Because of their high bulk porosity and low thermal conductivity, materials fabricated from refractory carbide fibers are likely to find application for the thermal insulation of high-temperature furnaces and apparatus. An important advantage of these materials is their comparatively high thermal cycling resistance, which is due to the mobility of the fibers and the ease with which thermal stress relaxation can occur in them.

Zirconium carbide felt specimens were prepared in this work by a technique of gaseous phase metalization of carbon fibers similar to that described in [1]. The resultant fibers, 15-20 μ in diameter, had a composition close to stoichiometric (9-10 wt. % C). Their nonmetallic impurity content was on an average 1.2 wt. % (nitrogen + oxygen). The bulk porosity of the felt specimens ranged from 70 to 90%. The structure of the material is illustrated in Fig. 1. As can be seen, most of the fibers were oriented parallel to the felt surface, and only a small proportion of them (~10%) were arranged at right angles to the surface. All measurements were performed, using apparatus with graphite heating elements, in an inert gas atmosphere containing not more than 0.003 vol. % O₂ and not more than 0.005 vol. % N₂.

Thermal Conductivity. Measurements of thermal conductivity λ were carried out by the radial thermal flow method, using an inner heating element, in helium and argon atmospheres under atmospheric pressure, in order to allow for the effect of the thermal conductivity of a gas occupying the spaces between the fibers. Maximum error in the measurements of λ was ±12%. The results of these measurements are illustrated in Fig. 2 in the form of curves of thermal conductivity plotted against temperature averaged over the specimen thickness. It was established that the curves are accurately described by the theoretical formula [2]:

$$\lambda = \lambda_1 \varphi_1 + \lambda_2 \varphi_2$$

where the dimensionless coefficient $0 < \varphi_1 < 2$ characterizes the alternating arrangement of the solid and gaseous phases in the felt material, $\lambda_1$ is the thermal conductivity of the nonporous carbide, $\lambda_2$ the thermal conductivity of the medium between the fibers, and

$$\varphi_2 = (1 - \varphi_1) + \frac{2c(2 - \varphi_1)}{1 + \frac{\lambda_2}{\lambda_1}}$$

here $\varphi_1$ is the volume porosity of the felt. The magnitude $\lambda_3 = \lambda_1 + \lambda_2$ is made up of a radiant component and the thermal conductivity of the gaseous medium; $\lambda_3 = 16\sigma_T^3/\beta$, where $\beta$ is the attenuation ($\beta = \varepsilon(2 - \varphi_1)/\sqrt{\pi}$) and $\sigma_T$ is the Stefan constant. Values of $\lambda$ and $\lambda_2$ were taken from [3, 4]. For the parameter $\varphi_1$, the relation $\varphi_1(1 - \Pi)$ was obtained. The fact that calculated and measured values of $\lambda$ for different temperatures, porosities, and gaseous environments are in good agreement indicates the possibility of calculating the thermal conductivity of carbide fiber materials. Calculated values are represented in Fig. 2a by the solid lines.

Electrical Resistivity. Measurements of electrical resistivity $\rho$ were performed at room temperature and revealed an appreciable scatter of values for specimens of the same porosity (±30%) and also anisotropy. The following results were obtained:

<table>
<thead>
<tr>
<th>Porosity,</th>
<th>0.75</th>
<th>0.80</th>
<th>0.85</th>
<th>0.90</th>
<th>0.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{\text{res}} \cdot 10^9$, $\Omega \cdot \text{cm}$</td>
<td>0.8—1.25</td>
<td>1.2—1.65</td>
<td>1.6—2.4</td>
<td>2.3—2.8</td>
<td>3.5—4.5</td>
</tr>
</tbody>
</table>

*As in Russian original - Publisher.
In the case of a current flowing in the felt plane, i.e., in the direction of the predominant fiber orientation, these data may be approximated by the expression

$$\varphi_{298} = 4.47 \cdot 10^{-3} \exp(-5.35(1-\Pi)) \, \text{cm}.$$  

The measurements showed that, in the temperature range 298–2000 K, $\rho$ increased linearly with rise in temperature. The temperature coefficient of electrical resistivity was $~0.5 \cdot 10^{-3} \, \Omega\cdot\text{cm/deg C}.$

**Strength.** The results of room-temperature bend, tensile, and compressive strength tests on carbide fiber specimens are shown, plotted against porosity, in Fig. 3a. The accuracy of the strength measurements was of the order of $\pm 1 \, \text{kg/cm}^2$. For bend testing, plane specimens of $6 \times (3-5)$-mm cross section were used, the bend base being 15, 30, or 80 mm long. Analyses of the scatter of the bend test results obtained, performed separately for batches of specimens of each of these three sizes (70 specimens in each batch, $\Pi = 85 \pm 1\%$), demonstrated that the mean strength $\bar{\sigma}$ increased with decreasing bend base length and specimen volume, which was in accord with Weibull's statistical theory of brittle strength. The nonuniformity coefficient lay in the range 5.5–7 and the variation coefficient was $B_k = S/\bar{\sigma} = 13–18\%$ (where $S$ is the standard deviation).

Tensile tests were performed on plane specimens, $14 \times (3-5) \times 46$ mm in size, with wedge-shaped ends. For testing at both room and elevated temperatures, self-adjusting graphite grips were employed. The results obtained in compressive strength determinations on specimens of various porosities are shown in Fig. 2b in the form of plots of the $\sigma_c/\sigma_{298}$ ratio. As the temperature is raised up to 1600–1700 K, the strength falls off only slightly (on an average by 25%) and the character of fracture is brittle. With further rise in temperature, the strength increases, attaining a maximum at 2100–2300 K. In this temperature range, specimens begin to show signs of ductility. A similar temperature dependence of bend strength has been observed in tests on bulk carbide specimens [5, 6]. The appearance of a strength peak at 0.55–0.6 $T_m$ is due to the transition of the material of the fibers into a ductile-brittle state, and coincides with a marked fall in the modulus of elasticity.

Generally, the carbide fiber materials were found to have bend strengths 2–2.5 times higher than their tensile strengths, and were thus similar in this respect to other sintered materials. However, their compressive strength was relatively low, as shown by the ratio $\sigma_c/\sigma_t = 1.2–1.5$. The rupture of specimens in compression was very characteristic. Rupture invariably commenced at an end face and advanced frontally, which was due to a weakening of the material on the specimen surface owing to the presence of emerging bundles of fibers and other surface irregularities.

To obtain an analytical relation between the strength of a fiber material and its porosity, use may be made of a model composed of cylindrical fibers, representing schematically the geometry of the material (Fig. 4a). Structural anisotropy is reflected in this model in the fact that the spacings between arbitrarily straightened fibers along the $x$ and $y$ axes are different. The ratio of these spacings, $t_x/t_y = K_A$, is termed the coefficient of anisotropy. From the model in Fig. 4a it follows that

$$\Pi = 1 - \frac{\pi}{4} \left( \frac{D}{t_x} \right)^2 (2K_A + 1); \quad t_x = D \sqrt{\frac{\pi(1 + 2K_A)}{4(1 - \Pi)}}.$$  

Fig. 1. Structure of carbide fiber material, $\times 40.$

Fig. 2. Effect of temperature on thermal conductivity (a) and relative compressive strength (b) of zirconium carbide fiber material. In Fig. 2a: 1, 2) Ar atmosphere, porosity 0.9 and 0.85, respectively; 3) He atmosphere, porosity 0.85, fiber diameter 16 $\mu$. In Fig. 2b, porosity: 1) 0.85; 2) 0.80; 3) 0.76; 4) 0.73.