Electroconductive Textile Homogeneity Tests Using Microwave Transmission

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Abstract
The stitch-bond nonwoven textile WOM-E, composed of 90 percent electro-conductive (polyacrylonitrile, chemically modified with copper and sulfur) fibres, was tested using the X-band microwave transmission and direct-current techniques. The resistance obtained from the microwave transmission was found to agree very well with that obtained in four-probe DC measurements. Microwave transmission is recommended for the contactless, non-destructive monitoring of electro-conductive textile quality in the manufacturing process.

Key words: *textiles, microwaves, electro-conductive fibres, non-destructive measurements.*

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Introduction

Electro-conductive textiles (ECT) are basic for innovations in many areas, such as anti-static-charge covering, physiotherapy-room shielding, electric-power cable screening, special cloth heating, etc. Materials technology and quality testing require the pre-definition of such basic notions as the material surface, its thickness, specific electrical resistance, etc., characterising irregular (soft) spatial structures before the elaboration of adequate methods of parameter measurements. In the literature on ECT characterisation, preliminary direct-current (DC) resistance and microwave (MW) transmission/reflection measurements have been reported [1, 2] for some samples of ECT products. However, there have been no data on electrical resistance monitoring in the ECT production process.

This article presents the first investigation into the feasibility of contactless, non-destructive monitoring of electric resistance in the ECT production process. For this task, moving ECT strips were tested experimentally with the use of DC probes as well as microwave transmission, and then analysed employing a simple mathematical model.

Object and model

The object

Let us consider WOM-E type textiles that are polyacrylonitrile fibres chemically modified with copper and sulphur according to the technology suggested by Okoniewski at the Textile Research Institute of Lodz so as to establish the electric conductance property. The fibres are fixed together by stitching with pure (non-conductive) polyacrylonitrile threads (***Figure 1***). The stitch-bond nonwoven textile structure is seen to exhibit both the periodicity of stitching and the irregularities of entangled fibre distribution.

Microwave transmission model

Let the microwave length be large compared to all the characteristic dimensions of textile, such as the fibre diameter, the mean inter-fibre distance, the textile layer thickness, the inter-stitch period and the size of the needling holes. One can then attempt to model the microwave transmission using an approximation of the effective medium that is supposed to be non-magnetic, provided that the fibres are chemically modified without using magnetic ions. There exists a chance of raising the dynamic magnetism using magnetic permeability dispersion due to the fact that the fibre curls, acting similar to a split-ring, are too dense to manifest appreciable dynamic magnetism at the selected X-band (long-wavelength) range.

With these assumptions, the complex dielectric permittivity can be written in its conventional form of

$$\varepsilon = \varepsilon_d - [\rho \varepsilon_0 \omega (i + \frac{\omega}{\nu})]^{-1} \qquad (1)$$

Here the first term stands for the displacement-current contribution, and the second term for the contribution of the effective electrical resistance ρ, with the charge carrier velocity randomisation rate ν; an angular frequency of the wave

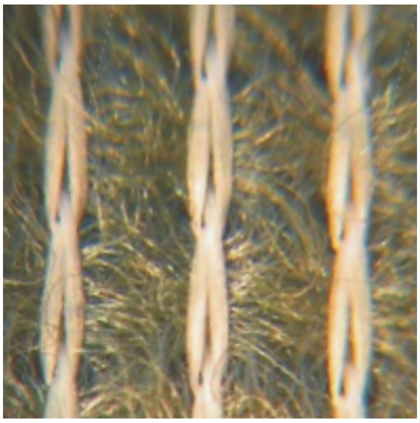

Figure 1. *Textile (WOM-E type) microscopic view; the electro-conductive fibres (thin ones) are bunched by the non-conducting double-thread stitches (vertical); the inter-stitch distance is 1.48 mm, and the conducting fibre diameter is 16 μm.*

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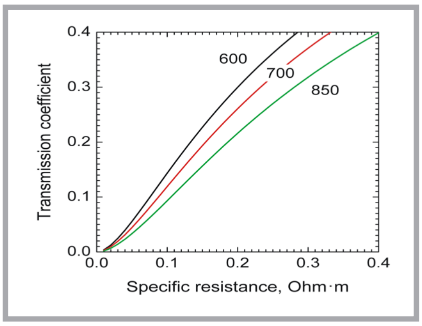


Figure 2. *Model microwave transmission coefficient as a function of the effective specific resistance; the curve labels show the strip thickness (in micrometers);* $\nu = 10^{13}\ s^{-1}$, $\varepsilon_b = 2$, $f = 9.82$ *GHz.*

electric field of $\omega = 2\pi f$, and electric constant of $\varepsilon_0 = 8.85\times10^{-12}$ F/m.

The coefficient of wave power transmission through the layer is [5]

$$T = \frac{\sinh^2[\ln(1/\sqrt{R_\infty})] + \sin^2\phi_\infty}{\sinh^2(\alpha d/2 + \ln(1/\sqrt{R_\infty}) + \sin^2(kd + \phi_\infty)} \qquad (2)$$

Here $R_\infty = [(n-1)^2 + \kappa^2]/[(n+1)^2 + \kappa^2]$ is the coefficient of power reflection from the half-space filled by the effective medium specified by Equation (1), ϕ_∞ is the phase of the wave reflected from the half-space,

$$\phi_\infty = arctg\frac{2\kappa}{n^2 + \kappa^2 - 1}, \qquad (3)$$

$\alpha = 2\omega\kappa/c$ is the wave absorption coefficient, $k = \omega n/c$ is the wave vector modulus, c is the speed of light, n, κ are the indexes of refraction and extinction determined from the square root of the complex permittivity, and d is the layer thickness.

One needs to account for the wave incidence on the layer from (and transmission to) the H_{10}-mode hollow metal waveguide. The simplest approach implies using the replacement of $n, \kappa \rightarrow (n, \kappa)/n_g$; here n_g is the effective refraction index of the waveguide:

$$n_g = \sqrt{1 - c^2/(2fb)^2}, \qquad (4)$$

and b is the waveguide width.

There are three parameters of the model in Equation (1). The first (displacement-current) contribution is supposed to be between 1 (air) and 2 (polyacrylonitrile). This contribution has been proved to be minor in ECT samples compared to that of the electrical conduction $1/\rho$. For the third unknown parameter, ν; the value of $10^{13}\ s^{-1}$ is acceptable as it is a quite common electron scattering rate in solids. The uncertainty of this parameter is not of great importance because the ratio of ω/ν is very small compared to the unity for the *X*-band microwave frequency. The only adjustable parameter is the effective specific resistance. In spite of quite complicated model functions, the output turns out to show a simple relation between the microwave transmission coefficient and the effective specific resistance of the thin strip (***Figure 2***).

With a further rise in specific resistance, the transmission coefficient tends to saturate at a certain level, depending on the layer thickness and its dielectric constant.

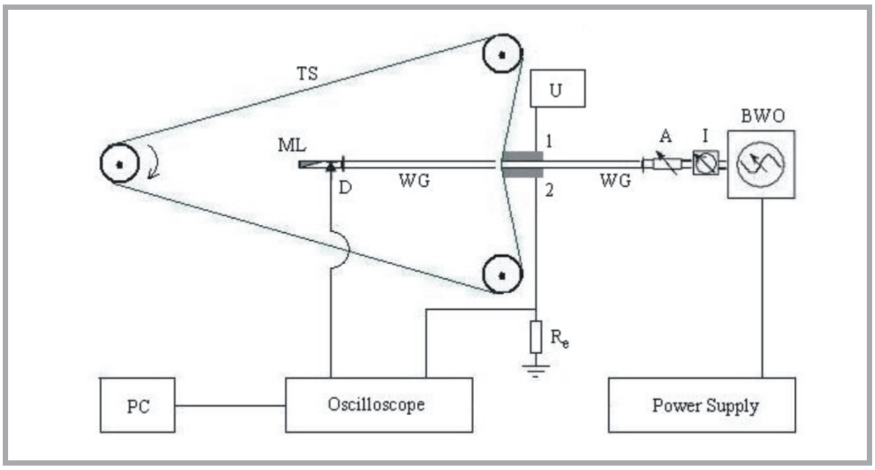


Figure 3. *Testing set-up scheme, including the textile strip sample TS on the motor-driven sheaves, microwave generator BWO with Power Supply, unidirectional microwave transmitting device I, microwave attenuator A, metal waveguides WG of 10 × 23 mm cross-section , microwave detector D, microwave end matched load ML, stabilised direct-current voltage source U, direct-current probe contacts 1-2, etalon resistor* R_e*, Oscilloscope, and personal computer PC.*

Experimental techniques

The width of the sample strip (4 ÷ 4.5 cm) was selected so as to cover the H_{10}-mode microwave guide aperture (its cross-section is 10 × 23 mm). The microwave electric field was parallel to the stitches. A mechanism with a motor and sheaves was designed to pull the endless strip sample between the wave source and detector at a constant velocity. For the simultaneous DC measurements, the *two-probe technique* was used: electric contacts were fixed mechanically to (but isolated electrically from) a transmitting waveguide; the current through the textile was registered using an etalon resistor (***Figure 3***).

During the strip motion time, the microwave detector output voltage $U_{MW}(S)$ as well as that of the the etalon resistor, $U_{DC}(S)$, were registered in the digital oscilloscope memory and stored on the personal computer. The MW voltage was also registered at the switched-off generator, and its values were referred to as the *dark* voltages. Without the strip, the voltage $U_{MW}(0)$ was registered, which was used to determine the 100-percent transmission reference values. The microwave transmission coefficient was calculated as

$$T = \left[\frac{U_{MW}(S) - U_{MW}(dark)}{U_{MW}(0) - U_{MW}(dark)}\right]^2 \qquad (5)$$

The square ratio is used because the microwave power was proved to be the square characteristics of the detector voltage.

The thickness d of the strip was determined by putting it in the dial-micrometer table loaded with a 69 × 69 × 2.9 mm glass plate, measuring the total glass-strip thickness with the micrometer sensor, and subtracting the glass plate thickness. The strip area covered by the plate was 69 × w square millimetres; here w is the strip width.

In order to eliminate contact resistance in the DC measurements, the non-uniformity of strip resistance distribution was also measured manually, using the *four-probe technique*. The DC source and drain contacts were clamped to the ends of the strip, stretched gently on the measuring table. The potential difference was measured using two other point-contact

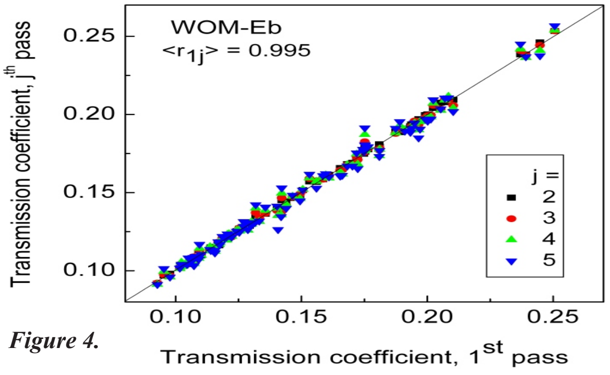
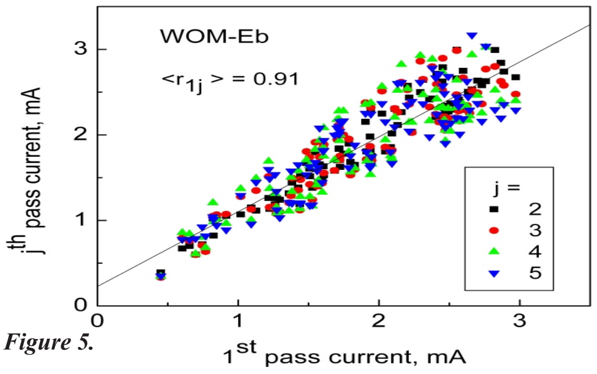


Figure 4.



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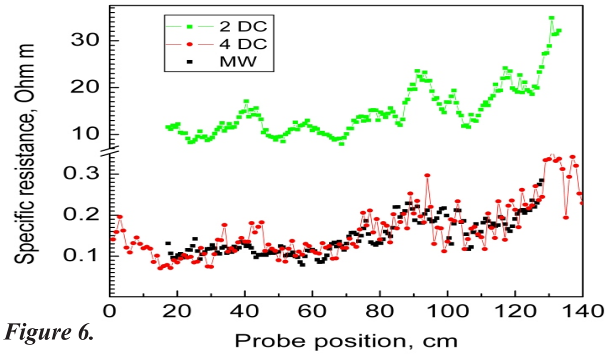

Figure 6.

Figure 4. *Correlation of sets of microwave transmission coefficients obtained at five passages of the WOM-Eb textile strip. The autocorrelation coefficient is 0.995.*

Figure 5. *Correlation of the DC current sets measured with two probes for five passages of the WOM-Eb textile strip. The autocorrelation coefficient is 0.91.*

Figure 6. *Distribution of textile specific resistance along the WOM-Eb sample strip measured using two 2 DC probes, 4 DC probes, and MW transmission. The mean-over-length values of the specific resistance are 15, 0.16, and 0.15 Ohm m, respectively.*

probes fixed together (at an inter-probe distance of 10 mm).

Results

The measurement reliability was checked by recording data for the multiple passage of the sample strip between the probing pairs. The microwave transmission coefficient autocorrelation is excellent, and the two-probe DC current autocorrelation is high (***Figures** 4* and *5*). The microwave-to-DC data cross-correlation coefficient is 0.82 (***Figure** 6*). Both the microwave and DC probes reveal the sites of reduced and enhanced effective electric resistance along the textile strip sample. The local resolution of the methods is 1 cm. The two-probe DC method exhibits higher resistance than that deduced from the MW measurements. The discrepancy is suspected to be due to the contact resistance, which is not important for microwaves but is critical in two-probe DC measurements. The four-probe DC method showed the resistance to be in reasonable agreement with the MW data (***Figure 6,*** and ***Table 1***).

The same type of fibre samples are seen to exhibit quite different MW and DC properties. This is due to different fibre package densities, and surface passivation.

Conclusion

Textile electrical resistance measurements using the two-probe DC technique are highly influenced by the contact resistance. The four-probe DC technique allows for the elimination of contact resistance; however, it is not suitable for contactless probing. Microwave transmission reveals local deviations of the textile electrical resistance from its mean value with excellent repeatability. Compared to the direct-current techniques of electrical resistance testing, microwave testing is advantageous: it is non-destructive, contactless and fast. Therefore microwave testing is recommended for monitoring electro-conductive textile quality in the manufacturing process.

Table 1*. Mean values of textile parameters measured by the DC and MW methods; *measured at 9.82 GHz.*

Textile type	Thickness, mm	MW transmission coefficient*	Two-probe DC specific resistance, Ohm m	MW specific resistance, Ohm m	Four-probe DC specific resistance, Ohm m
WOM-Ea	0.60	0.36	18	0.27	-
WOM-Eb	0.85	0.14	15	0.15	0.16
WOM-Ec	0.70	0.051	0.34	0.049	0.021

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