THERMAL EXPANSION OF KEVLAR 49 YARNS

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ABSTRACT: The paper presents an experimental investigation on the relationship between the coefficient of thermal expansion of Kevlar 49 yarns and applied stress. The investigation consisted of 30 individual tests at various stress levels between 3% and 45% of the ultimate tensile strength, while temperatures varied from 5°C to 75°C. Test results indicated that the material contracts longitudinally as the temperature increases and that the absolute value of the coefficient of thermal expansion increases with an increase in the applied stress. An empirical equation relating the coefficient of thermal expansion to the applied stress was developed.
KEYWORDS: aramid fiber, Kevlar fiber, thermal expansion

1 INTRODUCTION

Existing X-ray diffraction studies of oriented crystalline polymers demonstrate that their thermally induced deformations are highly anisotropic, with a negative coefficient of thermal expansion in the chain direction and positive ones in the other two crystallographic directions[1-5]. The coefficient of linear thermal expansion, α, is defined as the ratio of thermal strain changes to temperature changes, $\Delta\varepsilon / \Delta T$. Thus, a material with negative α contracts as the temperature increases. The thermal contraction with increasing temperature, in the chain direction, has been attributed to increased rotation around Carbon-Carbon bonds [3,4]. It has been suggested [5] that this mechanism is a general feature of crystalline polymers. Studies of the macroscopic thermal behavior of carbon [6] and Kevlar fibers [7] have shown that these materials also behave in a similar way.

Kevlar 49 yarns have been used in the manufacture of some aramid ropes. The general behavior of these ropes has been the subject of several investigations aimed at their application in structural engineering as tension members. In some cases, such as prestressed structures, these members are subjected to high tensile stresses. Data from the literature, on the influence of applied stress on the thermal behavior of Kevlar yarns, is very limited and has been obtained under varying conditions, mainly with respect to the stress applied to the specimens. Given the nature of the material, the application of a tensile load is necessary to stretch the yarn or filament in order to make possible any strain measurement. The magnitude of the tensile stress in the tests described in the literature, however, has been

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very low in comparison to that observed in structures, and has not been considered as a major variable in the investigations.

In this paper, attention is focused on the macroscopic thermal expansion behavior of Kevlar 49 yarns. The objective is to determine the coefficient of thermal expansion of the yarns, considering the stress applied to the material as the main variable. A series of 30 tests was carried out, within a range of temperature from 5°C to 75°C and at stress levels varying between 3% and 45% of the ultimate tensile strength. Test results indicated that the material contracts as the temperature increases and that the absolute value of the coefficient of thermal expansion increases with an increase in the applied stress. An empirical equation relating the coefficient of thermal expansion to the applied stress was developed.

2 TEST APPARATUS

Figure 1 shows details of the rig used in the tests. The yarn was fixed at one end and the load was applied at the opposite end. A yarn-clamp system consisting of a 45 mm diameter disc was used at both ends to assure a better stress distribution between individual filaments and to eliminate the possibility of yarn failure due to local stress concentration.

Yarn deformations were measured over a gauge length of 500 mm using two hinged rods attached to the yarn. Strain values were obtained from the difference between the two displacements given by the LVDT's divided by the gauge length. Thus, the dimensional variation of the bars, which were also in contact with the bath, were compensated. The LVDT's had a 12 mm linear range, sensitivity of 117.4 mV/mm and the energizing voltage was 6 V dc. They were calibrated with a micrometer placed at the level of the yarn.

The temperature was varied between 5°C and 75°C by heating or cooling the distilled water bath. The cooling and heating rates were approximately 40 °C per hour. The temperature was measured using three type K thermocouples positioned along the gauge length. The LVDT's and thermocouples were connected to a data logger which was monitored automatically by a program specially developed for these tests.

Thermally induced deformations of polymers consist of a reversible and an irreversible component. The reversible component is directly related to the coefficient of thermal expansion of the material. The irreversible deformation is associated with changes in moisture content, loss of plasticizers and/or solvents and phase changes of the material. The test apparatus was designed primarily to measure reversible deformation while eliminating or minimizing irreversible deformations. The moisture content was kept constant, while the loss of solvents and plasticizers were prevented by immersion of the specimens in the distilled water bath, which does not affect chemical properties of Kevlar [8]. Phase changes are not expected to occur within the temperature range between 5°C and 75°C. Creep, which could also affect the accuracy of the measurements, was allowed for by a procedure which will be described in section 4.

The precision of the apparatus for measuring temperature and strain was determined by taking several sets of temperature and strain readings using the same program written to control the real tests, at various times during the execution of the main tests, at different temperatures and stress levels. The results showed that the scatter of both temperature and

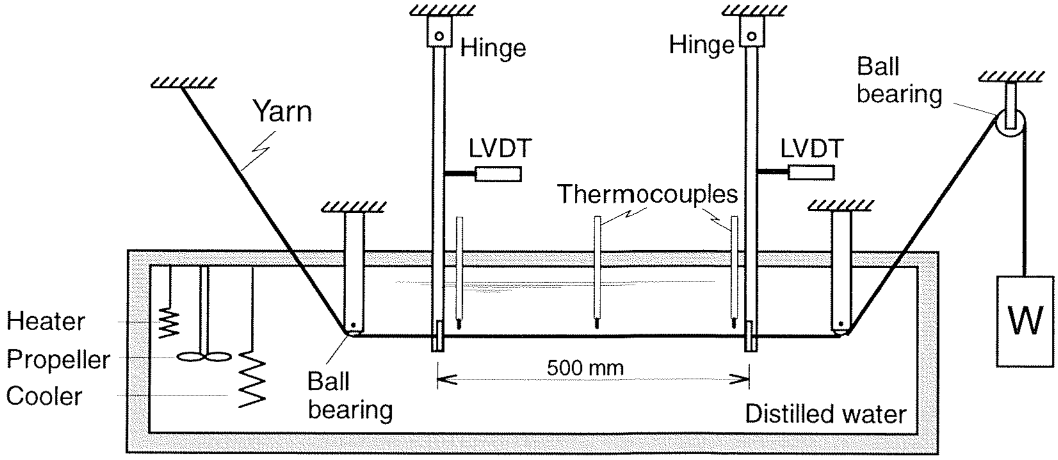

Figure 1 - Details of test rig

strain measurements could be described by the normal distribution, with standard deviations of 0.004°C for temperature, and 1.44 x 10^{-6} for strain. The limits of uncertainty are established by multiplying the standard deviations by a factor which depends on the desired confidence limit. For 90% confidence this factor is 1.645. Thus, the precision of individual measurements can be presented as ±0.007°C for temperature measurements and ±2.4 x 10^{-6} for strain measurements at the 90% confidence level.

3 SPECIMENS AND VARIABLES

Six spools (samples) of 2130 denier Type 965 Kevlar 49 yarns, with tensile properties shown in Table 1, were used in the tests. The values in the first three columns of the table were supplied by the manufacturer while the tensile strengths given in the last column were obtained by multiplying the ultimate strain values by the corresponding modulus of elasticity. (This is consistent with the linear stress-strain relationship of the material). To transform gram/denier into MPa, the specific gravity value 1.44 was used [8], resulting in the conversion factor 1 gram/denier = 127.1 MPa. The samples were supplied by the manufacturer and were representative of six different production periods. All the yarns were untwisted.

The stress levels considered in the analysis are summarized in Table 2. The first column gives the values of the applied load while the second shows the corresponding stresses. These values were obtained by assuming a cross sectional area of 0.164 mm^2, calculated from the denier, and assuming the specific gravity value 1.44. The third column presents the ratio stress/tensile strength, the tensile strength being taken as 2733 MPa which is the mean value given in Table 1.

Thirty thermal expansion tests were carried out using six specimens, one taken from each of the six samples. Each specimen was tested under five load levels shown in Table 2.

4 TEST PROCEDURE

Under applied load, creep strains would affect the accuracy of the measurements depending on the duration of the thermal expansion test. In order to determine the way time, stress and temperature affect the creep strain, a series of creep tests with the specimens subjected to different loads and temperature were carried out. The duration of each test was between 48 and 60 hours. The results of these tests showed that the most significant component of creep takes place within the first 18 hours. After 18 hours, however, it was observed that the highest creep rate was 5.2 microstrain/hour. Since the heating rate was to be 40°C/hour (see section 2), the time required for the complete cycle of temperature (5°C to 75°C to 5°C) would be 3.5 hours. Thus, the total creep strain that occurs during this time would be $3.5 \times 5.2 = 18.2$ microstrain. This value was small enough not to affect significantly the final value of the coefficient of thermal expansion obtained from the tests. The creep strain can, therefore, be disregarded in the evaluation of the coefficient if tests are conducted 18 hours after the application of the load.

Table 1 - Tensile properties of the samples

Sample No.	Ultimate strain (%)	Modulus (g/denier)	Tensile strength, σ_u (MPa)
1	2.50	870	2764
2	2.52	834	2671
3	2.40	881	2687
4	2.45	896	2790
5	2.64	842	2825
6	2.33	900	2665
Mean	2.47	870	2733

Table 2 - Load and stress levels

Load (N)	Stress, σ (MPa)	σ/σ_u
14.4	88	0.03
53.6	326	0.12
102.7	625	0.23
151.7	923	0.34
200.7	1222	0.45

To summarize, the procedure for the thermal expansion tests was:
1) apply the desired load for at least 18 hours, with the temperature of the bath maintained at 20°C;
2) begin the test at 20°C, with the gauge length recorded at that moment;
3) heat the bath up to 75°C, followed by cooling to 5°C and a further heating closing the cycle at 75°C;
4) the temperature rate to be 40°C/hour and the results recorded at approximately 2.5°C intervals.

5 TEST RESULTS

Typical results of the thermal expansion tests are shown in Figure 2. The figure indicates that the relationship between thermal strains and temperature is approximately linear for the temperature range used in this investigation. The coefficient of thermal expansion, which is the slope of the curves, is, therefore, constant for a given stress level. To estimate the α values, the least squares method was used to fit two straight lines, one for heating and one for cooling. The resulting correlation coefficients were greater than 0.98, indicating a good correlation between the experimental data and the fitted lines. The mean α values given in

Table 3 were calculated by averaging the values of the slopes of the lines corresponding to heating and cooling. This procedure compensates for the creep induced error, because creep occurring during the cooling cycle tends to increase measured deformation, while during heating cycle it tends to decrease it.

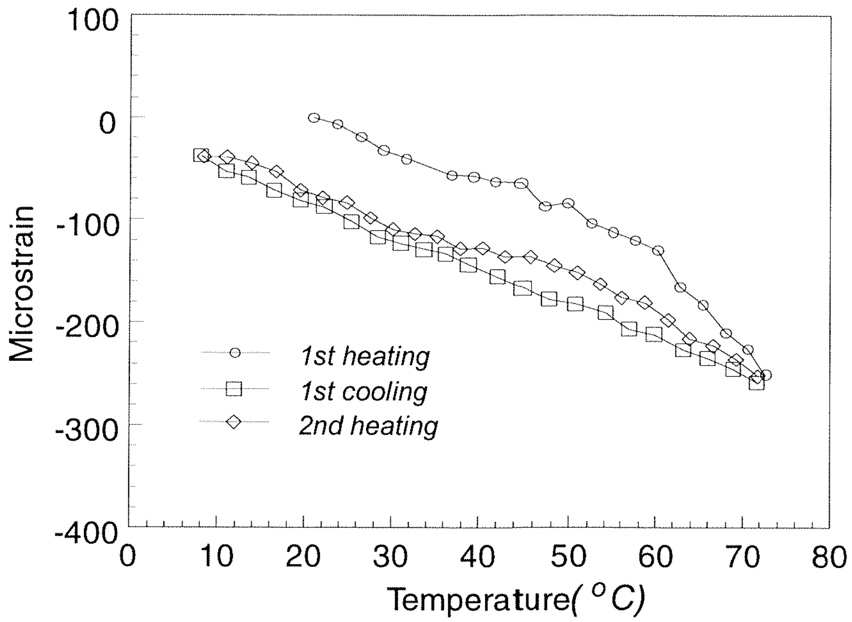

Figure 2 - Thermal expansion test results (Load = 14.4 N)

The relationship between the coefficient of thermal expansion, α, and the initial strain to ultimate strain ratio, $\varepsilon_o/\varepsilon_u$, is shown in Figure 3. The figure demonstrates that this relationship can be considered to be linear for the range of strain used in this work. The estimated regression line is represented by the equation

$$\alpha = -9.9\ \varepsilon_o/\varepsilon_u - 3.7 \quad (1)$$

where,

ε_o : initial strain

ε_u : ultimate strain

α : expressed in $10^{-6}/\,^{\circ}C$.

This equation was obtained using the least squares method, and the resulting correlation coefficient was -0.922. The equation can be rewritten as a function of the initial strain in the form (noting that the ultimate strain is 2.47%)

$$\alpha = -4.0\ \varepsilon_o - 3.7 \quad (2)$$

where,

ε_o : expressed in percentage

α : expressed in $10^{-6}/\,^{\circ}C$.

The 90% confidence limits, associated with the above equations, for a future individual observation of α were calculated by assuming that the results can be described by the normal distribution. The values obtained were approximately $(\pm 1.02 \times 10^{-6})/\ ^{o}C$.

Equations 1 and 2 can also be used for parallel-lay ropes. Since the Kevlar yarns are disposed in a parallel arrangement in the core of the ropes, the coefficient obtained for the yarns must be the same for the ropes.

Table 3 - Values of the coefficient of thermal expansion and $\varepsilon_o/\varepsilon_u$ ratio

Load (N)		Sample 1	2	3	4	5	6
14.4	$\varepsilon_o/\varepsilon_u$	0.031	0.032	0.030	0.030	0.031	0.030
	α	-4.140	-4.390	-4.510	-3.670	-3.730	-3.260
53.6	$\varepsilon_o/\varepsilon_u$	0.121	0.119	0.120	0.119	0.127	0.119
	α	-5.060	-5.550	-5.490	-4.470	-4.770	-4.080
102.7	$\varepsilon_o/\varepsilon_u$	0.228	0.238	0.205	0.206	0.219	0.210
	α	-6.710	-6.990	-5.910	-5.040	-5.930	-5.460
151.7	$\varepsilon_o/\varepsilon_u$	0.328	0.327	0.297	0.311	0.315	0.304
	α	-7.320	-7.730	-6.740	-6.170	-6.510	-6.040
200.7	$\varepsilon_o/\varepsilon_u$	0.404	0.440	0.394	0.392	0.410	0.398
	α	-8.300	-8.700	-7.650	-6.660	-7.650	-6.600

ε_o = initial strain due to applied load; ε_u = ultimate strain = 2.47%

α = coefficient of thermal expansion $(10^{-6}/\ ^{o}C)$

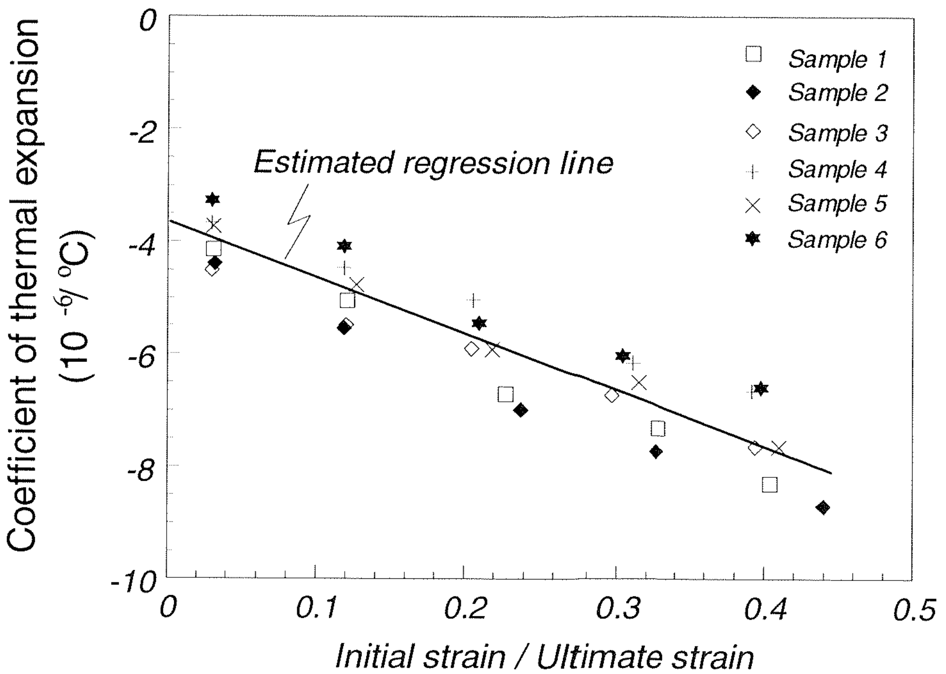

Figure 3 - Relationship between coefficient of thermal expansion and strain

6 COMPARISON WITH PUBLISHED DATA

A comparison between the α values of Kevlar 49, obtained from the available literature, and the values obtained by eq. 2 is made in Table 4 for the same stress levels. Note that to write eq. 2 as a function of stress, the initial strain must be replaced by the ratio Stress/Elastic modulus, where the modulus is the mean value given in Table 1 (E = 870 g/denier = 110630 MPa).

With the exception of values in the first column of Table 4, the discrepancy between the α values is not high. It could be attributed to a variety of factors such as dimensional variations of the clamp-systems used to stretch the specimen, temperature gradients along the specimen and whether the specimen (yarn) is twisted or not.

Table 4 - Comparison between α values obtained from eq. 2 and published data (Values in $10^{-6}/^{o}C$)

	Stress on the specimen		
	50 MPa	95 MPa	220 MPa
Pottick, et al.[9]	-	-3.2	-
Ii, et al.[10]	-6.7	-	-
Rojstaczer, et al.[11]	-	-	-5.7
Equation (2)	-3.9	-4.0	-4.5

7 CONCLUSIONS

The coefficient of linear thermal expansion of Kevlar 49 yarns, within the temperature range 5 °C to 75 °C, is a function of the strain imposed by applied loads. The relationship between strain and coefficient of thermal expansion can be considered linear and may be represented by the equation

$$\alpha = -4.0\, \varepsilon_o - 3.7$$

where,

ε_o : initial strain caused by loads, expressed in percentage

α : coefficient of thermal expansion, expressed in $10^{-6}/^{o}C$.

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REFERENCES

[1] Wakelin, J.H., Sutherland, A. and Beck, L.R., Jr, "Linear Thermal Expansion Coefficients for the Crystalline Phase in High Polymers", J. of Polymer Science, Vol.XLII, Issue 139, 1960, pp.278-280.

[2] Swan, P. R., "Polyethylene Unit Cell Variations with Temperature", J. of Polymer Science, Vol.56, 1962, pp.403-407.

[3] Davis, G.T., Eby, R.K. and Colson, J.P., "Thermal Expansion of Polyethylene Unit Cell: Effect of Lamella Thickness", J. of Applied Physics, Vol.41, No.11, Oct., 1970, pp.4316-4326.

[4] Kobayashi, Y. and Keller, A., "The Temperature Coefficient of the C Lattice Parameter of Polyethylene; an Example of Thermal Shrinkage Along the Chain Direction", Polymer, 11, 1970, pp.114-117.

[5] Choy, C. L., Chen, F. C. and Young, K., "Negative Thermal Expansion in Oriented Crystalline Polymers", J. of Polymer Science: Polymer Physics Edition, Vol.19, 1981, pp.335-352.

[6] Wolff, E.G., "Stiffness-Thermal Expansion Relationship in High Modulus Carbon Fibers", J. of Composite Materials, Vol.21, January, 1987, pp.81-97.

[7] Ii, T., Tashiro, K., Kobayashi, M. and Tadakoro, H., "X-ray Study on Lattice Thermal Expansion of Fully Extended Aromatic Polyamide Fibers", Macromolecules, Vol.19, 1986, pp.1772-1775.

[8] Du Pont, "Characteristics and Uses of Kevlar 49 Aramid High Modulus Organic Fibre", Bulletin No. K-5, September, 1981, 12p.

[9] Pottick, L.A., Allen, S.R. and Farris, R.J., "Force-Temperature Behavior of Rigid Rod Polymeric Fibers", J. of Applied Polymer Science, Vol.29, 1984, pp. 3915-3924.

[10] Ii, T., Tashiro, K., Kobayashi, M. and Tadakoro, H., "X-ray Study of Lattice Tensile Properties of Fully Extended Aromatic Polyamide Fibers Over a Wide Temperature Range", Macromolecules, Vol.20, 1987, pp.347-351.

[11] Rojstaczer, S., Cohn, D. and Marom, G., "Thermal Expansion of Kevlar Fibres and Composites", J. of Materials Science Letters, 4, 1985, pp.1233-1236.