CURRENT CONDUCTION EXPERIMENTS WITH SINGLE CARBON FIBERS

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Introduction

The electric current conducted by single horizontal carbon fibers, either plain or coated with thin layers of various metals (Au, Ag, Cu, Ni), has been measured in air, Ar, and He at fiber temperatures up to 1500°C. The observed resistance variations have been correlated with theory showing that gaseous conduction is the limiting factor in this case, even though convective cooling is the dominant loss mechanism. Current densities in coated fibers in excess of 1.2 MA/cm^2 have been achieved.

Apparatus

The measurements were made in a 38 cm high, 25 cm diameter domed glass bell jar which could be evacuated and filled through a 1.9 cm hole in the base plate. The fiber to be tested was placed horizontally between two clamps, 44.5 mm apart, and kept in slight tension by a light spring. Electrical current was provided by a 500 mA, 500 V dc supply and monitored by standard digital meters.

Theory

The heat balance for a horizontal, current-carrying fiber is obtained by equating the electrical heating with the losses arising from convective, conductive, and radiative cooling. In the present case, some valid approximations permit this general equation to be simplified.

Thus, because the fibers have a large length-to-diameter ratio ($\gtrsim$ 5000) in the present geometry, axial heat conduction along the fiber has a negligible influence on the fiber temperature over most of the fiber length.

Fiber temperatures in these experiments have been below 500°C in air, 1400°C in Ar, and 1500°C in helium. Under these circumstances, radiation can be shown to contribute a relatively small amount to the total cooling. Specifically, for the quoted temperatures, the radiative-to-convective cooling ratio is < 0.02 for air and He, and < 0.13 for Ar, showing that radiation may be neglected in most cases.

This is caused by the extremely high heat transfer coefficient for small fibers. For small diameters (d), the convective heat transfer coefficient (h_c) reduces to the simple expression

$$h_c = 0.45\ k_f/d \qquad (1)$$

where k_f is the thermal conductivity of the fluid. That is, h_c is dominated by conduction of heat from the fiber to the surrounding atmosphere.

To a good approximation, the heat balance for the fibers investigated here can, therefore, be represented by

$$I^2R/\ell = \pi\ d\ h_c\ (T - T_a) = 0.45\ \pi\ k_f\ (T - T_a) \qquad (2)$$

where I^2R/ℓ is the ohmic heating per unit length, and T_a the atmosphere temperature.

Experiments

Several different fiber/coating/atmosphere combinations have been tested, including: Thornel 300 in air, Ar, He; Modmor Type 2 in He; Ni and Ag-coated Modmor Type 2 in He; Au, Ni, and Cu-coated Thornel 300 in He. Thornel is manufactured by Union Carbide and Modmor by Morganite Inc.; both are based on a polyacrylicnitrile precursor.

Carbon Fibers

At 20°C, the measured resistance of the clamped Thornel fibers was from 19.4 to 24 kΩ. Scanning Electron Microscopy (SEM) photographs of typical fibers indicated a mean diameter of 6.3 μm, corresponding to a mean fiber resistivity of 1520 μΩ cm. Modmor Type 2 fiber exhibited a lower resistance (8 kΩ) and larger diameter (8.44 μm), corresponding to a resistivity of 1000 μΩ cm.

For comparison, manufacturers' data for Modmor Type 1 and Type 2 fiber gives 775 μΩ cm and 1500 μΩ cm, respectively, with fiber diameter variations of at least ± 5%.

Application of increasing voltages resulted in increasing currents and fiber temperatures, until burn-out occurred. For Thornel 300 this occurred at 7.4 to 8.2 μA in air, up to 30 μA in Ar, and 47 μA in He. Modmor Type 2 fibers carried currents of up to 86 μA in He at pyrometrically estimated fiber temperatures up to 1500°C.

In air, the fiber resistance increased slightly just before burn-out occurred, presumably because partial oxidation reduced the fiber diameter. In argon and helium, consistent results were obtained up to at least 800°C, but a time-dependent "run-away" effect occurred above about 1000°C. This effect, in which the fiber resistance decreased as the temperature increased, became particularly rapid above about 1400°C. Graphitization of the carbon is the likely cause, but oxidation may have also been involved, since noticeable thinning of the fiber was observed prior to burn-out.

Metal-Coated Fibers

Coating the fibers with metal substantially changed the observed behavior, with fiber resistances at ambient temperatures being as low as 12 Ω/cm.

Using coating thicknesses estimated from SEM photographs, some discrepancies between the derived and expected resistivities were found. Thus, measured coating resistivities were 2, 4.8, and 5.5 times the usual bulk values for Ag, Ni, and Au, respectively. Data for copper was uncertain, with some values being above and others below, the bulk values. These resistivity differences are likely to be caused by the non-uniformity and/or the strained nature of the coatings.

Relatively large currents were conducted with these coated fibers. For these particular specimens, Ag-coated fibers showed the highest mean value (161 mA in He), followed by Cu (106 mA), Ni (45 mA), and Au (33 mA). Maximum currents > 250 mA were conducted by single Ag-coated fibers, corresponding to coating current densities > 1.2 MA/cm^2.

As expected from heat transfer considerations, the highest currents were conducted in He, followed by air and Ar.

In the case of uncoated fibers, small visible hot spots developed at certain currents and presaged the subsequent breaking of the fiber at higher currents. With coated fibers, in contrast, most breaks occurred at lower temperatures (150 to 300°C), even in inert atmospheres and for no visible reason. This may have been caused by either chemical or mechanical weakness introduced during the coating process, or by an interaction between the coating and the underlying fiber.

Comparison of Theory and Experiment

Because k_f is a function of temperature, and the fiber temperature (T) was not easily measured, it is not simple to determine whether Equation (2) correctly describes the observed behavior. An alternative procedure has, therefore, been evolved. In this, the appropriate gaseous thermal conductivity variation is inserted into Equation (2) to give

$$I^2R/\ell = f\ (T) \qquad (3)$$

which describes how the heat dissipation varies with temperature. Using the measured current and voltage, Equation (3) enables the fiber temperature and resistance to be estimated simultaneously. Referencing the fiber resistance to the value at 20°C then permits the resistance ratio to be compared with independent values for the temperature coefficient of resistivity.

Typical results for uncoated Thornel and Modmor fibers in helium are shown in Fig. 1. The horizontal bars indicate measurements for which time-dependent effects occurred. The asterisk represents an extrapolation of manufacturers' data for Modmor Type 2 fiber for the temperature range up to 200°C (R_o is the resistance at ambient temperature).

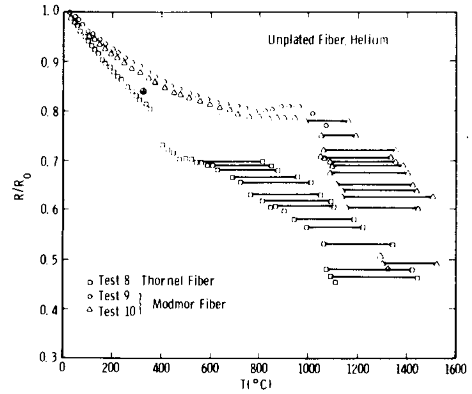

Fig. 1 - Resistance ratio for unplated fibers in helium.

The procedure denoted by Equation (3) was followed for coated fibers. Fig. 2 shows data for tests with silver-coated Modmor fibers in He.

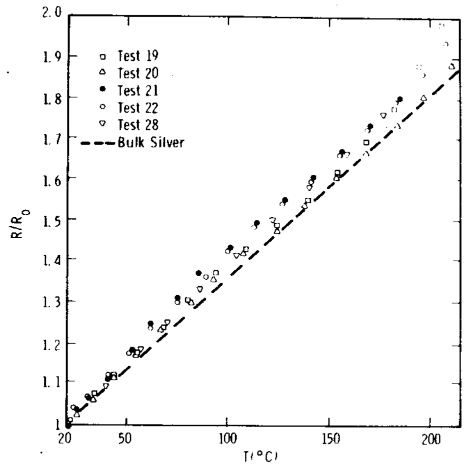

Fig. 2 - Resistance ratio for silver-plated fibers in helium.

Satisfactory agreement with independent temperature coefficient of resistivity values was only achieved when the constant in h_c was assumed to be about 20% higher than given in Equation (1). Since SEM photographs show the surface of coated fibers to be uneven, a possible explanation for this difference may be that the increased surface area causes an increase in h_c. Alternatively, the temperature coefficient of the thin coated layer may differ from that of bulk material, either because of structural or temperature inhomogeneities.

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