Calculating the Surface Resistivities of Conductive Fabrics

A simple method for predicting surface resistivity can guide one in selecting fabric substrates and coating levels for particular applications.

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INTRODUCTION

Conductive fabrics, both woven and nonwoven, have emerged as prominent materials for use in reducing radar signature, in shielding against electromagnetic radiation (EMR), and in numerous other applications requiring lightweight, drapable, conductive materials. Such applications include conductive tape, architectural shielding, shielded enclosures, shielding gaskets, shielding cable wrap, microwave absorption, static dissipation, resistive heating, and ground planes. Surface, or sheet, resistivity, which is the resistivity across the surface of a material given in ohm/sq, has been identified as one of the most important properties of a conductive fabric. Indeed, the surface resistivity is a critical determinant for many conductive fabric applications because a fabric's surface impedance, which depends directly on the surface resistivity,[1] determines the microwave response of a material and the ability of a fabric to shield incident radiation.[1,2] Furthermore, surface resistivity is an excellent indicator of the quality of a conductive product and can be related to the amount of coating on the fabric or film and the quality of the deposited, conductive layer.

Given the importance of surface resistivity to the performance of conductive fabrics and its role as an indicator of quality of such products, it is very useful to have a means of predicting the surface resistivity of conductive fabrics. Other than calculating the surface resistivity of a hypothetical thin foil made from the equivalent amount of the same metal deposited on a fabric, the author is not aware of any published method that predicts the surface resistivity of metallized or other conductive fabrics. [2,3] Moreover, the simple foil calculation is deficient inasmuch as it always results in an underestimation of the fabric's actual resistivity by at least a factor of two.

Having a method available for calculating surface resistivity also allows one the ability to estimate simply the volume (bulk) conductivity of a coating material whose bulk conductivity is not known or is highly variable. This method can be particularly helpful when dealing with conductive coatings, such as conducting polymers, which have bulk conductivities that are very sensitive to processing conditions.

This article presents a simple model for predicting the important property of surface resistivity of conductive *woven, filament-yarn* fabrics only. Nonwovens and spun-yarn fabrics are not discussed because they are much more difficult to treat mathematically in terms of their distribution of fiber orientation and the existence of fiber discontinuity. Comparisons with actual resistivity data of metallized woven fabrics are given. In addition, an estimate of the volume conductivity of an inherently conducting polymer, polypyrrole (PP), which was deposited on fabrics, is obtained via the method.

It should be noted from the outset that all surface resistivity data appearing in this article were generated using either a two-point probe technique for fabrics according to AATCC 76-1987 or the four-point probe method described in Reference 4. The latter method is basically a variation of the technique described in ASTM F390-78 that was modified specifically for fabrics.[4]

MODELLING THE RESISTIVITY OF METALLIZED FABRICS

For those not familiar with the details of textile products, a brief overview of woven goods is given here. Woven fabrics consist of synthetic or natural yarns (threads) of fiber interlaced in a regular pattern. The yarns themselves usually are bundles of several (sometimes hundreds or thousands) continuous or discontinuous filaments. Spun yarns are made up of short fibers (staple) spun together to form a yarn. Various types, sizes, and weights of yarns are available. Fabrics are constructed (woven) with a certain number of yarns in the lengthwise direction of the fabric, (the warp direction), and a certain number of yarns in the transverse or width direction (known as the weft or fill direction). The warp yarns are called ends, while the fill yarns are called picks. The end and pick counts, which, together with the type of weave (e.g., plain, ripstop, twill, satin, etc.) determine fabric construction, are given as the number of yarns per inch or centimeter.

An example is a 112 x 118 nylon ripstop made from a single-ply, high-tenacity 30/10 nylon yarn. This means that the fabric has 112 yarns/inch in the warp direction and 118 yarns/inch in the fill direction, and the yarn is made up of 10 individual continuous filaments of nylon bundled together, roughly in parallel, to give a 30-denier yarn. Yarn denier is the weight in grams of 9000 meters of the particular yarn. In this case, the denier per filament (dpf) is 3 (30/10).

For purposes of the proposed model, all yarns are assumed to consist of continuous, straight filaments with perfectly circular cross-sections (i.e., long, thin cylinders). This allows one to calculate the diameter, D, of each filament if one knows the dpf and the fiber density (e.g., 1.14 g/cc for nylon 6,6).

$$D = [(4/\pi)\ dpf/(9 \times 10^5\ d)]^{1/2} \qquad (1)$$

where d is the fiber density in g/cc.

When a fabric is treated with a coating material, each individual filament in the yarn bundle is coated, more or less, with a very thin layer of the material. Figure 1 describes what the cross-section of a metallized fiber (filament) in a conductive fabric looks like. D′ is the diameter of the composite yarn (yarn plus metal), and t is the thickness of the metal layer. Thus, $D' = D + 2t$.

Assuming that the metal coating is uniformly distributed over each individual, cylindrical filament in a fabric, it is easily shown that D′ can be computed as follows:

$$D' = D[(d_f + w_f d_m - w_f d_f)/w_f d_m]^{1/2} \qquad (2)$$

where d_f and d_m are the densities of the fiber and metal, respectively, and w_f is the weight fraction of the fiber in the composite fabric. The metal thickness is then readily calculated. As an example, a fabric made of 30/10 nylon yarn and containing 40% copper, by weight, has an average metal thickness t of 0.4 microns around each filament.

Now, the measured resistance R of any material depends on its cross-sectional area according to

$$R = \rho l/A \qquad (3)$$

where
l is the length of the conductor,
A is the cross-sectional area, and
ρ is the bulk resistivity of the material.

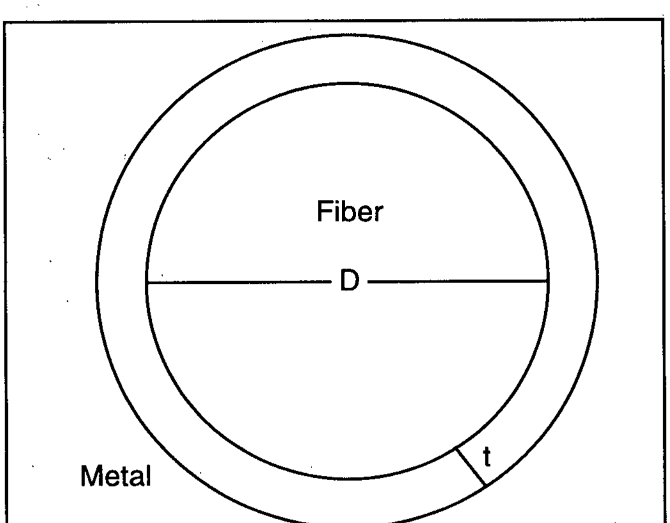

Figure 1. *Cross Section of a Metallized Fiber in a Conductive Fabric. t is the metal thickness.*

The bulk resistivity, or its inverse, bulk conductivity, is an inherent property of the material and should not depend on sample geometry. The bulk resistivity of copper is around 1.7×10^{-6} ohm-cm.[1]

For a wire or conductively coated yarn, it is convenient to define a "reduced resistance," R/l, with units in ohm/cm, as

$$R/l = \rho/A \qquad (4)$$

To calculate the reduced resistance of a conductively coated fiber, one then only needs the cross-sectional area of the conductive layer coating the filament. This is easily found as

$$A = \pi/4(D'^2 - D^2) \qquad (5)$$

For continuous filament yarns, the assumption is made that the bundle of n filaments can be treated as parallel conductors. Thus,

$$1/(R/\ell) = \sum_{i=1}^{n} 1/(r_i/\ell) \qquad (6)$$

where R is the yarn resistance, and r_i is the resistance of the i^{th} filament.

In reality, the r_i's will vary due to variations in the quality and uniformity of the coating and the degree of deviation of the filament from a perfect, smooth cylinder. For instance, textured or crimped yarn will not be perfectly smooth cylinders. From a practical standpoint, however, only an average filament resistance is needed. The reduced resistance of a yarn can be viewed as the average reduced resistance of an individual filament divided by the number of filaments in the yarn. As an example, the yarn in the conductive fabric made from 30/10 nylon yarn and 40% copper would have a reduced resistance of almost 0.7 ohm/cm if the copper were totally pure and perfectly distributed around all the filaments, assuming them to be perfect cylinders.

To calculate the surface resistivity of a conductive fabric, one again assumes that all the yarns in the warp direction conduct in parallel, and all the yarns in the fill (weft) direction do likewise. It is further assumed that each individual filament of every yarn is perfectly and uniformly coated, and the warp and fill yarns are *independent* of each other. That is, there is no contribution by the fill yarns to the conductivity in the warp direction and vice versa. This last statement is, of course, not entirely accurate since the crossing yarns are in contact with each other.

Given these assumptions, the surface resistivity, ρ_s, in, say, the warp direction becomes

$$\rho_s(w) = \left\{ \sum_{i=1}^{N_w} 1/(R_i\ (w) \right\}^{-1} \qquad (7)$$

where $R_i(w)$ is the reduced resistance of the warp yarn (ohm/cm), and N_w indicates the number of yarns per centimeter in the warp direction. Simply put, to compute the surface resistivity of a conductive fabric in a particular direction, one merely takes the mean reduced yarn resistance, as calculated above or measured, and divides by the number of yarns per centimeter in that direction of the fabric.

For the sample fabric discussed above, one would calculate a surface resistivity of 0.016 ohm/sq (= 0.7 ohm/cm/yarn/ 44 yarn/cm) in the warp direction.

RESULTS AND DISCUSSION

Figure 2 shows predicted surface resistivity, in both directions, of copper on polyester (PET) taffeta (100 x 68/ in.) as a function of metal content. The yarn in both directions is a 70/34 polyester yarn. As one can see, the absolute drop-off in resistivities as metal is added becomes less and less significant as one gets to very heavy metal loadings. This suggests that, for most common applications utilizing metallized fabric, only around 15 to 20% copper is needed on the fabric to be effective. Special applications requiring surface resistivities of only a few milliohms, on the other hand, would be limited to fabrics with substantial amounts of metal (≈80%). Nickel-plated fabrics, with pure nickel being over four times as resistive as copper, would require more metal weight than copper-plated fabrics to possess comparable performance. Note also that there is little absolute difference between warp and fill directions, especially at the high metal levels, for this particular fabric.

Calculations such as these reveal that, theoretically, for the same amount of metal, expressed in terms of g/cm^2, it is better to have a fabric made from large yarns (higher denier) rather than from smaller yarns. The number of filaments in the yarn is not significant in affecting the reduced resistance of the yarn other than the fact that the total yarn denier depends on the size and number of individual filaments. That is, for a given total denier, changing the number of filaments does not change the yarn resistance.

As verification of the proposed method, results were calculated for a sample of copper-coated Acrilan® yarn and several metallized fabrics and compared to observed resistivity data for those samples.

A filament of 2.2 dpf Acrilan®, teased from a 1000-filament bundle coated with 37% copper, was measured for reduced resistance using specially designed equipment. An average of 10 specimens gave 11 ± 0.8 ohm/cm at the 90% confidence interval. The predicted value is 10.5 ohm/ cm, which is in excellent agreement.

Table 1 shows predicted and measured surface resistivity data for some commercial and experimental copper-coated fabrics. As one can see, considering the variation in metal levels from place to place on a fabric, agreement between experiment and theory is good, particularly at the high metal loadings. In all instances, the predicted values are lower than observed. This is to be expected since it is known that not all individual filaments are perfectly and uniformly coated with copper. As noted above, there is almost always a small fraction of filaments that is discontinuously covered with metal. Heavy depositions of metal may be able to

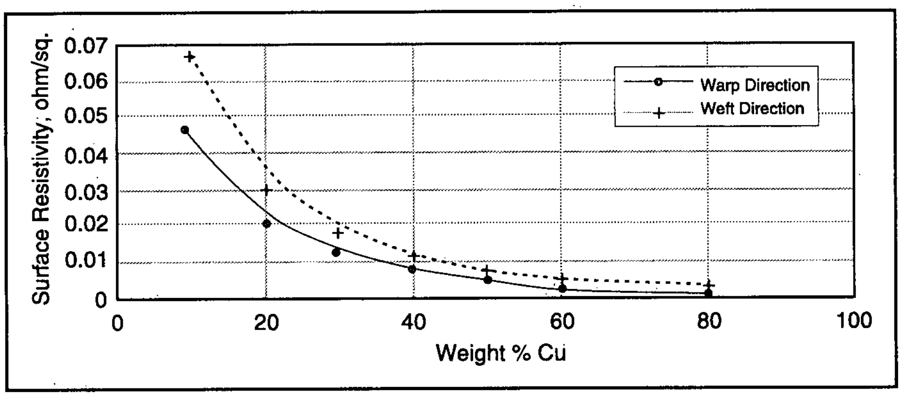

Figure 2. *Calculated Surface Resistivity of a Polyester Taffeta (100 x 68) Fabric Coated With Copper.*

FABRIC						SURFACE RESISTIVITY			
Type	Warp Yarn Ends/cm		Fill Yarn Picks/cm		Wt.% Cu	Measured Warp/Fill		Calculated Warp/Fill	
Nylon	30/10	57	40/34	35	21.2	56±3	74±2	31	37
Nylon	30/10	57	40/34	46	65.7	5.6±.3	6.7±.4	4	5
PET	70/34	39	70/34	27	19.5	45±3	71±9	21	30
PET	70/34	39	70/34	27	57.9	5.5±.5	7.8±1.5	4	5
PET	70/34	39	70/34	27	40.5	11±2.5	18±1	7	11

Table 1. *Measured and Calculated Surface Resistivities of Some Copper-plated Fabrics. All surface resistivities in milliohm/sq. Uncertainties listed at the 90% confidence interval.*

Considering the variation in metal levels from place to place on a fabric, agreement between experiment and theory is good, particularly at the high metal loadings.

bridge defects and fibers and overcome this problem to a certain extent. It is also likely that the deposited metal does not possess the volume resistivity of bulk copper used in the calculations due to various impurities and variations in crystal morphology.

Another fact to note in Table 1 is that there is a directional, or polarization, effect evident, as might be predicted for anisotropic fabrics in which warp and fill yarns and their counts differ. For the fabrics studied here, the warp direction always had the lower surface resistivity because it had the most filaments in that direction. The ratios of fill-to-warp measured values agree more or less with those calculated from first principles. Such orientational effects have importance for many applications, particularly as they may influence shielding effectiveness and microwave response characteristics.

The described calculations for surface resistivity can also be utilized for extracting values of the volume, or bulk, conductivities of coating materials whose conductivities are unknown. For instance, the bulk conductivity of several inherently conducting polymer (ICP) films, such as polypyrrole (PP), has been reported in the literature to vary widely.[5,6] By measuring the surface resistivity of PP-treated fabrics of known construction, one can determine the bulk conductivity of the doped polypyrrole deposited on the fabric. As an example, the same polyester taffeta fabric mentioned above, when treated with 5% PP by weight, had measured surface resistivities of 62±4 ohm/sq in the warp direction and 75±4 ohm/sq in the fill direction (90% confidence level). Taking a density of 1.50 g/cc for the PP[6] leads to a value of 172 s/c (siemens/cm) for the freshly deposited polypyrrole. Another polyester fabric, made from 2/150/34 (two-ply, textured) yarn in a 70 x 55 twill construction and treated with 5% PP, had initial surface resistivities of 17±0.8 ohm/sq in the warp direction and 23±1.3 ohm/sq in the fill direction (90% confidence level). Assuming the same density for PP, back calculations afford a bulk conductivity again of around 170 S/cm. While these values are about 5 times higher than those reported by Armes et al.,[6] who measured aged PP-coated, single quartz filaments, their consistency is quite encouraging. The value of 170 S/cm is well below the bulk conductivities reported for PP films.[5] Presumably, the higher the bulk conductivity of the PP, the higher the quality of deposition.

SUMMARY

A simple method for predicting the important property of surface resistivity of conductive woven fabrics is given and shown to be very much in line with experimental data. The method can guide one in selecting fabric substrates and coating levels for particular applications and help in verifying directional differences in fabric properties. Calculating surface resistivities based on the amount of coating and fabric construction can also be of use in gauging the quality of deposition on a treated fabric and determining the bulk conductivity of a coating material.

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