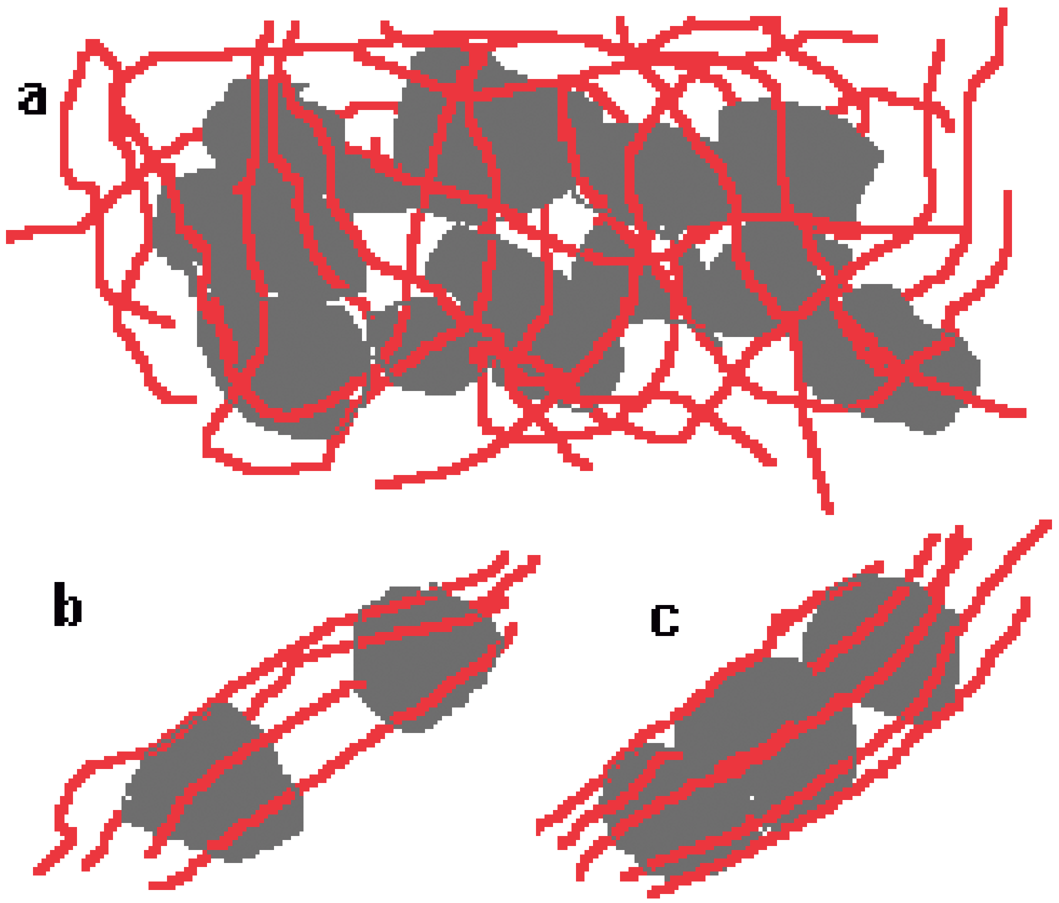

Figure 1. Polymer chains (red) mixed with carbon black particles (gray) as conductive filler.

Melt spinning of conductive textile fibers

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In the year of 1889 the first man-made fiber, viscose, was introduced. Since then many different kinds of man-made fibers have been introduced and used for areas such as clothing, hygiene products, geo-textiles and medical applications. The development has allowed for production of highly functional fibers, for example antistatic, flame resistant or waterproof fibers. Today an important research area concerns production of electrically conductive fibers, fueled by the development of so-called smart textiles. Smart textile applications are for example sensors (pressure, strain, ECG signals, temperature, chemical substances and gases), wearable electronics (computing, communication, or heating/cooling systems), electromagnetic interference (EMI) shielding, and appearance-changing garments[1].

Melt spinning at IFP Research AB

Fiber spinning is an area in focus at IFP; hence we have large experience of melt spinning. We have a well equipped polymer-processing laboratory with compounding machinery and bench scale facilitates and a pilot plant were we can spin single and bi-component polymer fibers and stretch them into yarns. For the time being we are focusing on melt spinning of temperature regulating fibers (phase change materials) and of electrically conductive fibers.

Electrically conductive fibers

IFP have been running a project where we have been working with polymer materials commonly used for melt spinning. To obtain conductivity these materials are mixed with electrically conductive fillers such as carbon black or carbon nano tubes. The work described in this article is based on polypropylene (PP) and carbon black (CB).

Principle

The polymer is mixed with CB in a melt compounding operation at elevated temperature. The idea with conductive fillers is shown in Figure 1. For the material to be conductive the amount of CB must be so large that the percolation threshold is reached. The percolation threshold is the very point where the CB particles form a conductive network within the polymeric matrix as shown in Figure 1a. To accomplish conductive properties within a fiber the amount of filler must be even higher. As the fibers are spun and stretched the distance between the particles is increased, as illustrated in Figure 1b. For the fiber to be conductive the particles must be in contact with one another, as in Figure 1c.

Bengt Hagström has been working at IFP Research since 1997. He is managing the fibre-spinning group and is a specialist in polymer processing and polymer melt rheology. His present research focus is on melt spun functional textile fibres.

[1] *Smart and interactive textiles - a market survey*. International Newsletter Ltd (2005)

Spinning

We have used a capillary rheometer to extrude PP mixed with different amounts of CB. The samples were extruded at 230 °C through a narrow capillary (Figure 2). Initially samples were taken from all compounds without any stretching, resulting in threads with a diameter of approximately 0,9 mm.

To obtain thinner fibers the PP/CB-compounds were winded on a small rotating aluminum drum, placed half a meter below the capillary exit (again see Figure 2). The speed of the drum was varied in the range 75-220 m/min, resulting in fiber diameters of 70-40 µm corresponding to draw ratios in the range of 165-482 (speed of drum divided by the speed at the capillary exit).

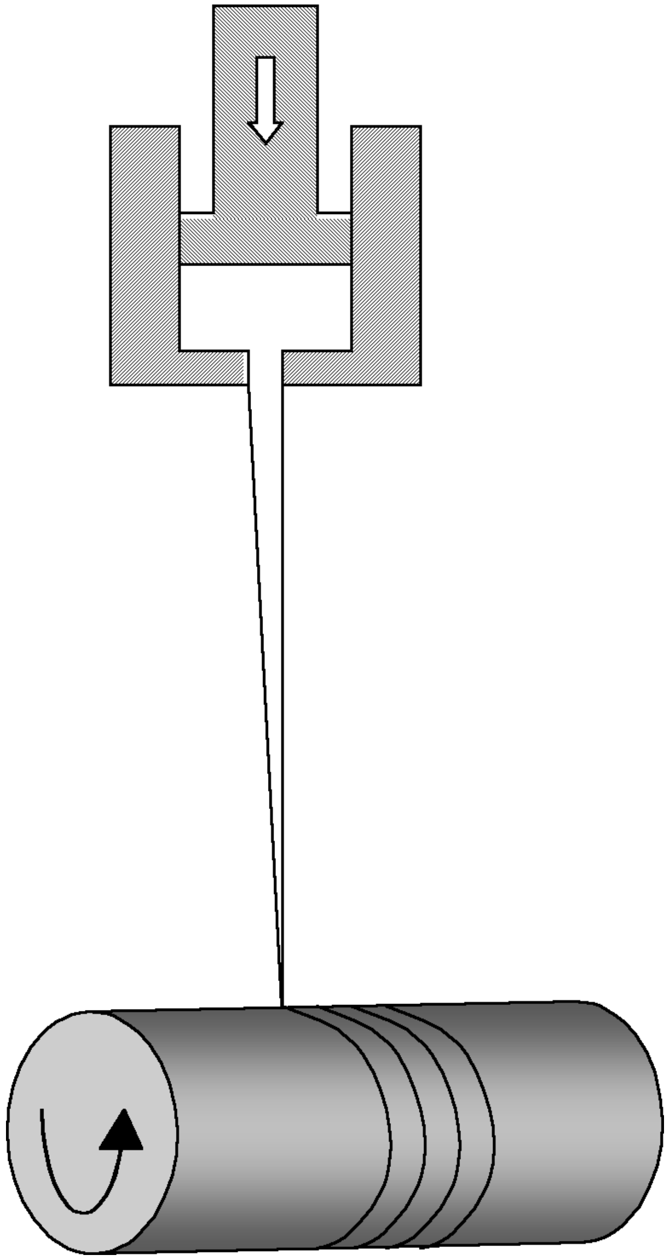

Figure 2. Fiber spinning from capillary rheometer.

The compounds holding 8 wt % CB and more were not spinable due to spin line break, meaning simply that they cracks when we try to stretch them. Another problem we came across during the spinning experiments was spin line instability see Figure 3.

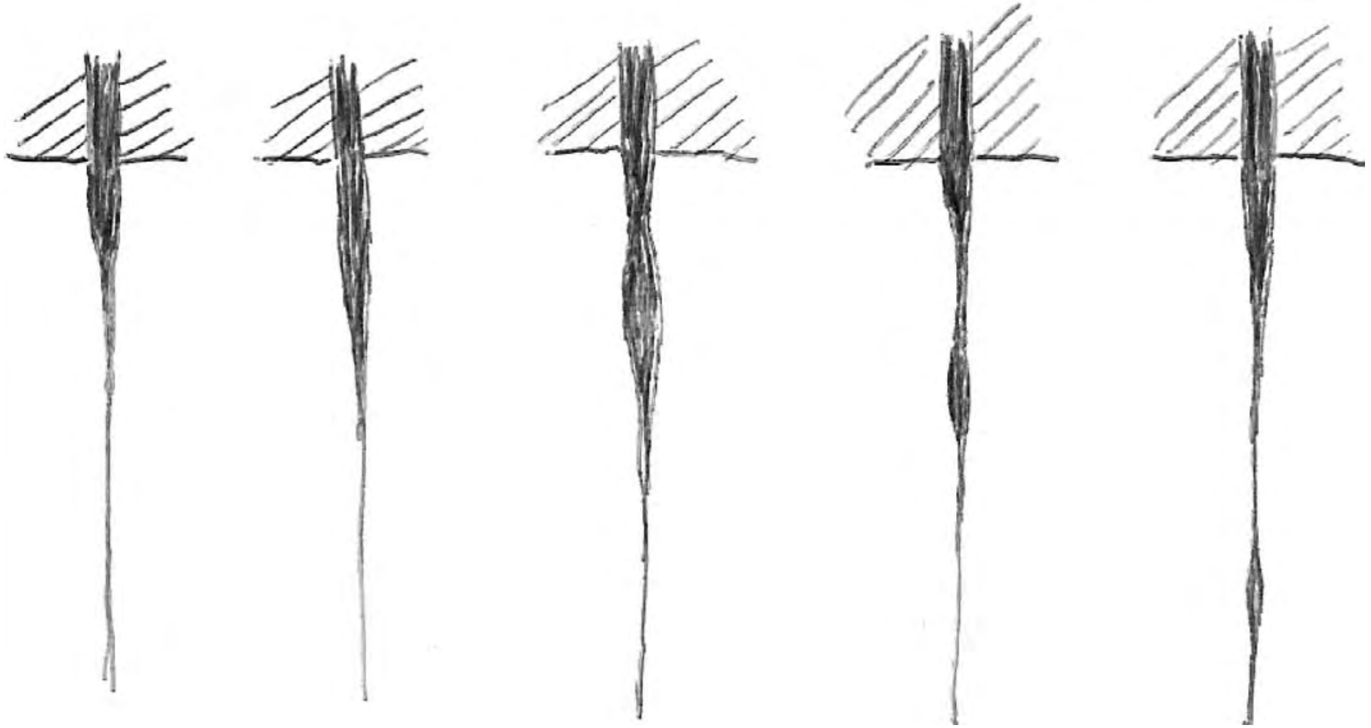

Figure 3. Schematic illustration of spin line instability.

This phenomenon could be seen for every compound of PP/CB that was spinable, that is, compounds with 7 wt % CB or less. Hence, the diameter of the fibers so produced varies slightly along their length. The smaller amount of CB the compound is holding, the lesser is the problem. However, the instability was still observed even when spinning a compound holding 1 wt % CB.

Rheological measurements

The shear viscosity (magnitude of the complex viscosity) was measured by means of a cone-and-plate rheometer in oscillating mode. The results can be seen in Figure 4.

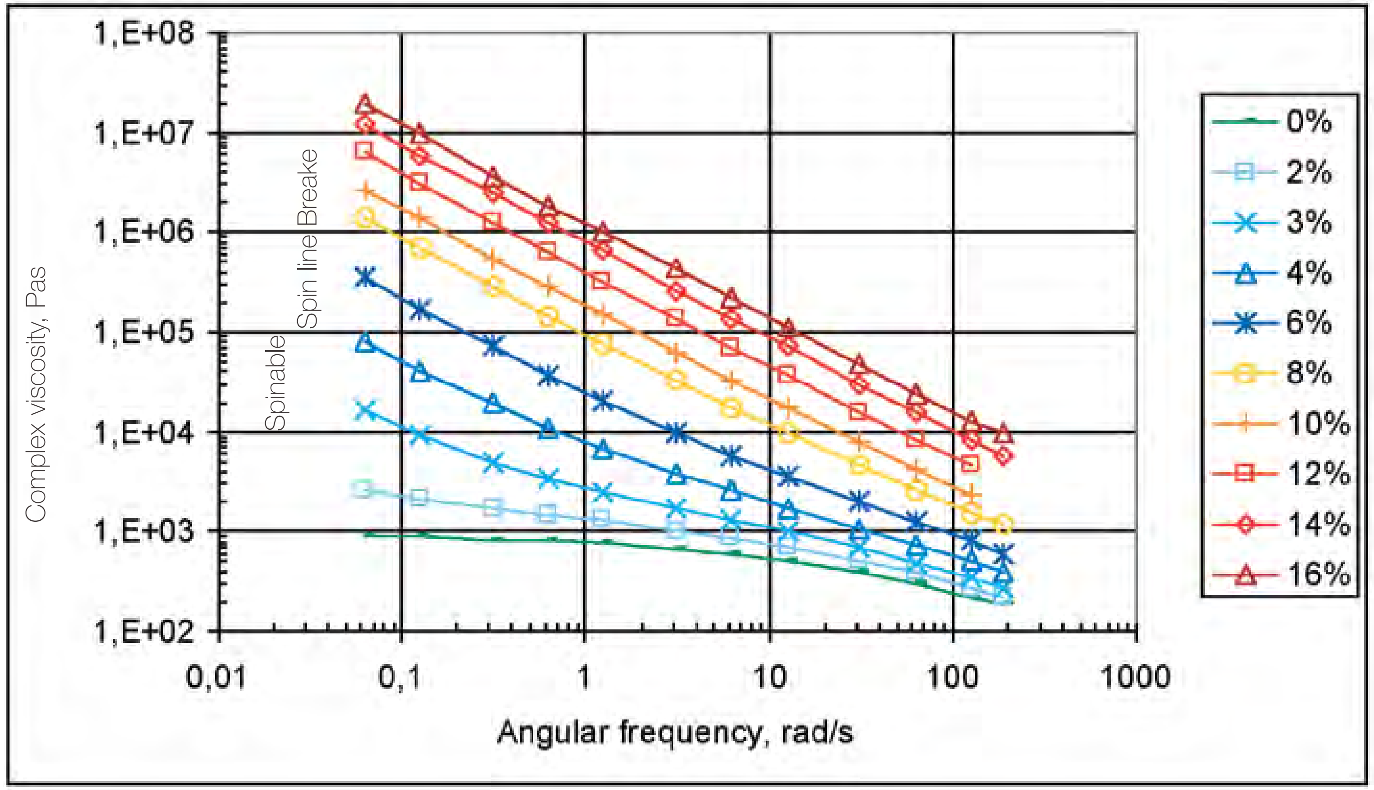

Figure 4. Complex viscosity of polypropylene with different loadings of carbon black at 210°C. The shear strain amplitude was 1%.

It is not possible to spin the compounds with an amount of 8 wt % CB and higher (red lines in Figure 4) due to spin line breakage. Those compounds have a rheological behavior more or less like an elastic material (no viscous flow), indicated by the straight lines with the slope -1 in the double logarithmic diagram. The compounds with 7 wt % CB or less (blue lines in Figure 4) is spinable. As the amount of CB in the compounds decreases the spinability improves.

The rheological behavior of the compounds show that 7 wt % CB in PP is almost, but not entirely, elastic (*slightly* curved line). The elastic behavior of the compounds is decreased, as the loading of CB gets smaller, shown by the shapes of the curves.

Conductivity measurements

The conductivity of the fibers was measured by means of a four-point method shown in Figure 5.

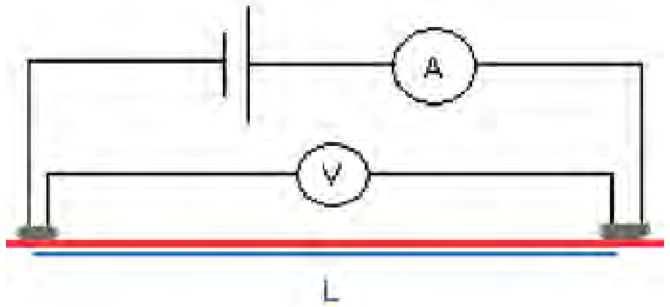

Figure 5. Four-point method for conductivity measurements.

This method is used in order to minimize problems with contact resistance. In the case of un-stretched threads, the method is simple and straightforward. In the case of stretched fibers we took a bundle of fibers and used silver paint to obtain contact between each fiber in the bundle. The current I (A), and the voltage U (V), in the circuit are measured. The electrical resistance is calculated according to Ohms law:

$$R = U / I$$

The cross section area, A (cm^2), for the threads is based on measured values of the diameter. For the bundles of fibers the cross section area is based on the bundles weight and length and the density of the PP/CB mixture. L is the length of the conductive thread/bundle in the circuit. By this we can calculate the volume resistivity, ρ_V (cm):

$$\rho_V = R * A / L$$

The conductivity σ (S/cm) is the inverse value of the resistivity:

$$\sigma = 1/\rho_V$$

The results from measurements on the threads are showed in Figure 6. As to be expected, the conductivity is increasing with the amount of CB. The same behavior can be seen in Figure 7 were measurements on fibers are shown. The conductivity decreases the more the fibers are stretched. The compound of 6 and 7 wt % CB can obviously withstand more stretching than the one of 4 wt %.

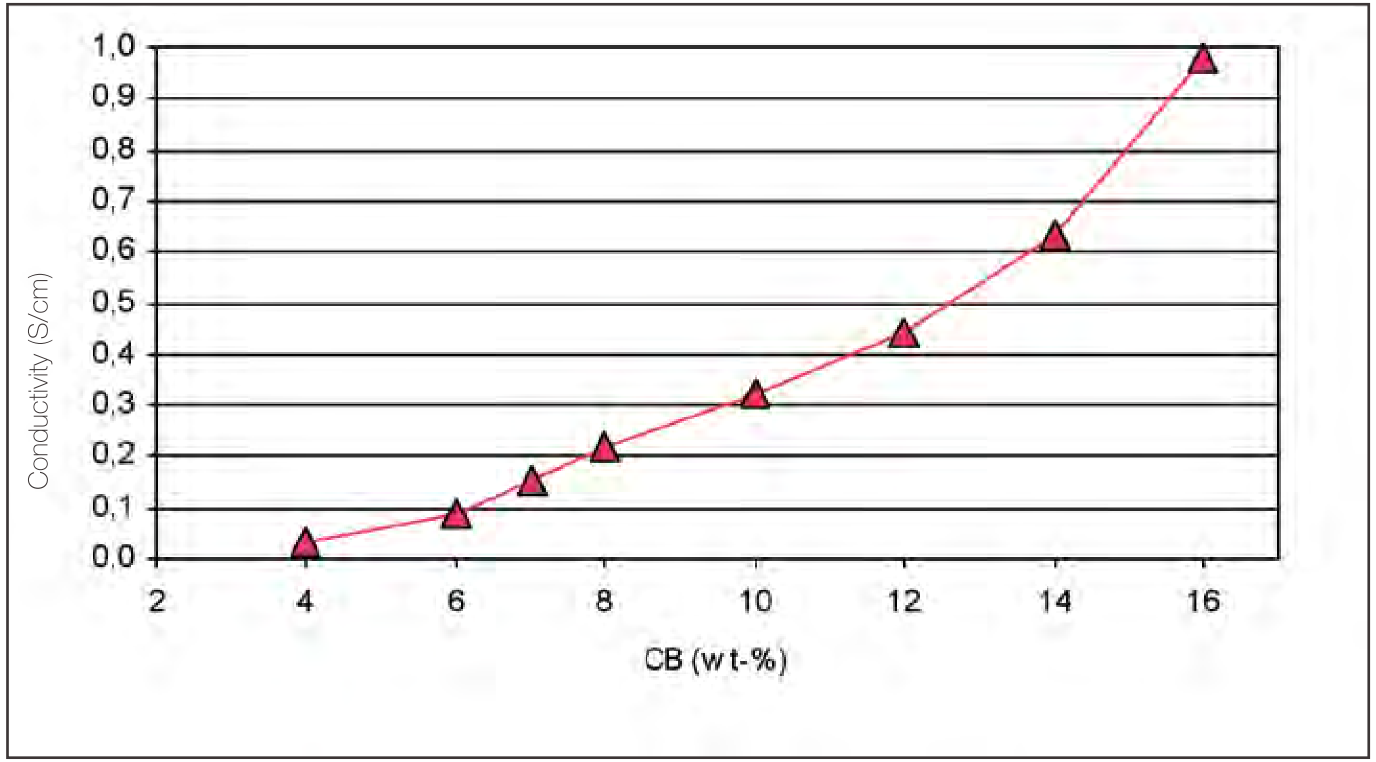

Figure 6. Conductivity of polypropylene threads, 0,9 mm diameter, with different loadings of carbon black

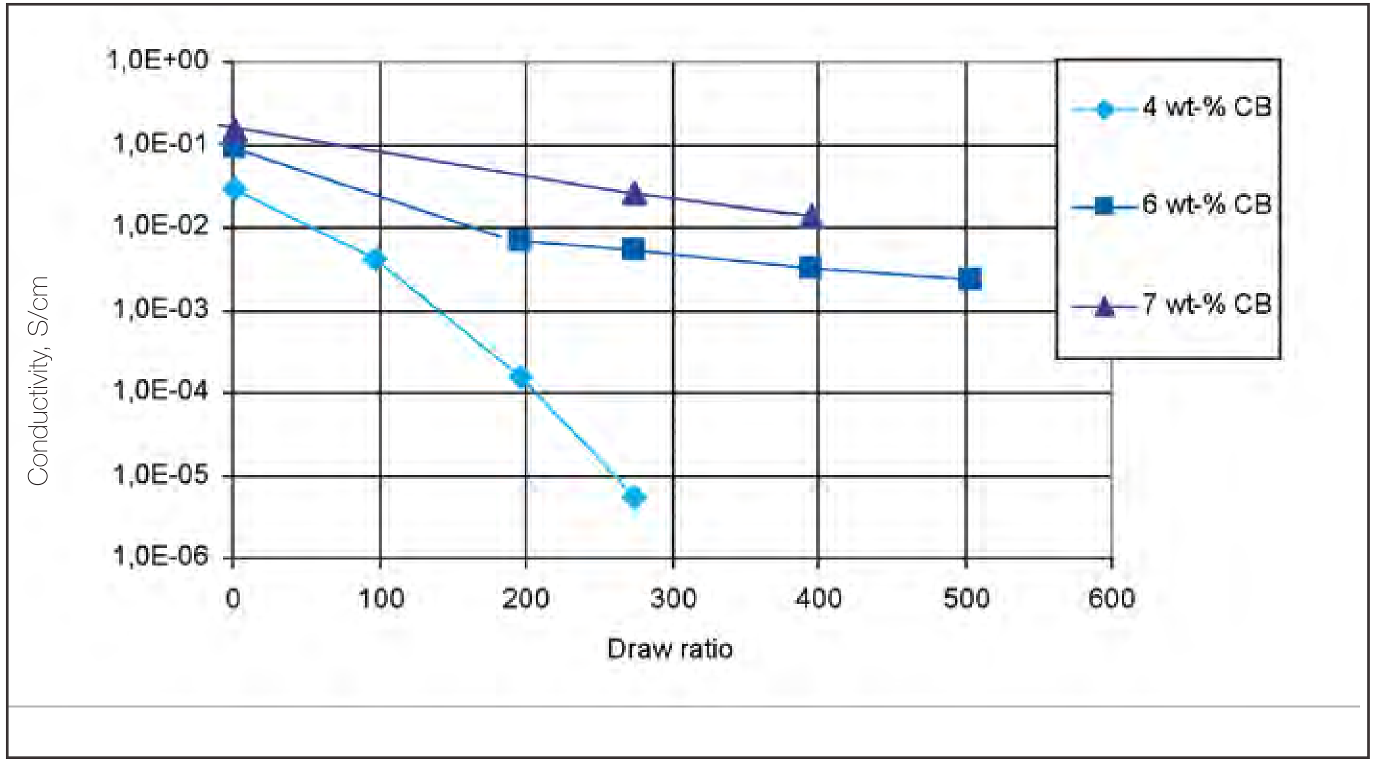

Figure 7. Conductivity in spun polypropylene fibers with different loadings of carbon black.

Applications for conductive fibers

Volume resistivity of different classes of materials is shown in Figure 8.

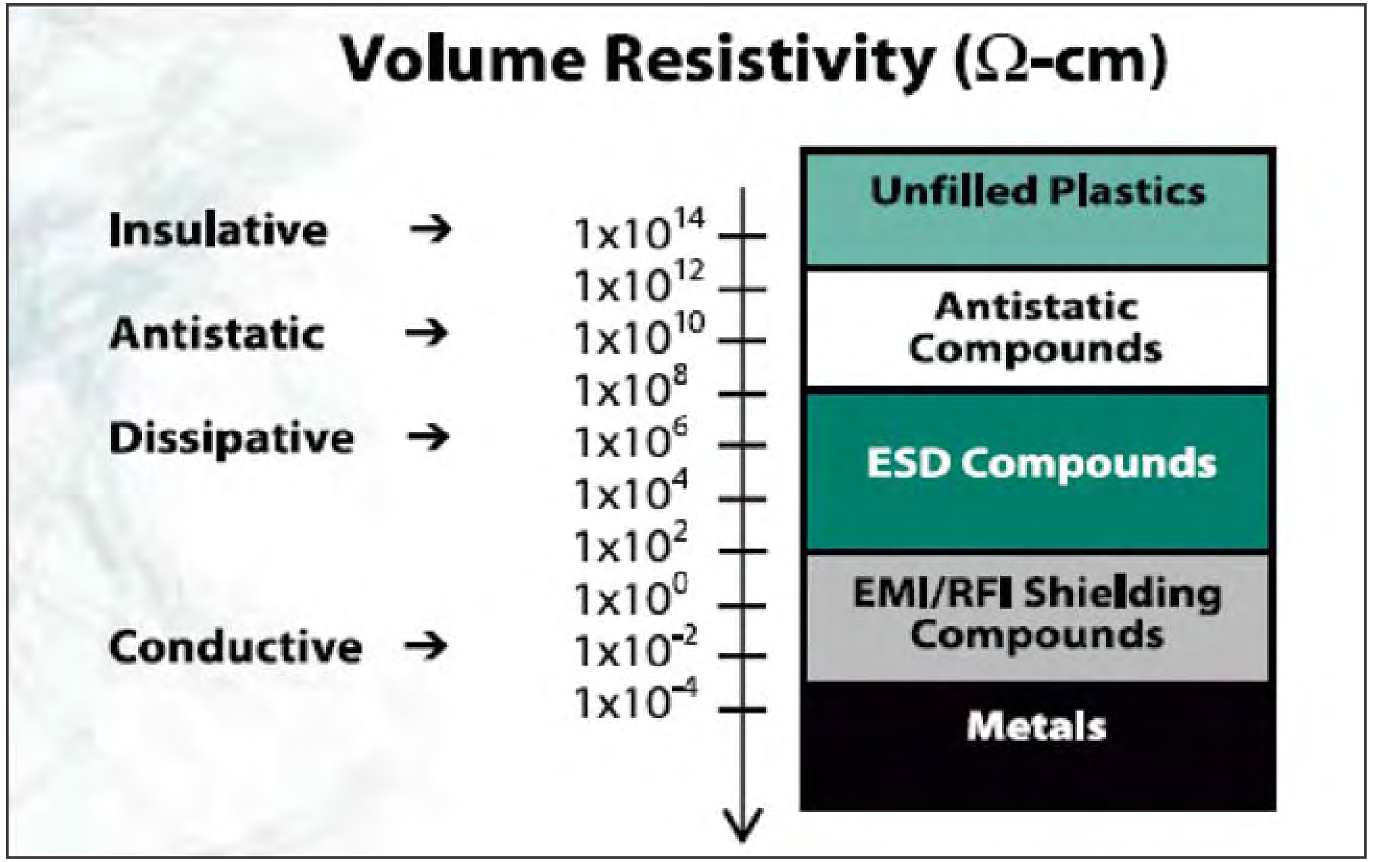

Figure 8: Volume resistivity of different classes of materials[2]. ESD: Electrostatic dissipative. EMI: Electromagnetic Interference. RFI: Radio Frequency Interference.

The fibers presented in this work, see Figure 7, show resistivities in the range 40 – 10^6 Ω cm. Higher resistivities are of course easily obtained by decreasing the CB loading further below 4 wt-%. Such fibres can find uses in applications requiring antistatic properties like carpets and furniture. Fibers in the range 10^2-10^8 Ω cm may find applications in work wear for people working in the electronics industry. Fibres with the highest CB loading may find applications in cloths and textiles with the ability to shield from electromagnetic fields and radio frequency radiation (e.g. mobile phones).

Today's electronics rely on highly conductive metals like silver, gold and cupper for signal transfer and power supply. Metallic threads are knitted or weaved into textiles for usage as sensors, for example measuring movements or heartbeats, and to transfer signals and electric power. In order to implement the metal in the textile the machines needs to be rebuild. By using conductive polymeric fibers instead of metallic threads, it would be possible to produce lighter and more flexible textiles on already existing machines.

[2] http://www.fibrils.com/PDFs/perc%20curve-crystalline.pd