Electromagnetic wave absorption properties of carbon microcoils/PMMA composite beads in W bands

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Keywords: A. Carbon microcoils; B. Chemical treatment; D. Magnetic properties

Received 27 January 2003; accepted 14 June 2003

In recent years, the application of electromagnetic (EM) waves, especially in the higher GHz regions has significantly increased. For example, EM waves of 0.8–1.2 GHz are used for portable phones, 2.45 GHz for electronic ranges, 5.6–8.2 GHz (G band) for synthetic aperture radar (SAR) or microwave communication on the ground, 8.2–12.4 GHz (X band) for SAR or electron spin resonance apparatus (ESR), 30–75 GHz (V band) for an intelligent transportation system (ITS), and 75–110 GHz (W band) for ESR apparatus, etc. However, there are many problems to be resolved, such as EM wave interference (EMI) of electronic devices and apparatus, missed signals in the transportation systems of railways, airplanes or medical instruments, etc., because of their increasing use of EM waves in the GHz regions. Conductive metal powder or films are generally used for shielding EM waves in the MHz regions. Ferrites, carbon powder, metal-coated carbon fibers or synthetic organic fibers are also used for the shielding/absorbing of the MHz and lower frequency EM waves in the GHz regions. However, few studies on EM wave absorbers for higher V or W bands have been carried out while much research has been done on the EMI properties of carbon powder, straight carbon fibers (CF) or metal-coated CF in the lower bands of 1–12 GHz [1–6].

With regard to the use of chiral materials as EM wave absorbers, Varadan et al. first reported that conductive chiral polymers showed excellent absorption properties for EM waves and proposed new EM absorption materials [7]. It was in 1990 that we first found that carbon microcoils (CMCs) with micron-order coil diameters could be obtained with high reproducibility by the catalytic pyrolysis of acetylene at 700–800 °C [8] and then examined the preparation conditions, morphology, growth mechanism and some properties in detail [9–12]. The carbon microcoils have a double 3D-helical chiral structure with a 1–10-μm coil diameter and 0.1–10-mm coil length. Furthermore, we first found that the CMCs could effectively absorb EM waves in the 2–18-GHz regions [13–19]. Du et al. reported the electromagnetic properties of a microcoiled carbon fiber–paraffin wax composite in the Ku band (12.4–18 GHz) [20]. However, the EM absorption properties of the CMCs as well as other materials including carbon powder or CF in the V or W bands have not been examined.

The bulk CMC has a powder-like and fluffy form, and thus is not convenient for handling. However, CMCs embedded into plastic sheets or beads can be handled conveniently. In this study, we prepared CMC–polymethyl methacrylate (PMMA) composite beads and examined their EM wave absorption properties using the open space method in the W band.

As-grown CMC obtained using a Ni catalyst at 700–800 °C was used. The detailed morphology of the CMC as well as the preparation procedure are given by Chen et al. [12].

Fig. 1 shows the representative SEM image of the CMC used. They have a double 3D-helical–spiral chiral morphology with coil diameters of 2–10 m and coil lengths of 0.1–3 mm. The diameters of the carbon fibers from which the CMCs were formed were generally from 0.03 to 1.0 m. The as-grown CMCs have an amorphous structure with high specific surface area of about 100 m²/g, while they can be graphitized by a heat treatment at high temperature. The bulk electrical resistivity of the bulk (powder) CMCs was 10–0.1 cm, depending on the bulk density. The CMC–PMMA composite beads were prepared by conventional dispersion polymerization of methyl methacrylate (MMA), in which the CMCs were uniformly dispersed into MMA monomer solution and polymerized at 50 °C for 4 h while mixing (500 rpm). The reflection loss (absorptivity) of the EM waves was measured using the free space microwave measurement system (JFCC-HVS), which is shown schematically in Motojima et al. [14]. A collection of beads was filled in a 150×150×8 mm³ measurement cell (PET box) without pressing and the cell was placed between two antennas. Next, the complex dielectric cor-
Fig. 1. Representative morphology of carbon microcoils.

The reflection loss of the EM waves was calculated using the following equation:

\[ |S_{11}| = 20 \log_{10} \sqrt{S_{11}^2 + S_{11}^2} \, [\text{dB}] \]

A reflection loss of \(-20\) dB indicates that 99% of the introduced EM waves are absorbed, and this value is a target value to be attained for the EM absorbers from an industrial point of view.

Fig. 2 shows the CMC–PMMA beads that contained 1 wt.% CMC. The beads have a spherical or slightly spheroidal form and a black color, and the bead diameter was 0.01–2 mm depending on the preparation conditions. In this study, beads with a diameter of about 1 mm were used. Fig. 3 shows the reflection loss of the CMC–PMMA beads containing different amounts of CMCs, and as well as that of carbon and ferrite powders as reference samples, in which the CMC with a coil length below 90 \(\mu\)m was used. It can be seen that neither the PMMA beads without CMC, ferrite powder and carbon powder can absorb the EM waves in the W bands. However, the PMMA beads containing 1–2 wt.% CMC strongly absorb the EM waves in the different absorption bands. The sample with 1 wt.% CMC addition showed the sharpest absorption peaks and strongest absorptivity of the EM waves, more than \(-30\) dB at 81, 91 and 102 GHz, while the absorptivity decreased with the increasing addition of the CMC. The sample with the higher addition (above 5–10 wt.%) showed no absorption of the EM waves. This may be caused by the increased reflection of the EM waves caused by increased electric conductivity. The absorption band shifts to a lower frequency with increasing addition of CMC, while the width of the absorption band increased. Fig. 4 shows the effect of the coil length on the reflection loss, for which the additional amount of the CMC was 2
It can be seen that the absorption band width of the longer CMC increases in the 90–96-GHz range, while
sharp peaks are observed for the shorter CMC as well as for the lower addition of 1 wt.% (see Fig. 3b). The reasons
for this are not yet known.

Materials generally absorb EM waves by dielectric loss, conductive loss and magnetic loss. For example, Du et al.
[20] reported that a CMC-paraffin wax composite was mainly a type of dielectric loss material with a small
magnetic loss and diamagnetism in the Ku band. However, CMC is a type of representative chiral material with
micro-coiling morphology and thus expected to have different interactions with the EM waves from non-chiral
materials. Accordingly, it is necessary to discuss the interaction of the EMCs with EM waves from a chiral
material point of view, not from simple dielectric materials without chirality. We have found that an electromotive
force was induced when the CMC was exposed in an alternating magnetic flux of 1–1000 Hz [21]. Accordingly,
it was reasonably considered that when the EM waves were irradiated on the CMC, the EMCs acted as micro-
chiral coils (micro-solenoid) and an inductive electromotive force was generated and thus current was induced in
the CMC according to Faraday’s law. The coiling-chiral morphology was considered to be the most favorable form
for the effective generation of an inductive current than that of the straight- or powder-like form. It was also
considered that the irradiated EM waves on the CMCs were effectively polarized to form planar and/or circularly
polarized waves; right-handed (RCP) or left-handed (LCP) waves, and also were reflected or dispersed, and thus were
then sharply attenuated. Furthermore, the CMCs were oriented in different directions and thus could effectively
attenuate even if the EM waves were incident from any direction. The coil diameter of the used CMC was 2–10
µm and the coil length was 0.1–3 mm, while the wave-
length of the EM waves of 10 GHz was 30 mm and of 100
GHz was 0.3 mm. That is, the CMCs could absorb the EM
waves with two or three magnitude larger wavelengths
than that of the CMCs dimensions. The CMCs used in this
work have almost the same number of right- and left-

handed chiral-coiling morphologies. The correlation be-
tween the coiling-chirality of the CMCs with the EM
waves is not well known. However, it was considered that
the EM absorption materials were required to have a chiral
structure and high chiral parameters in order to obtain an
effective absorption ability in the higher GHz regions.

In conclusion, the electromagnetic (EM) wave absorption
properties of the CMC–PMMA composite beads of
about 1-mm diameter were examined in the W bands. It
was found that only a 1–2 wt.% addition of the CMC in
PMMA beads resulted in strong EM wave absorptivity.
The addition of greater than 5 wt.% CMC resulted in
decreased EM absorptivity. Wider absorption bands could
be obtained using longer carbon coals.

References

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Fig. 4. Reflection loss of CMC–PMMA composite beads. Added amount of CMC in PMMA: (a) <90 µm, (b) 150–300 µm.