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Bending Strength of Artificial Graphite at High Temperatures*

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Abstract

Bending strength of artificial graphite was measured in the temperature region from 20° to 2700° in a reducing atmosphere. The strength increased gradually up to about 2000°, the fracture being brittle. Above about 2000° the apparent strength showed a rapid increase with temperature amounting to about 3 times as that of room temperature, accompanied with the change of the nature of fracture from brittle to plastic. Measurement by x-ray of the lattice constant in the c-direction indicated the existence of high internal stresses in the polycrystalline state of graphite which favours the fracture at low temperatures.

I. Introduction

Few has been known about the mechanical strength of carbon materials at high temperatures. Recently, however, there appeared a report[1] describing those of artificial graphite produced by The Acheson Electrode Co. from petroleum coke. This paper reports on the results of the experiments carried out on the artificial graphite manufactured from pitch coke.

Mechanical properties of graphite at high temperatures are interesting both from theoretical and industrial viewpoints inasmuch as that material is used widely as a conductive refractory material for various purposes.

II. Experimental

The speciments were cut from blocks of artificial graphite of commercial grade produced by The Tokai Electrode Co. from compacts of pitch coke mixed with a small amount of carbon black.

The properties of the specimens were on the average as follows: true density = 2.10 g/cm^3, apparent density = 1.65 g/cm^3, specific resistance = 1.55 Ω cm, ashes = 0.11%. Though the graphite materials have a more or less porous structure, these had very smooth appearances and homogeneity of the properties as the

* Main part of this work has been done in 1950

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1) C. Malmstrom, R. Keen and L. Green, Jr: Jour. of App. Phys., 22, 593 (1951)

blocks had been prepared from compacts of very fine particles.

Principal parts of the testing apparatus are shown in Fig. 1. It is an electric

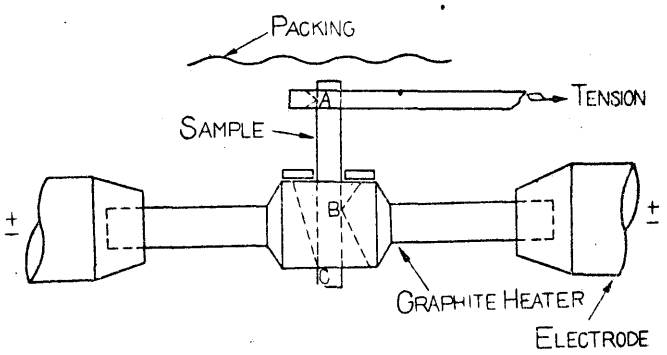

Fig. 1. Testing apparatus

resistance furnace equipped with fixed edges for the bending test. The parts shown are entirely made of artificial graphite (ashes = 0.1%). Each specimen is placed vertically in the central part and supported by the two edges B and C. Tension is applied at the other end of the specimen by a spring balance, not shown in the figure, on which the tension at the instant of fracture was indicated. The rate of the increase of the tension was such that the fracture occured after a few tens of seconds from the instant of the application of the tension. Possible influences of the curvature of the supporting edges on the results were examined for a few samples and were not detected. The furnace was prevented from oxidation by the packing of pitch coke dust (ashes = 0.5%) and carbon black (ashes = 0.02%).

The temperature was observed by an optical pyrometer through a peep pipe plugged in the central portion of the heater tube. The temperature measured by a thermocouple in a small hole drilled in that part of the specimen facing the edge B, where the bending stress becomes maximum, was about 10° lower than that determined by the pyrometer at about 800°. Corrections were not made, however, though this difference may not be small at higher temperatures. The oxidation of the samples during the test was not observed in any case and also the change of the resistivity before and after the test could not be attributed to any causes other than that of the application of the tension. Further graphitization of the samples should not have taken place.

The heater tube was heated by passing a heavy current to the desired temperature in a few min. and was held at that temperature for about one min. before the tension was applied.

III. Results aud Discussion

Bending strength at various temperatures are shown in Fig. 2 as a function of temperature. They are calculated as the tensile stress at the surface of the speci-

men at the instant of fracture under the assumption that the bulk deforms according to the Hooke's law. Therefore, the bending strength plotted in the figure is to be regarded as being proportional to the actual bending moment which was needed for the fracture. Corrections for the change of size of the specimens by the thermal expansion were not included, which were considered small as the expansion is estimated to be about 1.5% in length between 20° and 2000°.

The angles of the plastic deformation which remained after the fracture are given in the same figure.

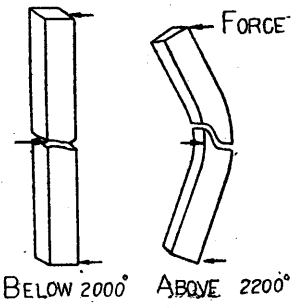

Fig. 2. Shapes of the fracture planes at high and low temperatures

Between 20° and 2000° the bending strength increased gradually with temperature and attained a value of about 1.5 times as high as that of room temperature. The fracture was always brittle in that temperature region.

Above about 2000° plastic deformation became appreciable accompanied at the same time with a rapid increase of the apparent strength. The shape of the fracture plane differed in these two temperature regions as shown in Fig. 3.

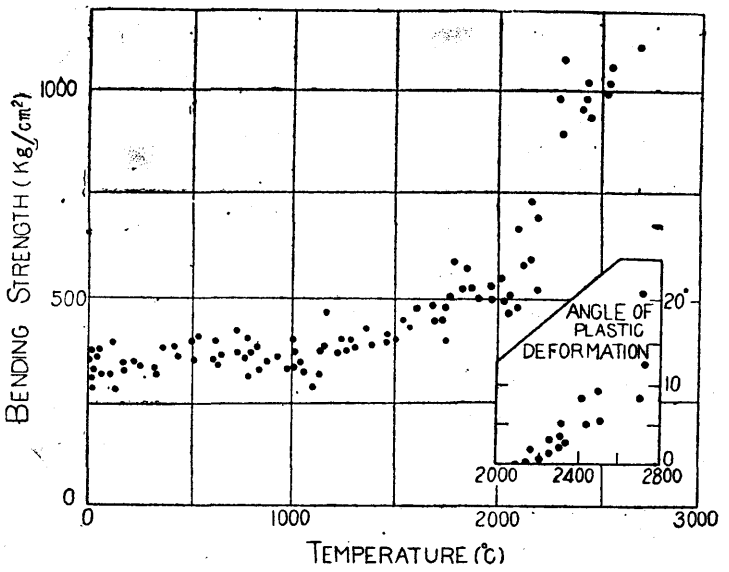

Fig. 3. Bending strength at different temperatures

The results described here are on the whole in coincidence with those of the American investigators. As before, it remains to be a remarkable fact that the strength increases with temperature, which is seldomly observed in cases of metals. A plausible explanation is as follows. On account of its porous structure, graphite materials fail under tension as soon as the local tension reaches a critical

value, which acts on the surfaces surrounding cracks or voids contained in the material. At high temperature, however, owing to the plastic flow the local stress is relaxed resulting to an apparent increase of the strength. A question arises in that connection. Then, is it possible to restrengthen the specimen by a previous application of tension at high temperatures? We tried it on several specimens with negative results. None of them showed any change in the low temperature strength in spite of the previous application at high temperatures of a tension amounting to about 2 times as high as that corresponding to the room temperature fracture. Besides, the following test was made. A specimen was cooled from high temperature under a constant load which surpassed greatly the fracture tension at room temperature, down to low temperature. It broke at temperatures near 2100°.

Another possible explanation was examined. Owing to the large anisotropy of the thermal expansion coefficient of a graphite crystal, polycrystalline solid blocks contain inevitably internal microstresses when they have been cooled down from high temperatures where crystalline deformation is allowed without any limitations, to low temperatures where normal contraction of the crystals is inhibited on account of their mutual interferences. These stresses, if they are present, act as tensile stresses normal to the layer planes of crystals as the thermal expansion coefficient in this direction is known to be far larger than that parallel to the layer plane. At low temperatures, therefore, the crystals remain in a state having the sizes corresponding to those at higher temperatures. These stresses may be considered to lower the tensile strength of the material.

We measured the lattice spacing between neighbouring layers or the lattice constant in the c-direction by the usual Debye-Scherrer method on an artificial graphite specimen, on the one hand in a solid needle-like form and on the other hand in the form of fine powder ($<2\mu$).

The diameters of the camera and of the samples were 9 cm and 1 mm respectively. Comparing the general hkl lines on the respective photos, the relative accuracy of the following data was estimated to be about 0.1%.

$$c = 6.724 \pm 0.005\,\text{A} \quad \text{Powder}$$
$$c = 6.748 \pm 0.005\,\text{A} \quad \text{Solid}$$

These results show that in the solid state of that specimen each crystal is elongated in the c-direction by about no less than 0.4% as compared with those of stress free state. Adopting the compressibility data of natural graphite, it is concluded that a tensile stress about above 0.9 ton/cm^2 acts on each crystal in favour of the breaking of the neighbouring layers at room temperature.

Thus, the increase of the strength at high temperatures seems to be caused by the diminution of the internal stresses.

In conclusion the author wishes to thank Dr. Majima for kind guidance and Mr. Ikezawa of The Tokai Electrode Co. for collaboration.