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Thermal Expansion of Graphite Fiber-Reinforced Metals[1]

R. E. Taylor[2]

The presence of graphite fibers in metal matrices greatly influences the properties of the composites. Graphite fibers have been used in conjunction with aluminum, magnesium, and copper matrices. The type of graphite fiber, layup of the fiber, and volume percentage of the fibers are all important parameters in controlling the properties of the composites. The present status, particularly in the case of graphite/copper, can be considered to be the original developmental stage and is definitely far-removed from a matured technology. The present paper focuses on thermal expansion behavior of several graphite–metal matrix composites from -60 to $+200$°C.

KEY WORDS: composites; graphite fiber; thermal expansion.

1. INTRODUCTION

Graphite fibers have been successfully incorporated into aluminum, magnesium, and copper matrices in addition to graphite and polymer matrices. The presence of these fibers dramatically alters the thermal conductivity (and diffusivity) and the thermal expansion of the matrices. For openers, their presence converts isotropic matrices (OD) into 1D, 2D, 3D... matrices, depending upon the layup of the fibers. Also, depending upon the ultimate strength of the fibers and the area fraction oriented in each direction, the magnitudes and temperature dependencies of the thermal conductivity and coefficient of expansion are changed—often dramatically. Some-

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[2] School of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47906, U.S.A.

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Table I. Sample Characteristics at 23°C

Sample designation	Density ($g \cdot cm^{-3}$)	Specific heat ($J \cdot g^{-1} \cdot K^{-1}$)
Gr/Al-Uni	2.302	0.816
Gr/Al-0/90	2.285	0.815
Gr/Cu-Uni	5.172	0.460
Gr/Cu-0/90	4.878	0.467

what similar effects have been obtained by joining thin sheets of dissimilar metals. Thus it is becoming possible to fabricate specialized composites with greatly improved properties for particular applications.

2. SAMPLES

While the Thermophysical Properties Research Laboratory (TPRL) has measured the thermophysical properties of a number of fiber reinforced materials, many of the samples (and hence the data) are proprietary. However, several samples, furnished by the Naval Avionics Center, were unrestricted. The samples are described in Table I. High modular (P120) graphite fibers were used in all these samples. The bulk density values were calculated from the samples' geometries and masses and the specific heat values were measured with a Perkin–Elmer differential scanning calorimeter [1]. While the exact composition is not known accurately, the specific heat and density results (Table I) indicate that all the samples

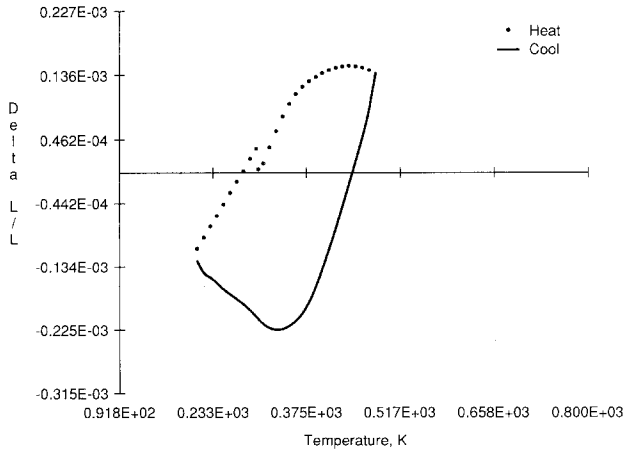

Fig. 1. Visual display of experimental data for Gr/Al 0/90.

Table II. Computer Output from Dilatometer

Standard list:	Ran from Dilatometer 1	
1. Fused silica	Standard	1
2. Borosilicate	Thermocouple material	CR/AL
3. Tungsten	Sample lensth (in.)	1.000
4. Sapphire	Standard lensth (in.)	2.000
5. Copper	Reference temp. (K)	288.000
6. Secondary	Starting temp. (K)	310.000
	Turnaround temp. (K)	480.000
		210.000
Test sample: GRAL 090	Final temp. (K)	300.000

Temperature					
°C	F	Data	Delta L/L	Alpha (1/K)	Time
29.9	85.9	0.6631E − 04	0.3782E − 05	0.0000E + 00	13:57:56
36.8	98.2	−0.1821E − 02	0.1263E − 04	0.1850E − 05	14:02:18
46.8	116.2	−0.5381E − 02	0.3572E − 04	0.2123E − 05	14:07:03
56.8	134.2	−0.8879E − 02	0.5868E − 04	0.2185E − 05	14:11:47
66.8	152.2	−0.1191E − 01	0.7943E − 04	0.2155E − 05	14:16:21
76.8	170.2	−0.1438E − 01	0.9743E-04	0.1956E − 05	14:20:51
86.8	188.2	−0.1596E − 01	0.1112E − 01	0.1956E − 05	14:25:17
96.8	206.2	−0.1682E − 01	0.1214E − 03	0.1816E − 05	14:29:42
106.8	224.2	−0.1724E − 01	0.1294E − 03	0.1685E − 05	14:33:43
116.8	242.2	−0.1718E − 01	0.1352E − 03	0.1557E − 05	14:37:49
126.8	260.2	−0.1704E − 01	0.1406E − 03	0.1452E − 05	14:41:56
136.8	278.2	−0.1673E − 01	0.1452E − 03	0.1359E − 05	14:46:10
146.8	296.2	−0.1611E − 01	0.1484E − 03	0.1270E − 05	14:50:27
156.8	314.2	−0.1529E − 01	0.1505E − 03	0.1186E − 05	14:54:49
166.8	332.2	−0.1425E − 01	0.1516E − 03	0.1108E − 05	14:59:10
176.8	350.2	−0.1278E − 01	0.1505E − 03	0.1025E − 05	15:03:32
186.8	368.2	−0.1106E − 01	0.1482E − 03	0.9452E − 06	15:07:55
196.8	386.2	−0.9176E − 02	0.1451E − 03	0.8697E − 06	15:11:54
206.8	404.2	−0.6812E − 02	0.1396E − 03	0.7893E − 06	15:15:25
206.8	404.3	−0.6824E − 02	0.1397E − 03	0.7896E − 06	15:15:26
196.9	386.4	0.2714E − 02	0.8572E − 04	0.5135E − 06	15:19:19
186.9	368.5	0.9280E − 02	0.4661E − 04	0.2969E − 06	15:22:40
176.9	350.4	0.1421E − 01	0.1565E − 04	0.1065E − 06	15:24:22
166.9	332.4	0.1881E − 01	−0.1365E − 04	−0.9965E − 07	15:25:44
156.9	314.5	0.2475E − 01	−0.4960E − 04	−0.3905E − 06	15:42:17
146.9	296.4	0.2910E − 01	−0.7759E − 04	−0.6632E − 06	15:43:38
136.9	278.4	0.3423E − 01	−0.1095E − 03	−0.1024E − 05	15:49:17
126.9	260.5	0.3815E − 01	−0.1352E − 03	−0.1394E − 05	15:50:39
116.9	242.5	0.4240E − 01	−0.1626E − 03	−0.1869E − 05	15:53:26
106.9	224.5	0.4547E − 01	−0.1840E − 03	−0.2389E − 05	15:55:10
96.9	206.4	0.4770E − 01	−0.2012E − 03	−0.3005E − 05	16:02:06
96.9	188.5	0.4874E − 01	−0.2123E − 03	−0.3724E − 05	16:04:00
76.9	170.4	0.4891E − 01	−0.2189E − 03	−0.4659E − 05	16:11:30
66.9	152.5	0.4895E − 01	−0.2248E − 03	−0.6077E − 05	16:13:40

consisted of about 55 vol% graphite. Presumably the 0/90 samples had equal fractions (27 vol%) in two perpendicular in-plane directions.

3. APPARATUS

A dual push-rod dilatometer (Theta Dilatonics II) was used to measure linear thermal expansion between 210 and 480 K. The differential expansion between the sample and a known standard reference material was measured as a function of temperature. The expansion of the sample was computed from this differential expansion and the known expansion of the standard. The measurements were made under computer control and linear expansion was calculated at preselected temperature intervals. The expansion was monitored with the visual display during the measurement process. Five standard reference materials for thermal expansion were obtained from the National Institute of Standards and Technology (NIST) and these include materials with low, moderate, and large expansions.

In the present case, fused silica [2] was used as the reference standard because of its low expansion. A copy of the visual display for Gr/Al-0/90 is shown as Fig. 1. Heating data are represented by points and cooling data by solid lines. Part of the computer output is shown as Table II.

4. RESULTS AND DISCUSSION

During a preliminary run, it was discovered that the expansion behavior was different upon heating and cooling and that it made a difference which occurred first, i.e., heating from room temperature (RT) to

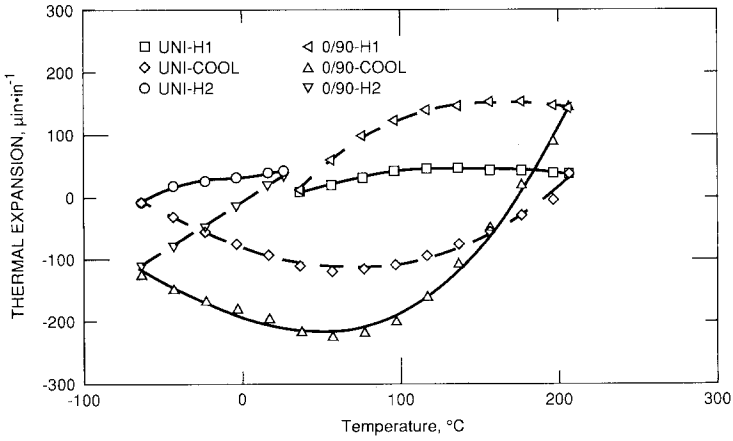

Fig. 2. Thermal expansion of Gr/Al samples.

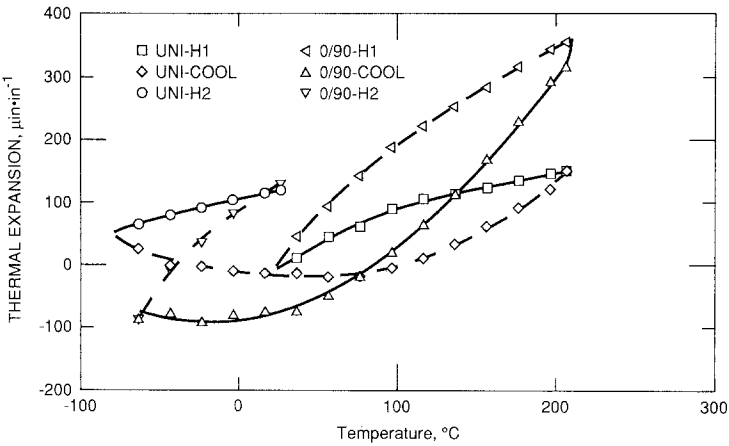

Fig. 3. Thermal expansion of Gr/Cu samples.

200°C, cooling to −60°C, and then heating to RT yielded different results than cooling from RT to −60°C, heating to +200°C and then cooling to RT. It was decided to heat, cool, and reheat the samples. Plots of the experimental data for initial heating, cooling, and heating of the Gr/Al samples are shown in Fig. 2. Arrows indicate the direction of temperature change. Note that the dimensional changes in the fiber direction are larger for the 0/90 fiber orientation than for the unidirectional layup. This is the result of the larger area fraction of fibers in the direction of measurement for the unidirectional sample. Also note that the sample length did not

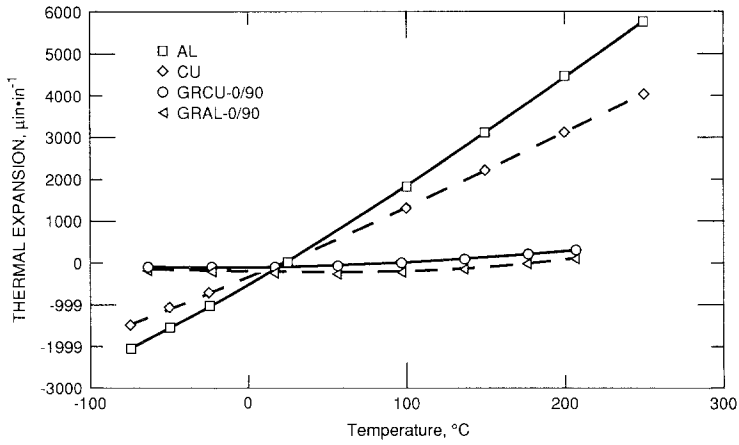

Fig. 4. Comparison of thermal expansion of graphite fiber-reinforced metal matrix samples with those for the metals.

return to its original dimension. Plots of the corresponding data for Gr/Cu samples are shown in Fig. 3. Again, the dimensional changes are larger for the 0/90 sample and the sample dimensions do not return to their original values. The results, in chronological order for the first temperature cycle, are given for both sets of data in Table III. Experience has shown that the amount of permanent offset and the magnitude of the hysteresis decrease during subsequent thermal cycles [3].

An overview of the effects of the graphite fibers can be seen in Fig. 4. The cooling data for the Gr/Cu-0/90 and for the Gr/Al-0/90 are compared

Table III. Thermal Expansion (μin · in.$^{-1}$) Results on Graphite Fiber-Reinforced Metals

Temp. (°C)	Gr/Cu-UNI	Gr/Cu – 0/90	Gr/Al-UNI	Gr/Al-0/90
37	10	45	7	13
57	43	94	17	59
77	58	142	30	97
97	89	188	41	121
117	104	222	44	135
137	112	253	45	145
157	121	284	41	151
177	134	317	40	151
197	146	345	36	145
207	150	356	35	140
207	150	314	35	140
197	120	292	−7	86
177	90	229	−31	16
157	60	167	−58	−50
137	32	113	−77	−110
117	9	62	−96	−163
97	−6	18	−110	−201
77	−18	−21	−117	−219
57	−20	−50	−120	−225
37	−15	−75	−112	−217
17	−14	−76	−94	−197
−3	−10	−81	−75	−181
−23	−4	−92	−55	−168
−43	−1	−78	−31	−150
−63	24	−87	−9	−127
−63	64	−87	−9	−108
−43	79	−6	19	−77
−23	90	35	24	−46
−3	102	82	31	−13
17	114	114	39	20
27	117	129	41	34

to the expansion values for copper and aluminum. Even though the expansion of aluminum is larger than that for copper, the expansions for the Gr/Al composites are less than those for the Gr/Cu composites. This is due to the fact that aluminum is softer than copper and its expansion is more easily constrained by the graphite fibers. From other experiments [3] we know that if we heated the Gr/Cu samples to higher temperatures, the expansion will go through a maximum usually between 200 and 300°C. The huge decrease in the expansion of metals that can be achieved by the incorporation of graphite fibers is clearly evident in Fig. 4.

In view of the shapes of the heating and cooling curves and the fact that except for the initial heating curve, they do not go through zero at RT, average coefficients of expansion for metal matrix composites are not very meaningful. The average coefficients for initial heating from 22°C are 0.19, 0.76, 0.81, and $1.92 \times 10^{-6}°C^{-1}$ for Gr/Al-Uni, Gr/Al-0/90, Gr/Cu-Uni, and Gr/Cu-0/90, respectively.

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