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Influence of the pressing direction on thermal expansion coefficient of graphite foam

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Abstract The aim of this article is to examine the influence of the pressing direction on the behavior of the thermal expansion coefficient $\alpha(T)$ of graphite foam in the 300–780 K temperature range. The thermal expansion coefficients of two samples, one pressed along the direction of strong interactions and the other pressed along the direction of weak interactions, were measured along three directions X, Y, and Z. The results show that the dilatometric behavior of the material changes from one direction to another. The values of $\alpha(T)$ vary widely depending on the measurement direction. Anisotropy becomes even more intense when the sample is pressed along the direction of weak interactions.

Keywords Anisotropy · Expansion · Graphite · Membrane effect · Pressing

Introduction

The 1960s witnessed a surge in the development of graphite foam, and since then particular attention has been given to this type of materials [1–3]. Nowadays the use of foam has become a must. Graphite foams have many characteristics which have opened numerous and varied areas of applications. They are light materials and have good thermal stability. They also have interesting mechanical properties: a low thermal expansion coefficient and thermal and electrical conductivities which can be easily controlled [4, 5]. The latter characteristic has favorably impacted applications in the thermal field in general, and particularly in heat-exchanger technology.

The lack of research on the thermal expansion of graphite may have many reasons. The characteristics of graphite depend on its nature and the particular site it has been extracted from. Indeed, the order coefficient, defining the stacking of the layers in the material, differs according to the origin of the material [6–8]. Another factor which may play an important role is the fact that the pressure of the push-rod varies from one dilatometer to another, with the consequence of altering the dilatometric behavior of the material [9].

This article examines the influence of the pressing direction on the thermal expansion coefficient of graphite foam in the 300–780 K temperature range.

Experimental

The graphite used in this experiment is prepared from natural graphite powder; it was subjected to chemical treatments resulting in a material of 99.95% purity. After hydrolysis and oxygenation, the material was treated at a temperature exceeding 1180 K. It was then subjected to pressing along the direction of strong interactions. To measure the thermal expansion coefficient, three samples, 5 mm long each, were cut along the directions X, Y and Z. Measurements were taken with a DI24 Adamel Lhomargy dilatometer. The measurement of the variation of the thermal expansion with temperature was carried out with an absolute error equal to $\pm 10^{-7}$ K^{-1}. The thermal expansion coefficient was measured along the following directions X, Y and Z (Fig. 1).

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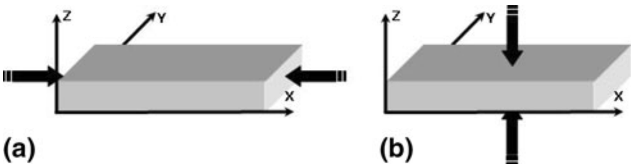

Fig. 1 Directions as defined in this article (*arrows* indicate the pressing direction) **a** pressing along the direction of strong interactions. **b** pressing along the direction of weak interactions

We use the notation α_{ij} where i stands for the direction of measurement X, Y, Z and j represents the direction of pressing ($j = 1$ for the pressing along the axis of strong interactions and $j = 2$ for the direction of weak interactions).

Results and analysis

Pressing along the direction of strong interactions

The measurements show that the coefficients α_{x1}, α_{y1}, and α_{z1} are different (Fig 2). The dilatometric behavior of the material depends heavily on the direction of measurement. From 320 to 780 K, α_{x1} is smaller than α_{y1}. α_{x1} is negative throughout the temperature range. From 580 K on, α_{x1} varies in linearly, and at 780 K it reaches -3.10^{-6} K^{-1}. At low temperatures, the α_{y1} curve has the same shape as that of α_{x1} and the difference between the values of α_{x1} and α_{y1} is small. Above 730 K, the difference between α_{x1} and α_{y1} becomes substantial. In the range 680–780 K, α_{y1} increases noticeably and departs completely from α_{x1}. At 780 K, the ratio α_{y1}/α_{x1} is almost 200%. α_{y1} is negative from room temperature to 680 K, then becomes positive and reaches $+3.10^{-6}$ K^{-1} at 780 K. α_{z1} has a totally different shape from those of α_{x1} and α_{y1}, and that of $\alpha_{z(\mathrm{pure})}$ [6]. In the range 300–480 K, α_{z1} increases from 20 to 110 K^{-1}. At 330 K, the ratio $\alpha_{z1}/\alpha_{z(\mathrm{pure})}$ is almost a unit, and at 780 K the same ratio is 400%.

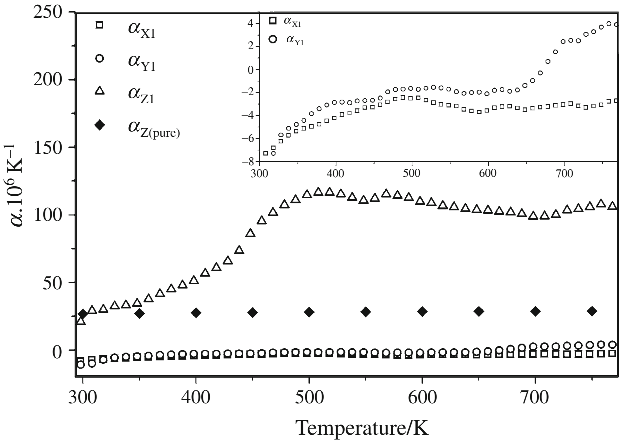

Fig. 2 Thermal expansion coefficients of graphite foam, pressed along the direction of strong interactions, measured along the X, Y, and Z directions and of pure graphite, measured along the Z direction

The results indicate that graphite foam is more anisotropic than pure graphite. This feature may be due to the high density of pure graphite in comparison with that of graphite foam. Indeed, the density of the latter is a 100 times lower than that of pure graphite.

Each of the three curves (α_{x1}, α_{y1}, and α_{z1}) exhibits a dilatometric singularity (anomaly) which is related to the membrane effect [9–11]. The anomaly has the same shape in α_{x1} and α_{y1}; they are spread in temperature with a maximum located at around 500 K. The anomaly in α_{z1} has a different shape; the peak exceeds 110.10^{-6} K^{-1}, and is sharper while appearing at the same temperature as that of α_{x1} and α_{y1}.

The values of α_{z1} are very large compared to those of α_{x1} and α_{y1}. At 780 K, the value of α_{z1} is three times that of α_{x1} and 26 times that of α_{y1}. These important differences between the values of the thermal expansion coefficient measured along the direction of weak and strong interactions may be explained by the intensification of the membrane effect.

Thus, the shape of the thermal expansion coefficient has been completely altered; $\alpha(T)$ is heavily affected by the direction of the measurement. The material has become anisotropic in the basal plane. The measurements of electrical conductivity σ and thermal conductibility κ of the same foam confirm the heavily anisotropic nature of the material, and yield the ratios $\sigma_{//}/\sigma_{\perp} \approx 10^4$ and $\kappa_{\perp}/\kappa_{//} \approx 50$ [3].

Pressing along the direction of weak interactions

The following step consisted in studying the effect of changing the direction of pressing on the thermal expansion coefficient of graphite foam. In this case, the sample was pressed along the direction of weak interactions. It is important to note that this sample has been taken from the same area as the one which served in the first experiment. This was done in order to avoid the difficulties mentioned above and thus exclude the factors that may affect a change in the thermal expansion coefficient.

The results obtained reveal changes in the dilatometric behavior of the material (Fig 3). The anisotropy in the basal plane, between α_{x2} and α_{y2}, is very clear. α_{y2} is significantly higher than α_{x2} throughout the temperature range. We observe that α_{x2} is negative from 300 to 780 K, whereas α_{y2} is positive from 310 to 780 K.

At 780 K, α_{y2} is equal to 20.10^{-6} K^{-1} whereas α_{x2} is less than -3.10^{-6} K^{-1}. The thermal expansion coefficient of pure graphite $\alpha_{xy(\mathrm{pure})}$ in the basal plane falls between α_{y2}

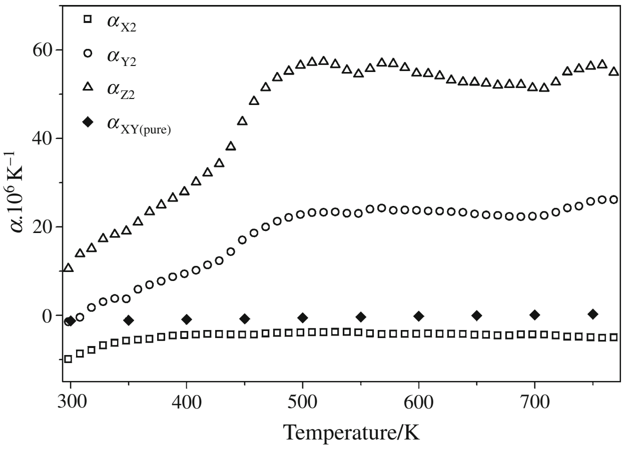

Fig. 3 Thermal expansion coefficient of graphite foam, pressed along the direction of weak interactions, measured along the X, Y, and Z directions, and of pure graphite, measured in the basal plane

and α_{x2}. The behavior of α_{x2} is monotonous and similar to that of $\alpha_{xy(\mathrm{pure})}$, while α_{y2} shows a dilatometric anomaly. α_{z2} is significantly higher than both α_{x2} and α_{y2}. At 780 K, it is more than twice as large as α_{y2} and more than six times larger than α_{x2}. It is positive throughout the temperature range and exhibits a dilatometric anomaly around 510 K, peaking at $55.10^{-6}\ \mathrm{K}^{-1}$. Figure 4 shows the variations of $\alpha(T)$ along the Z direction of both our materials and of pure graphite. When the temperature exceeds 380 K, the expansion of pure graphite $\alpha_{z(\mathrm{pure})}$ is smaller than that of α_{z1} and that of α_{z2}.

Note the interesting particularity concerning the absence of a dilatometric anomaly in $\alpha_{z(\mathrm{pure})}$, while it is present in α_{z1} and α_{z2}. This behavior is most probably due to pressing which has caused the intensification of the membrane effect. The peak of α_{z1} is more apparent than that of α_{z2} but the shape of the two curves remains globally the same (Fig. 4). α_{z1} is higher than α_{z2} from 300 to 780 K. Above 460 K, the material pressed along the direction of strong interactions has a thermal expansion coefficient twice as large as that of the samples subjected to pressing along the direction of weak interactions. It seems that the effect of pressure is lesser when the material is pressed along the Z axis than when it is pressed along an axis perpendicular to Z. This effect may be explained through the very strong interactions resulting from pressing along the Z axis, which influence the membrane effect. It is amplified when the pressing is done along the direction of strong interactions.

Figure 5 shows that the coefficients α_{x1} and α_{x2} are negative from 300 to 780 K. They overlap up to 400 K, above where temperature α_{x2} is higher than α_{x1}. From 630 K up, the difference between the values of the two coefficients keeps increasing.

But the analysis of the curves in Fig 6 shows that α_{y1} is twice as high as α_{y2} throughout the temperature range. α_{y2} is negative up to 680 K, whereas α_{y1} is positive throughout the temperature range. The values of α_{y1} and α_{y2} exceed

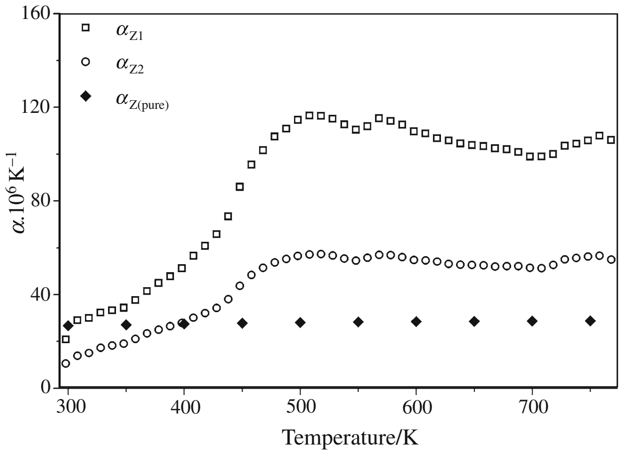

Fig. 4 Thermal expansion coefficients along the Z direction

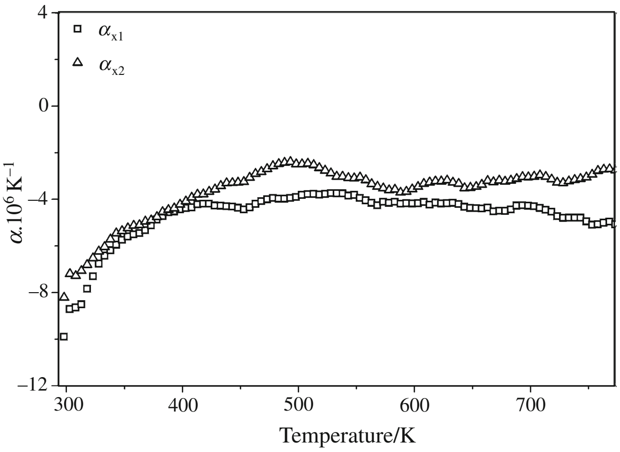

Fig. 5 Thermal expansion coefficients along the X direction

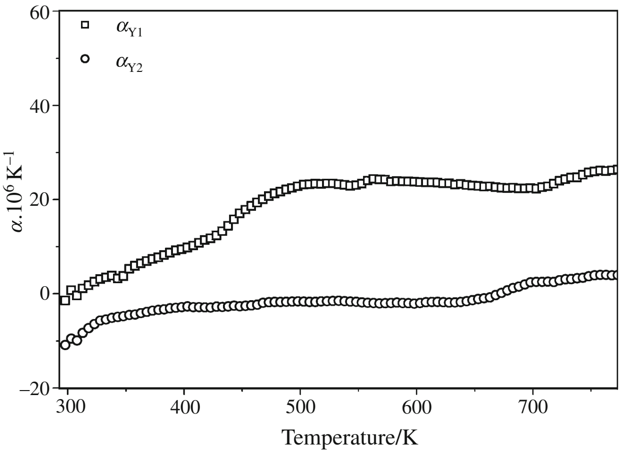

Fig. 6 Thermal expansion coefficients along the Y direction

clearly those of α_{x1} or α_{x2}. The effect of pressing works differently on the shape and the intensity of the dilatometric anomaly. When the pressing is applied in the basal plane, the peak noticed on the α_{y1} curve is more intense than that on the α_{x2} curve. But the roles are inversed in the case of pressing along the X direction. The anomaly is more intense in α_{x1} than in α_{x2}. It occurs at a slightly different temperature compared to that of α_{y1} or that of α_{y2}. Calorimetric measurements of the two samples which were pressed along the two directions, as before, taken from the same foam, have revealed the presence of an exothermal peak located in the same range of temperature as that present on the dilatometric curves. Nevertheless, there is a slight difference. The peak on the DSC curve of graphite foam pressed in the basal plane is more spread in temperature compared to that of graphite foam pressed along the Z direction.

The results of previous studies [1, 12, 13] concerning the dilatometric measurements of various kinds of foam are different from the results obtained in the present article: the dilatometric behavior of the foam studied here is anisotropic in the basal plane independently of the direction of pressing. We have also noticed that there is a difference between the values of $\alpha(T)$ in this article and those in [12, 14]. Each of the dilatometric curves of this foam has an anomaly which does not appear in the studies mentioned above. However, in Tondi et al. [5], the authors noted the presence of an anomaly in the thermal expansion coefficient, measured along the Z and XY directions, and suggested two areas of strain on both sides of 410 K. We have also demonstrated that regardless of the direction of pressing, $\alpha(T)$ measured along the X direction is inferior to the other two directions and to that reported in [12–14]. This change in the dilatometric behavior of the foam may be traced to the very low density of this foam.

Conclusions

The pressing of graphite foam plays an important role because it causes a fundamental change in the dilatometric behavior of the material. α_{zj} is a lot higher than α_{yj} and α_{xj}; the anisotropy becomes intense. Pressing also causes the appearance of anisotropy in the basal plane; it leads to a dilatometric anomaly which is due to an amplification of the membrane effect and to a privileged X direction, where α_{xj} is smaller than α_{yj} and to α_{zj}. The appearance of this direction may be due to a consolidation of inter-atomic bonds. The dilatometric behavior of graphite foam depends heavily on the axis along which the pressure is applied.

Finally, it seems that the anisotropy is more intense when the pressing is applied along the direction of weak interactions.

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