FERROMAGNETIC PARTICLES FOR COMPOSITES

An electrostatic shield is generally used to enclose or exclude electromagnetic (EM) waves. The magnetic analog of the electrostatic shield has been used with indifferent success to shield static or quasi-static magnetic fields, but there has been little use of such a shield to protect against high frequency EM fields, mostly because of problems with skin depth.

This article covers a class of materials which do not have the skin depth problem. Instead of attenuating by shorting the e-vector, they work by absorbing power from the m-vector. These materials are ferro-magnetic metal particles in a plastic or elastomeric binder. They can be used to shield non-conductive surfaces or they can be used to coat conductive surfaces in order to reduce EM wave reflections. They are especially useful in shielding *sources* of EM radiation, since the waves near the source are often unbalanced toward the m-vector.

These composite materials have three loss modes:

1. Eddy current loss in the isolated particles;
2. Ferromagnetic hysteresis loss in the particles; and
3. Eddy current loss in the bulk composite material.

All three modes have frequency characteristics. Mode 1. depends on the particle size, shape, electrical conductivity (σ), and intrinsic magnetic permeability (μ). Mode 3. depends on the σ and the μ of the composite, on its dimensions, and on the impedance of the impinging EM wave.

Particles

The research discussed herein has been mostly confined to iron and nickel particles. Since the composite material should be conductive, a process was developed to render the surfaces of the particles chemically passive to attack by oxygen; especially in warm, humid atmospheres. This process forms interstitial lattice compounds in the surface layer of the particles. Such compounds are well-known in the magnetic and metallurgical literature. The particles stay electrically conductive at the surface, and the magnetic changes have been too small to detect by saturation measurements on a VSM. The particles were large enough to be multidomain, and so are magnetically soft.

Since the composite materials have potential uses throughout the radio frequency range, it is of interest to look at possible frequency limitations. Using the formula for the ferromagnetic resonance frequency[1]:

$$\omega_o = \frac{g\mu\beta}{h} \frac{2K}{M_s}$$

(which assumes that the effective field is due to anisotropy), the frequency limit for iron is 1.08×10^{10} Hz and for nickel 2.77×10^{9} Hz. Under this assumption, these two metals will be useful into the microwave range. Thus, frequency control is a matter of geometry.

To get some idea of the effect of size, μ_1, and σ of the particles, an expression for the power loss in a conducting, magnetic sphere immersed in an alternating magnetic field[2] was used. Calculations are available from the author.

In addition to the particle parameters, the power loss depends on the square of the magnetic field intensity (H^2) and on its frequency. A relative permeability of 200 for iron and nickel were selected, and the conductivity values from the literature[3]. The only other inputs are the frequency and the particle radius. Curves of specific power absorption vs. particle radius are shown in Figure 1. Note that as the frequency goes down, the particle radius for peak absorbed

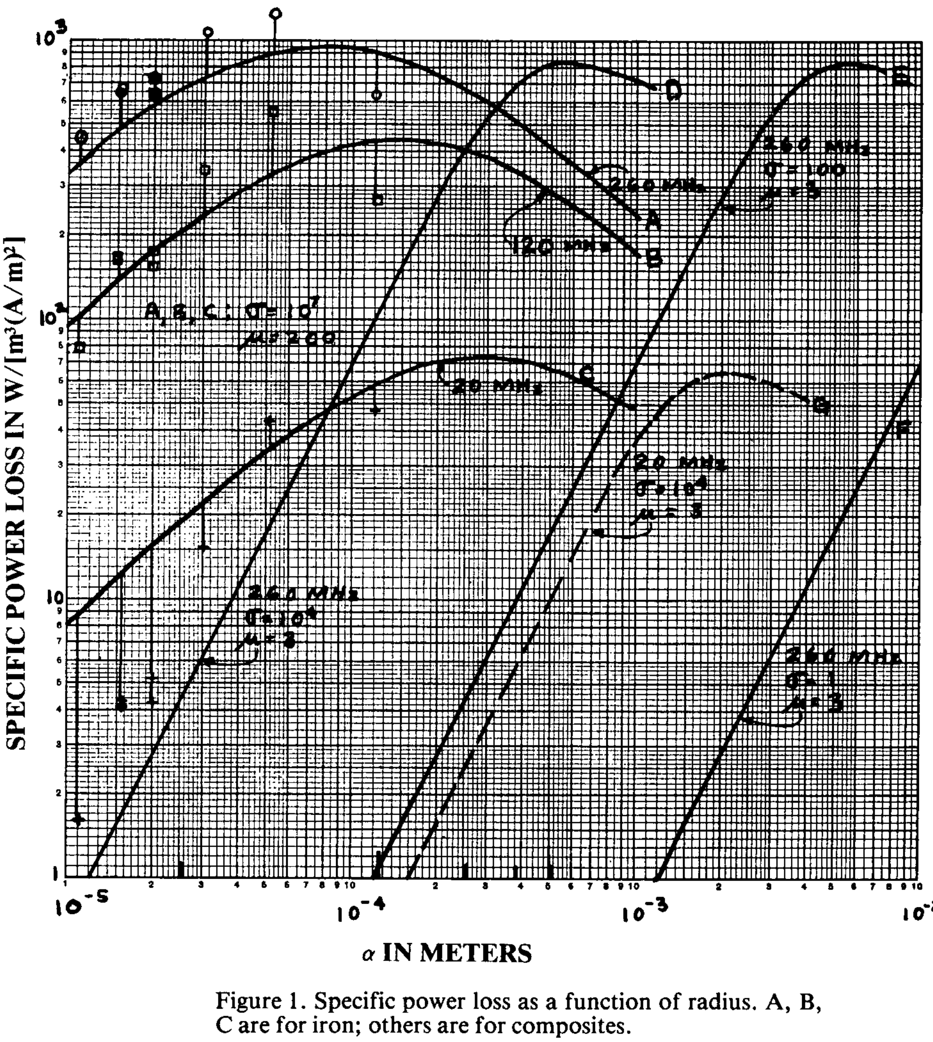

Figure 1. Specific power loss as a function of radius. A, B, C are for iron; others are for composites.

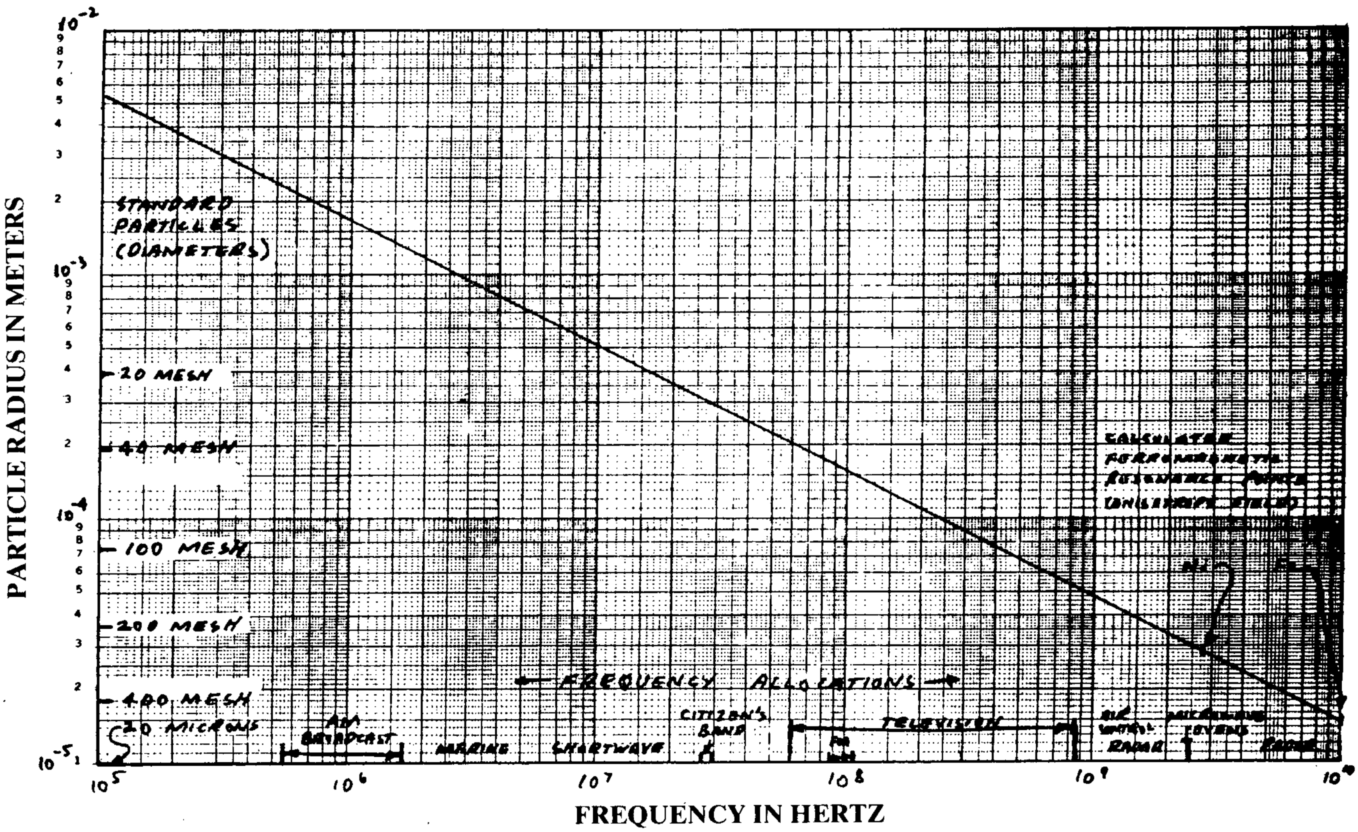

Figure 2. Particle radius for peak power loss as a function of frequency for Ni and Fe. $\mu = 200$, $\sigma = 10^7$.

power goes up. Figure 2 shows how this peak absorption particle radius changes with frequency. Also on Figure 1, some of the U.S. standard frequency allocations are shown, as well as some standard screen-sieved particle sizes. As can be seen, the particles get too large for paint as the frequency drops below those used for television. Smaller particles can be used at lower frequencies, but with less efficiency.

Composites

The problem of what happens to properties such as conductivity, permeability, permittivity, etc., when mixtures and composites are constructed, is an old one. Maxwell and Lord Rayleigh made contributions, and papers are still being published[4]. There are two parameters of interest in the composites: μ and σ. One of the most useful expressions was derived by Rayleigh for the permittivity of a cubical array of spheres in a matrix, when spheres and matrix have different permittivities:

$$\varepsilon^* = \varepsilon_2 \frac{2\,\varepsilon_2 + \varepsilon_1 + 2\,V_1\,(\varepsilon_1 - \varepsilon_2)}{2\,\varepsilon_2 + \varepsilon_1 - V_1\,(\varepsilon_1 - \varepsilon_2)}$$

Here, ε^* is the permittivity of the mixture, ε_1 that of the spheres, and ε_2 that of the matrix. V_1 is the volume fraction occupied by the spheres. Another is the self-consistent calculation (SCC) derived independently by several people:

$$\varepsilon^* = \varepsilon_2 + \frac{3\,V_1\,\varepsilon^*\,(\varepsilon_1 - \varepsilon_2)}{2\,\varepsilon^* + \varepsilon_1}$$

The same notation is used. Note that ε^* appears on both sides of the equation, so this is really a quadratic, of which only the positive root is used. Where ε's are shown above, one may substitute σ or μ. A study on μ alone has not been performed, but usual volume loadings are in the range of 0.35 to 0.45, and relative permeabilities of from 2.5 to 4.5 are normally attained, so that Rayleigh curve seems to be the most useful one for magnetic permeability. Changing the μ of the particles doesn't help much at these loadings. For a volume fraction of 0.4, and a particle μ of 200, the Rayleigh equation gives a composite μ of 2.9510. When the

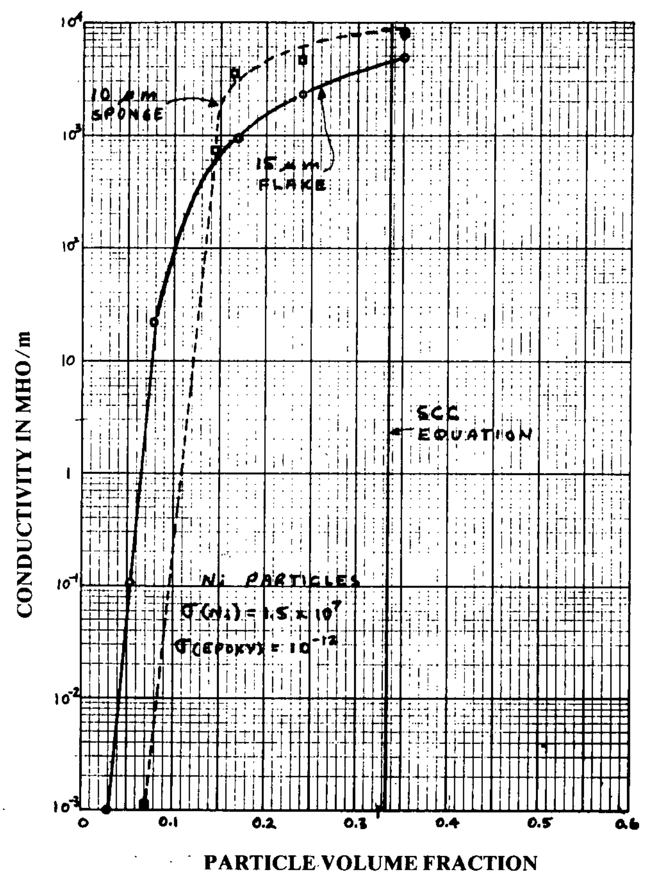

Figure 3. (Right) Conductivity as a function of volume fraction for Ni particles and the SCC equation.

particle μ is changed to 20,000, the composite μ goes to 2.9995!

Composite σ is not very well defined by any of the equations. A typical case is shown in Figure 3, where two different nickel particles were used. The only calculation which is even on the graph is the SCC. It shows a transition at V_1 of about 0.335. The real particles make a slower transition at much lower loadings. Obviously, something is happening which was not taken into account. The most obvious thing is chaining and contact of the particles. One might think that the ferromagnetic character of the particles has something to do with this behavior, but silver particles behave the same way. Since contact is taking place between the particles, one would expect the particle surface characteristics to influence the composite σ, and this is the case. The point to make here is that the composite σ is under our control, while μ can be varied only over a limited range.

To check the curves in Figure 1, a series of epoxy binder "plugs" were loaded with iron particles of graded size. The loadings were such that the composite σ was quite small (V_1 was about 0.1), and the μ (relative) was not much different from 1. The power loss was evaluated in a small coil, using a Boonton-HP Q-meter at frequencies of 20 MHz, 120 MHz, and 260 MHz, to match the theoretical curves drawn in Figure 1. The Q of the coil was measured first with no sample in it. This Q is calculated by[5]:

$$Q_L = \frac{\omega L}{R_L}$$

where L is the inductance of the coil and RL is its equivalent resistance. When the sample was inserted into the coil, it changed L very little (since μ was nearly 1), but the Q dropped due to the power loss in the sample. This power loss was equivalent to an added resistance in the circuit:

$$Q_s = \frac{\omega L}{R_L + R_s}$$

Then, taking the reciprocals, subtracting, and rearranging:

$$R_s = 2\pi f L \left(\frac{1}{Q_s} - \frac{1}{Q_L}\right)$$

There were several possible errors in the measurement. The power loss in the sample is proportional to the square of the applied magnetic field, and Q-meters are not designed to hold a constant field in the coil. The size grading was done by taking "cuts" in a repetitive sieving operation, which gives an unknown size distribution. The particle sizes were calculated by taking the geometric mean of the particle sizes which just barely pass through the two screens used to make the "cut" (i.e., a "+200, -100" cut has sizes of 74 micrometers and 149 micrometers associated with the two screens. The geometric average is the square root of their product, or about 105 micrometers. In this case, it is not much different from the arithmetic mean). The particles were not spherical. The numbers obtained from the Q-meter were only proportional to the specific power losses calculated according to appendix A, so they had to be multiplied by arbitrary constants to get them in the vicinity of the curves on Figure 1.

A 1-turn coil was used for the 260 MHz points, a 2-turn coil for the 120 MHz points, and a 15 turn one at 20 MHz. The field strengths were unknown. The power loss seems to drop off faster from the peak than the theory indicates. The actual peak seems to occur at about half the predicted size.

No way was found to quantitatively evaluate the ferromagnetic hysteresis loss in the particles. This loss might be the cause of the sharp drop at the high end of the particle size range. Large particles do not allow as much magnetic field penetration, and the hysteresis loss per unit volume would drop off sharply. Strangely enough, the particle radius at the peak is about 100 times the skin depth.

The question naturally arises as to the relative amounts of absorption due to the particles and to the conductivity of the composite. This is difficult to estimate, as the composite losses depend upon the thickness of the composite layer, the geometry of the shield, and the location and type of the source. To get an order-of-magnitude estimate, it is assumed that all the losses are from the m-vector, and it is also assumed that the radius of a sphere in a similar situation will be roughly equivalent to the thickness of a shielding layer. Then we can just plug in the values for σ and μ and obtain a loss at a given thickness.

The curves for the composite are also plotted in Figure 1. At 260 MHz, a coating would have to have a σ of 1×10^4 mho/m to be equivalent in loss to the particles alone. It would also have to be quite thick (3×10^{-4} m is about 11 mils) for a paint. At lower frequencies, the situation is even worse. Higher (and unobtainable) σ's are necessary, or the coating thickness required is more than a millimeter. A much more desirable situation exists at UHF where thickness and σ are practical. The losses at UHF are much higher per unit volume of both particles and composites. Of course, the particle losses will drop off as the composite losses increase, since the magnetic field will decrease inside the composite.

It should be possible to use these composites as impedance matching coatings between conducting surfaces and the air. Considering the material as a conductor (actually, they can be in the semiconductor range), the impedance is given by:

$$|Z| = \sqrt{\frac{\mu\omega}{\sigma}}$$

For a composite with $\mu = 3$, $\sigma = 10^4$, and with the frequency at 360 MHz, the impedance magnitude is about 0.6 ohm. With $\mu = 3$, $\sigma = 1$, and the frequency at 20 MHz, the impedance magnitude of about 15 ohms. Obviously, other combinations are possible.

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