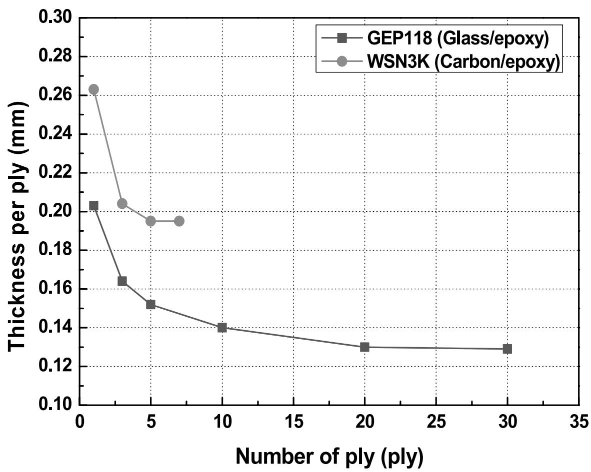

Figure 7. Experimental result of thickness per ply.

inary experiments and previous data, and the number of plies to obtain the desired thickness of the structure was calculated.

A glass fiber/epoxy plain-weave composite (GEP 118, SK Chemical Co. Ltd) and a carbon fiber/epoxy plain-weave composite (WSN 3K, SK Chemical Co. Ltd) were used for the dielectric substrate and the ground plane of the designed radar absorber, respectively. According to the results of the preliminary experiment, the thickness per ply of the GEP 118 and the WSN 3K converged to 0.129 mm and 0.195 mm by increasing the number of plies, as shown in Fig. 7. Therefore, the GEP 118 of 21 plies and the WSN 3K of 2 plies were needed to produce a dielectric layer with 2.7 mm thickness and a reflection layer with 0.5 mm thickness for the semi-cylindrical RAS.

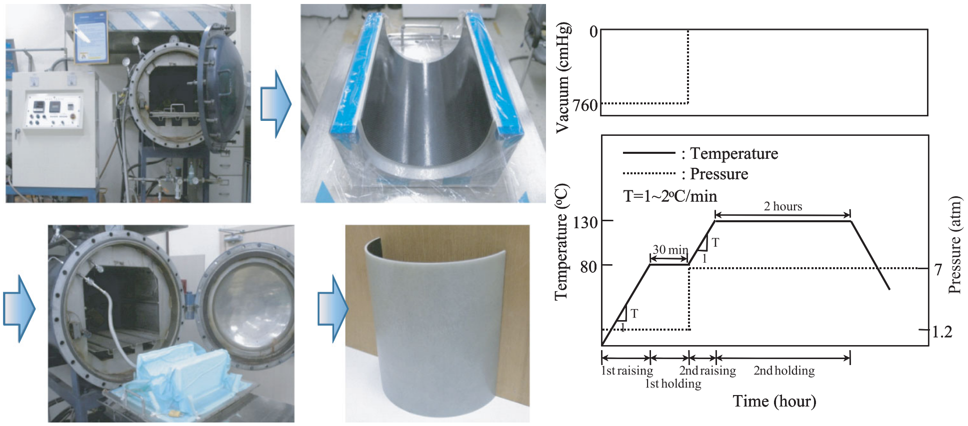

Figure 8. Manufacturing process of composites structure. This figure is published in color on http://www.brill.nl/acm

In this paper, the designed semi-cylindrical structure using composite materials was fabricated by an autoclave mold process. Figure 8 shows the manufacturing process of the composites structure, where the glass fabric/epoxy composite (GEP 118) and the carbon fabric/epoxy composite (WSN 3K) were layered on a female-mold and then cured under high temperature, high pressure, and low vacuum. The detailed curing conditions are shown in the right hand side of Fig. 8. The thickness of the final product was nearly 3.19 mm, comprising a dielectric substrate of 2.71 mm and a ground layer of 0.48 mm. Thus, the fabricated semi-cylindrical structure corresponded closely with the design presented in Section 2.3; the manufacture error ranged approximately from 0.01 mm to 0.02 mm compared to the design.

3.2. Fabrication of Periodic Pattern using Conducting Polymer

Conducting polymer materials were used in order to fabricate the designed layer of periodic square patterns, which provides radar absorbing characteristics in the X-band. Conducting polymers are good candidates for the resistive sheet of the CA absorber due to their controllable electric conductivity. They also offer advantages, such as simple and effective surface coating, and compatibility with other polymers [11].

In this paper, the designed resistive sheet was made by a screen printing method using a conducting polymer and a PVC mask in order to apply periodic square patterns to the surface of the fabricated semi-cylindrical structure. The detailed printing process of the periodic patterned layer is schematized in Fig. 9. First, a patterned PVC mask was attached on the upper side of the substrate and CP paste was subsequently applied. After coating the CP paste onto the substrate, the water-based solvent was removed during the curing stage such that only PEDOT and polyurethane remained. Through repeated iterations of the above procedure, the thickness of the periodic square patterns was nearly adjusted to that of the original design. Note

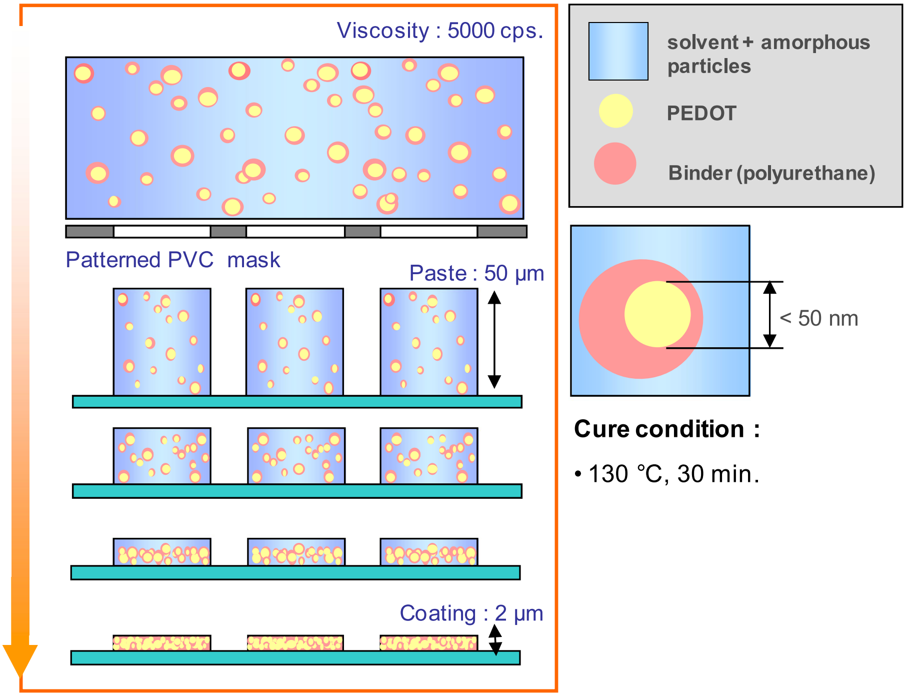

Figure 9. Printing process of periodic pattern layer. This figure is published in color on http://www.brill.nl/acm

that the resistance can be controlled by the thickness and the conductivity of the CP paste. The conducting polymer paste used in this study was synthesized by Lee *et al.* [11], and contains PEDOT (poly(3,4-ethylenedioxythiophene)) with a polyurethane binder. The conductivity of the CP paste was 1300 S/m and curing was carried out for more than 30 min at 130°C. The detailed configuration of the semi-cylindrical structure before and after application of the periodic square patterns using CP paste is shown in Fig. 10.

4. Results and Discussion

4.1. Measurement of Radar Cross-section

The purpose of this study is to develop a radar absorbing structure with a curved surface by using fiber-reinforce composites and a conducting polymer. Thus the radar cross-section of the fabricated semi-cylindrical RAS was measured in order to confirm the radar absorbing performance in the X-band. The RCS was measured at a compact range facility at Pohang University of Science and Technology (POSTECH) in Korea. The compact range system generates a uniform plane wave at short distance in order to measure RCS, ISAR images, and antenna patterns. This facility consists of a feed antenna, reflector antenna, target positioner, signal

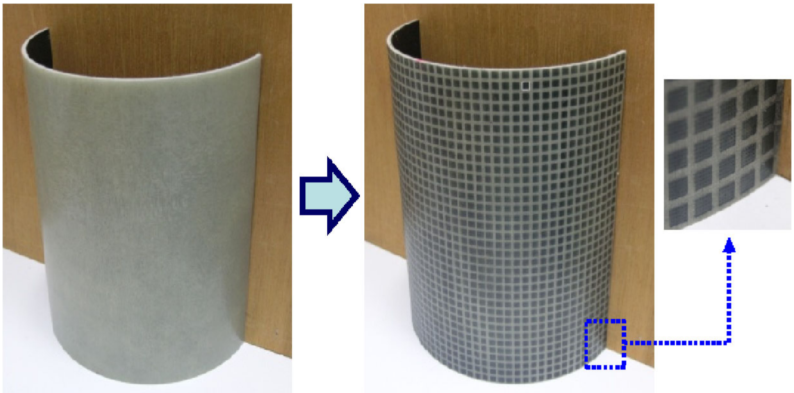

Figure 10. Configuration of semi-cylindrical RAS. This figure is published in color on http://www.brill.nl/acm

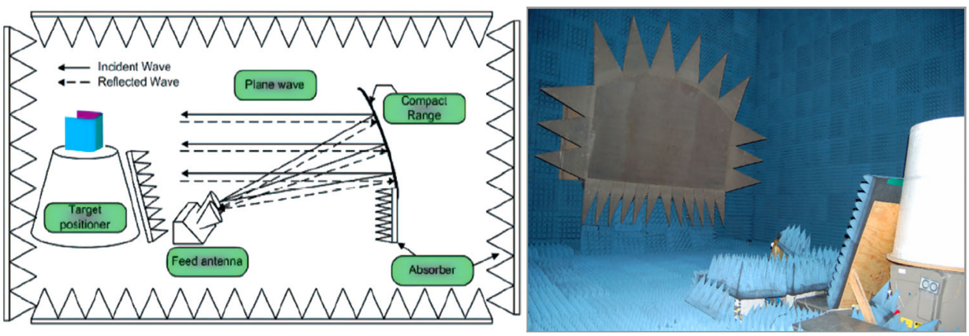

Figure 11. Compact range facility of POSTECH. This figure is published in color on http://www.brill.nl/acm

source, and receiver. The quiet zone (plane wave field) for the measuring equipment is 1.2 m × 1.2 m × 1.8 m and the overall sensitivity of the system is below −50 dBsm [12].

Figure 11 shows the device configuration and a real system image of the compact range facility. The measuring equipment was calibrated using a metallic sphere, the theoretical RCS value of which was determined by numerical analysis. The reliability of POSTECH's facility was verified by a RCS comparison between the theoretical value and the measured value of the metallic flat-plate specimen.

4.2. Radar Absorbing Performance of Semi-cylindrical RAS

In this study, the measured RCS of the semi-cylindrical RAS was compared with that of a graphite epoxy (non-radar absorber) specimen having the same geometric shape as the RAS in order to evaluate the radar absorbing performance of the proposed absorber. Figure 12 shows the RCS values measured by the compact range system in the normal incidence angle of the X-band. According to the graph, the RCS of the semi-cylindrical RAS declined by nearly 89.0%, from −2.2 dBsm for

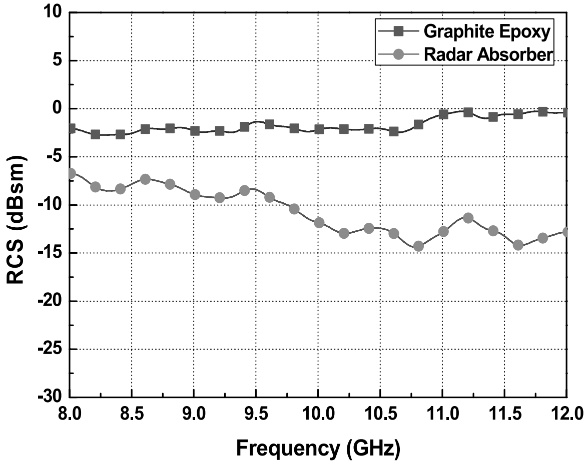

Figure 12. RCS measurement of semi-cylindrical RAS.

Table 4.
RCS measurement of semi-cylindrical RAS in X-band

Frequency	Graphite epoxy	Radar absorber	Absorption
8.0 GHz	−2.1 dBsm ($0.62\ m^2$)	−6.7 dBsm ($0.21\ m^2$)	65.3%
9.0 GHz	−2.3 dBsm ($0.59\ m^2$)	−8.9 dBsm ($0.13\ m^2$)	78.1%
10.0 GHz	−2.2 dBsm ($0.60\ m^2$)	−11.8 dBsm ($0.07\ m^2$)	89.0%
11.0 GHz	−0.6 dBsm ($0.87\ m^2$)	−12.9 dBsm ($0.05\ m^2$)	94.1%
12.0 GHz	−0.4 dBsm ($0.91\ m^2$)	−12.8 dBsm ($0.05\ m^2$)	94.2%

the graphite epoxy to −11.8 dBsm for the radar absorber, at target frequency of 10.0 GHz. In addition, the RCS also fell at least 65.3% (8.0 GHz) and at most 94.2% (12.0 GHz) within the X-band, as summarized in Table 4.

Comparing the simulation and the measurement results, the maximum radar absorbing efficiency was 98.4% for the simulation and 94.2% for the measurement, respectively. Thus, there is approximately 4% error between the results. Also, the simulation showed that the minimum RCS value was at around 10.0 GHz, whereas the minimum RCS value was at around 11.0 GHz according to the measured data. The main causes of this error can be grouped into two categories. The first is manufacture error in the fabrication relative to the simulation, such as difference in substrate thickness, pattern size, pattern thickness, and electrical properties. The second is measurement error deriving from the measuring equipment and environment, including specimen size, old equipment, temperature, and humidity.

5. Conclusions

In this research, a semi-cylindrical RAS with a periodic square patterned layer was designed and simulated in order to develop a load-bearing radar absorbing structure with curved surfaces. The designed RAS was fabricated using fiber-reinforced composites and a conducting polymer. The RCS of the fabricated RAS was measured in order to evaluate its radar absorbing efficiency.

Although there were small discrepancies between the simulation and measurement results, it was found that the semi-cylindrical RAS successfully absorbed incident radar energy. The radar cross-section of the RAS declined by nearly 90% at the target frequency of 10.0 GHz relative to a non-radar absorber. In addition, the RCS decreased to a range of 65% to 94% within the whole X-band.

From the above results, we found that the RCS of the semi-cylindrical structure can be effectively reduced by implementing periodic square patterns using a conducting polymer in the X-band. The results also show the feasibility of realizing stealth platforms for military application.

Acknowledgement

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