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*Tensile and Structural Properties
of Glassy Carbon*

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ABSTRACT**13554**

Tensile properties of two different grades of glassy carbon (called GC-20 and GC-30 by the manufacturer) have been measured from room temperature to 2900°C. The test specimens had a gauge section 0.08 in. in width by 0.10 in. in thickness with a 0.75-in. gauge length. Tests were made in a helium atmosphere, and heating was accomplished by means of an external graphite heater. Tensile strengths at room temperature for both grades were approximately 6000 psi. Both grades showed an increase in strength with increasing test temperature, reaching a maximum within the 20,000 to 25,000 psi range at 2500°C. At 2900°C, strengths of about 12,000 psi for GC-20 and 16,000 psi for GC-30 were measured. Differences in the deformation of the two grades were evident from their ductility. At 2700°C, maximum elongations of 33% for GC-20 and 5.4% for GC-30 were measured. Density, unit cell dimension, hardness, and diamagnetic susceptibility measurements were used to investigate the structural changes accompanying deformation and heat treatment. Electron micrographs revealed a difference in fracture mode for GC-20 and GC-30. The tensile and structural behavior of glassy carbon has been compared with that of conventional carbon-base materials. It is suggested that cross-link bonding is responsible for the high strength of glassy carbon; however, the small crystallite size and the small pore size may also be contributing factors.

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I. INTRODUCTION

During the past five years, a number of new types of carbon-base materials, such as pyrolytic carbon (pyrolytic graphite), pyrolytic carbon alloys, hot-pressed recrystallized pitch-coke graphite, glassy carbon, and pitch-coke graphite metal composites, have been developed with properties that are unique compared with conventional pitch-coke graphite. Glassy carbon is one of the most recently introduced of these carbon-base materials. Cellulose carbon and vitreous carbon, which are similar to glassy carbon, have also recently become commercially available.

Previous work at the Jet Propulsion Laboratory (JPL) has been directed toward investigating the relationship

between structure and the high temperature mechanical properties and deformation behavior of pitch-coke graphite, pyrolytic carbon, pyrolytic boron nitride, and boron pyrolytic carbon (Ref. 1 through 4). This work has been followed by studies at JPL on glassy carbon.

The results contained in this report represent some of the first high temperature tension tests made on this material, although preliminary accounts of this work were presented before all the analyses were completed (Ref. 5). Structural changes and deformation behavior of glassy carbon are presented in this report and compared with other carbon-base materials.

II. MATERIALS TESTED

Glassy carbon is a turbostratic (disordered layer stacking) form of carbon that is produced by carbonizing a polymer under carefully controlled conditions of temperature and pressure. The manufacturer, for proprietary reasons, has not divulged detailed information on the starting material or processing history.¹ It is known that glassy carbon is made from a resin that is carbonized at a very low heating rate. As reported by others (Ref. 6, 7, and 8), glassy carbon has a density of approximately 1.5 g/cm³, is as impermeable to gases as pyrex glass, is hard and brittle, and has a lower oxidation rate than either conventional or high-density graphites.

The glassy carbon used in this study was purchased in the shape of flat plates approximately $4 \times 4 \times \frac{1}{8}$ in. One-eighth inch is the maximum thickness available for flat plates and shaped pieces. Two grades, which the manufacturer calls GC-20 and GC-30, were tested. These were reported by the manufacturer to have been heat-treated at maximum temperatures of 2000°C (in the case of GC-20) and 3000°C (in the case of GC-30). The GC-20 material was heat-treated over a period of several weeks under a carefully controlled heating program. The GC-30 material was produced by subsequently heat treating GC-20 for several hours at 3000°C. Table 1 lists some properties given by the manufacturer for the two materials tested at JPL. These properties should be considered as typical, average values representative of the current state of the

¹Tokai Electrode Manufacturing Co., Ltd., Tokyo, Japan.

Table 1. Properties of glassy carbon^a

Property	GC-20	GC-30
Heat treat temperature, °C	2000	3000
Apparent density, g/cm ³	1.46-1.47	1.43-1.46
Shore hardness	100-110	70-80
Flexural strength, lb/in. ²	10,000-11,400	5700-7100
Young's modulus, lb/in. ²	$3.5-4.1 \times 10^6$	$2.1-2.8 \times 10^6$
Electrical resistivity, Ω -cm	$40-45 \times 10^{-4}$	$30-35 \times 10^{-4}$
Coefficient of thermal expansion, 1/°C	$2.0-2.2 \times 10^{-6}$	$2.0-2.2 \times 10^{-6}$
Thermal conductivity, cal/cm/sec/°C	$1.9-2.2 \times 10^{-2}$	$3.5-4.1 \times 10^{-2}$
Ash	0.1-0.2	0.10

^aData supplied by Tokai Manufacturing Co., Ltd., Tokyo, Japan.

Table 2. Spectrographic analysis of glassy carbon^a

Element	GC-20, %	GC-30, %
Silicon	0.005	0.01
Magnesium	0.0002	0.0006
Iron	0.003	Not detected
Calcium	0.07	0.001
Copper	0.0004	0.0005
Strontium	Trace	Not detected
Other elements	Not detected	Not detected

^aAnalyzed by Pacific Spectro Chemical Laboratory, Los Angeles, California.

art. Table 2 gives spectrographic analyses of the two grades of glassy carbon used for this work.

III. TESTING EQUIPMENT AND PROCEDURE

The tensile test apparatus and procedure were the same as those used for other graphite tests, which are described in detail in Ref. 2 and 9. The specimens had a 0.08 by 0.10-in. gauge cross section with a 0.75-in. gauge length. Three-quarter-inch-radius fillets at each end of the specimen provided a seating surface against the holders. The tests were made in a graphite tube furnace in a helium atmosphere at a constant crosshead speed of 0.009 in./min. The displacement of the specimen holders was used as a measurement of elongation. Stress was measured by means of a standard 1000-lb load cell. For test temperatures up to and including 2700°C, specimens were held at temperature for approximately 20 min prior to testing; at 2900°C, this holding time was approximately 10 min.

Unit cell dimensions were calculated from X-ray diffraction powder patterns, which were obtained with a 14.59-cm diameter Debye-Scherrer camera and nickel-filtered copper radiation.

Knoop hardness measurements were made using a microhardness testing machine. Because of the resiliency of glassy carbon, direct penetration hardness measure-

ments were difficult to analyze. Modification of an indirect method (Ref. 10) was found to be satisfactory. This method consisted of evaporating a thin film of silver approximately 1000 Å thick onto the specimen surface, and determining the hardness by measuring the size of the impression left in the silver coating by a diamond indenter under a 100 g load.

Bulk density was calculated from the sample weight and measured volume. Real (kerosene) density was calculated from weight measurements made in air and in kerosene.

Diamagnetic susceptibility measurements were made at room temperature by the Faraday method. A detailed description of this apparatus can be found in Ref. 11. Susceptibilities were measured in three orthogonal directions.

Electron micrographs were made by a standard two-step parlodion-carbon replication and germanium shadowing technique.²

²Sloan Research Industries, Inc., Santa Barbara, Calif.

IV. RESULTS

A. Tensile Properties

Tensile data over the room temperature to 2900°C range are given in Table 3. The error in ultimate strength is estimated to be ±200 psi. The uncertainty in elongation measurement after correcting for deformation in the fillets is approximately ±15% of the reported value.

Table 3 shows that the ultimate tensile strength for the two grades is not markedly different over the temperature range investigated. At room temperature, the strength was approximately 6000 psi. The strength increased to a maximum of 20,000 to 25,000 psi at 2500°C, and then decreased as the test temperature was increased to 2900°C. On the other hand, the elongation at 2500°C and above was markedly greater for GC-20 than for GC-30. At 2700°C, maximum elongations of 33% for GC-20 and 5.4% for GC-30 were measured. The scatter in the tensile data at a given temperature was not considered to be unusual for these materials. Nicks and chips in the gauge section corners were common. The lower strengths were generally associated with lower elongations and could have been due to these notches or other surface defects produced during machining, as well as to variations in material properties inherent in the manufacturing and processing.

Photographs of typical fractured specimens are shown in Fig. 1. The macroscopic appearance of the fractured surfaces for both grades of glassy carbon was quite similar, appearing brittle and glassy with no systematic variation with test temperature. Fractures normally occurred within the gauge section, and approximately one fourth of the samples tested gave a multiple break as shown in Fig. 1. Several fractures occurred outside of the gauge section; these were evidently associated with the surface defects mentioned before.

It was postulated that the difference in fracture elongation between the GC-20 and GC-30 grades was due to the cyclic heat treatment received by GC-30; i.e., heating to 3000°C and cooling to room temperature. To check this postulation, the GC-20 samples were heated to 3000°C in a graphite tube furnace, held at that temperature for 1 hr, cooled to room temperature, and then tested at 2500°C and above. Tensile data for these GC-20 samples are also given in Table 3. Good agreement is seen with the tensile data given for GC-30.

The difference in the deformation of these two materials can be seen more clearly in Fig. 2, which shows typical

Table 3. Tensile data for glassy carbon^a

Test temperature, °C	GC-20		GC-30		Heat-treated GC-20 ^b	
	Ultimate tensile strength psi	Fracture elongation, %	Ultimate tensile strength psi	Fracture elongation, %	Ultimate tensile strength psi	Fracture elongation, %
25	6,100	—	5,900	—	—	—
1600	8,100	0.5	8,100	0.7	—	—
1600	6,700	0.2	6,400	0.6	—	—
1900	11,300	1.2	11,800	1.1	—	—
1900	16,100	2.5	10,100	1.4	—	—
2200	17,600	2.4	12,100	1.1	—	—
2200	16,800	2.8	14,800	3.7	—	—
2500	20,400	13	20,800	3.4	11,060	0.5
2500	20,100	8	25,300	3.9	17,400	4.2
2700	16,300	23	20,800	5.4	20,080	4.7
2700	17,800	33	16,400	1.9	—	—
2900	10,500	12	15,500	3.9	17,100	8.7
2900	12,700	24	16,600	4.8	—	—

^aCross head speed 0.009 in./min.
^bPre-treated 1 hr at 3000°C. Tests were only run at 2500, 2700, and 2900°C for these samples.

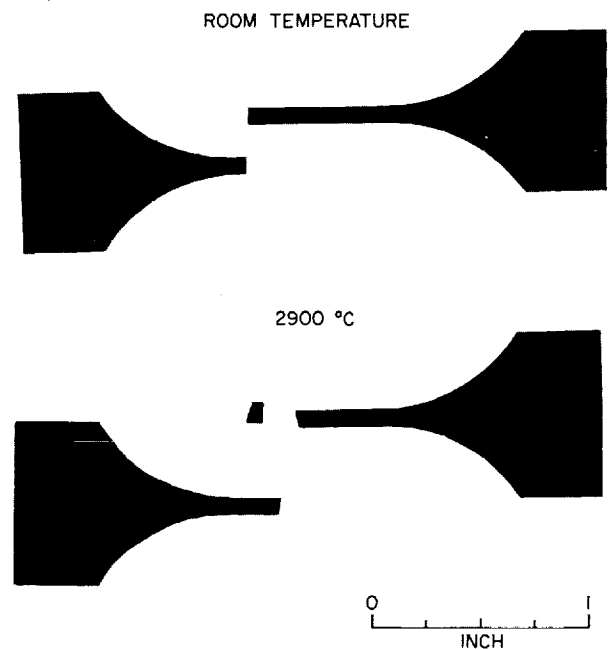


Fig. 1. Fractured specimens of GC-30 glassy carbon

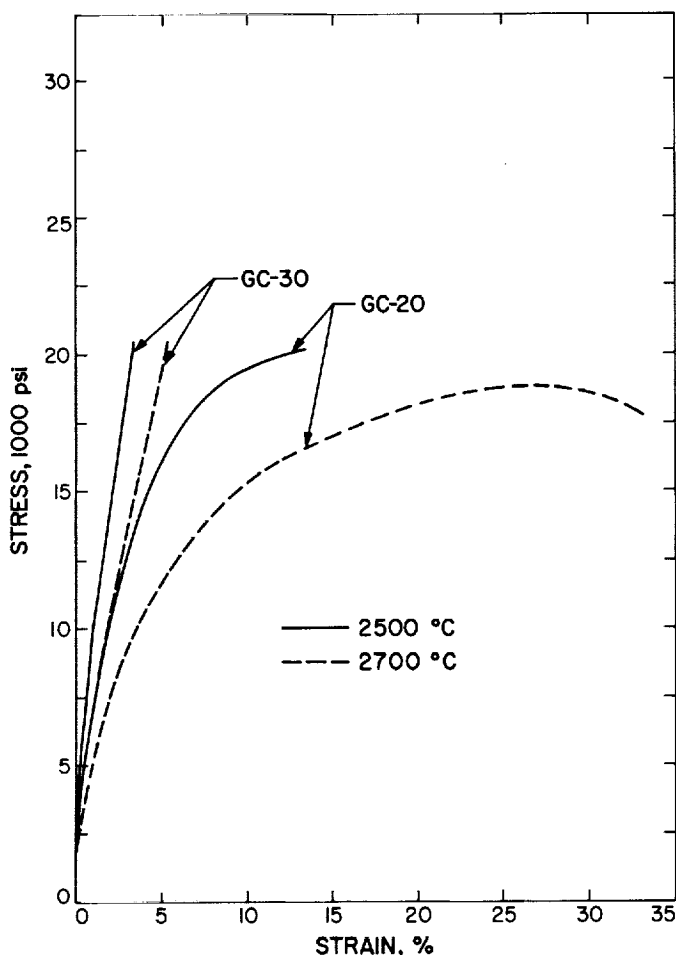


Fig. 2. Typical engineering stress-strain curves for glassy carbon

engineering stress-strain curves at 2500 and 2700°C. The strengths were not markedly different, as mentioned before, but the GC-20 curves show a much greater elongation at fracture. An interesting feature of the GC-20 curve at 2700°C is the decrease in stress prior to fracture after reaching a maximum. While this is the usual behavior for metals and alloys, it is uncommon in carbons and graphites. No necking in the gauge section was detected. Another interesting feature of glassy carbon is that it does not maintain constant volume during tension testing. This means that crack or void formation and growth are associated with the deformation.

B. Structural Changes Accompanying Deformation

The results of structural studies made on deformed and undeformed glassy carbon specimens are given in Table 4. The bulk density for GC-20 decreases with deformation from a value of 1.5 g/cm³ to 1.29 g/cm³ after 33% elongation; the real density, as measured in kerosene, increases

Table 4. Glassy carbon structural data

Treatment	Density, g/cm ³		Knoop micro-hardness 100 g	c ₀ ^b Å ± 0.03	a ₀ ^c Å ± 0.01
	Bulk	Real ^a			
GC-20					
As received	1.50	1.68	192	7.00	2.43
Heated to 3000°C	1.50	1.66	127	6.87	2.44
Heated to 3200°C	—	—	—	6.84	2.45
13.3% strain at 2500°C	1.41	1.71	145	6.91	2.44
23.2% strain at 2700°C	1.28	1.76	117	6.90	2.44
33.1% strain at 2700°C	1.29	1.82	114	6.84	2.43
23.6% strain at 2900°C	1.37	1.74	112	6.87	2.44
GC-30					
As received	1.50	1.68	127	6.86	2.45
Heated to 3200°C	—	—	—	6.83	2.45
1.1% strain at 2200°C	1.54	1.65	—	6.86	2.45
5.4% strain at 2700°C	1.46	1.66	119	6.87	2.45
4.8% strain at 2900°C	1.44	1.65	115	6.87	2.45

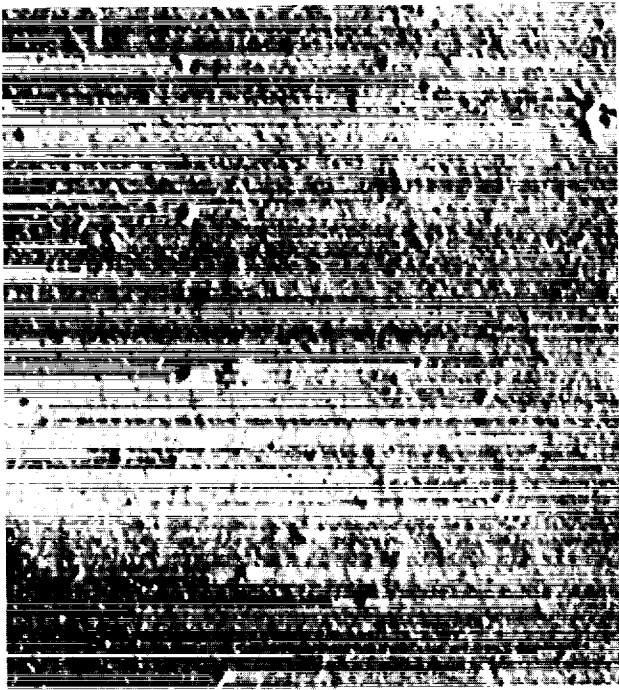
^aMeasured by kerosene displacement.
^bAverage from (002) and (004) reflection.
^cAverage from (10) and (11) reflection.

from 1.68 g/cm³ to 1.82 g/cm³ for the same amount of deformation. A slight decrease in bulk density appears to accompany deformation in GC-30, but there is no significant change in real density. An increase in real density means that some of the voids that are formed as well as previously closed pores are opened to the surface.

The as-received GC-20 is quite hard, but after heat treatment at 3000°C it reaches the same value as the as-received GC-30. After deformation at 2700 and 2900°C, both the GC-20 and GC-30 samples reached hardness values within the range of 112 to 119.

The X-ray structural data are in general agreement with values published in Ref. 7 and 12. The unit cell height for GC-20 decreases from a value of about 7.0 to 6.84 Å and the unit cell width increases slightly from 2.43 to 2.45 Å after heat treatment at 3200°C. There was no consistent effect of deformation on unit cell height. The unit cell height as well as the unit cell width of GC-30 remained essentially unchanged after heat treating at 3200°C or after deformation.

Electron micrographs of polished and fractured surfaces are shown in Fig. 3 for GC-20 and in Fig. 4 for



POLISHED



FRACTURED AT ROOM TEMPERATURE

1 μ



FRACTURED AT 1600°C, 0.5% ELONGATION



FRACTURED AT 2900°C, 12.4% ELONGATION

Fig. 3. Electron micrographs of GC-20 glassy carbon surfaces



POLISHED

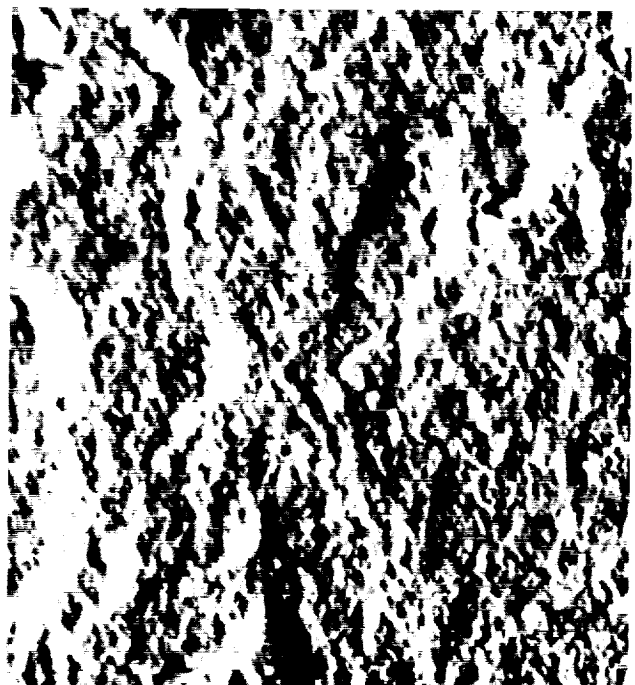


FRACTURED AT ROOM TEMPERATURE

1 μ



FRACTURED AT 1600°C, 0.7% ELONGATION



FRACTURED AT 2900°C, 3.9% ELONGATION

Fig. 4. Electron micrographs of GC-30 glassy carbon surfaces

GC-30. These micrographs are of shadowed two-stage positive replicas, with the shadow cast from left to right. The polished surface of as-received GC-20 in Fig. 3 reveals a random distribution of fine pits having an average diameter of 350 Å, which is near the resolution limit of this type of replica. If only the most sharply defined pits are considered to be pores, a porosity of 34% is calculated from pore count. This is in good agreement with a porosity of 31% based on the bulk and X-ray densities of this material. However, small angle X-ray scattering studies indicated inhomogeneities on a scale of only 10 to 20 Å diameter.³ The pits observed in the micrographs may be polishing or replication artifacts, and the density agreement may be fortuitous. The three electron micrographs of the fractured surfaces (Fig. 3) show a distinct grain structure in the fracture surface that is particularly pronounced in the 2900°C fracture.

The polished surface of as-received GC-30 in Fig. 4 is not appreciably different from that of GC-20. Polishing scratches are more pronounced in GC-30, possibly because of its greater softness. The texture of the GC-30 fractured surfaces in Fig. 4, on the other hand, is easily distinguishable from GC-20. The impression of graininess is largely absent. There is, instead, a high density of randomly oriented chains of adjacent pits and microcracks. These microcracks are interconnected in a random way rather than around individual or a cluster of grains as in GC-20.

³R. H. Bragg, M. L. Hammond, *X-ray Study of Pyrolytic Graphites and Glassy Carbon*, Paper 17, presented at the Seventh Conference on Carbon, Cleveland, Ohio, June 21-25, 1965.

Despite the differences in fracture surface appearance, electron micrographs of unetched polished sections of the same gauge sections revealed no well-defined structural differences as a function of grade, test temperature, or amount of deformation. They were similar to the as-received structure with no indication of pronounced grain structure or microcracks. In all of the samples, occasional pores a few microns in diameter were observed, but the frequency of these was low.

An indication of change in preferred orientation with deformation of glassy carbon was obtained from measurements of the diamagnetic susceptibility. For a graphite single crystal, the susceptibility perpendicular to the layer planes χ_c is 21×10^{-6} emu/g, and the susceptibility parallel to the layer planes χ_a is 0.3×10^{-6} emu/g (Ref. 13). The anisotropy ratio χ_c/χ_a is 70. The anisotropy ratio χ_{\max}/χ_{\min} of polycrystalline samples is about 8 for as-deposited pyrolytic carbon, and about 1.2 for a conventional pitch-coke graphite (Ref. 14). A value of 1.0 was measured for as-received GC-20 and GC-30. After 33% elongation at 2700°C, the anisotropy ratio of the GC-20 increased to 1.8, with the low susceptibility parallel to the stress axis. This indicates that layer-plane orientation parallel to the stress direction resulted from deformation. For a similar amount of deformation, pyrolytic carbon gave an anisotropy ratio of 40, and pitch-coke graphite gave an anisotropy ratio of 1.5. In addition, the total susceptibility increased with test temperature, indicating an increase in crystallite diameter consistent with the X-ray results (Ref. 7).

V. DISCUSSION

The structure and the strength of carbons and graphites as well as the behavior and interrelationship of these two characteristics are associated with the processing history. Unfortunately, detailed information is unavailable on the starting material and processing of glassy carbon. Some pertinent features of the structure and deformation behavior may be inferred from the available data.

A. Structure of Glassy Carbon

Using the classifications of Franklin (Ref. 15), the present X-ray and magnetic susceptibility data confirm that glassy carbon must be classified as a nongraphitizing hard carbon. Such a carbon is characterized by a random crystallite orientation, a finely-porous low-density structure, and a strong network of cross-link bonding that inhibits crystallite growth and graphitic layer stacking during heat treatment.

Noda and Inagaki (Ref. 12) proposed a model that is composed of small crystallites of parallel-stacked layer planes (turbostratic crystallites) jointed together in a random manner by extensive tetrahedral (diamond-type) carbon-carbon cross-link bonds. Kakinoki (Ref. 16) explained the unusual electronic properties of glassy carbon by suggesting a structure of turbostratic crystallites linked together by oxygen bonds. However, it is difficult to believe that extensive oxygen bonding could persist after heat treatment at 2000°C and above. In any case, it is generally agreed that cross-link bonding is an important feature of the structure of glassy carbon.

B. Structural Behavior

When pitch-coke graphite and pyrolytic carbon are deformed in tension at high temperatures, certain structural changes are known to accompany the deformation (Ref. 1, 2, and 17 through 23). Pitch-coke graphite shows a decrease in bulk density and an increase in real density, an increase in preferred orientation, and an increase in graphitization. Pyrolytic carbon shows a decrease in bulk density and a marked increase in strength, preferred orientation, and degree of graphitization with deformation produced by applying a tensile load parallel to the substrate. Glassy carbon shows similar structural changes with deformation, as seen in Table 4, except that it does not graphitize under the usual graphitization treatment. Graphitization is defined as the development of an ordered layer stacking structure and is associated with a decrease in the unit cell height to (or near) the single

crystal value of 6.708 Å. Even after heat treatment at 3200°C the unit cell height of glassy carbon is 6.84 Å, which indicates a turbostratic, nongraphitizing structure. The absence of any effect of tensile deformation on graphitization is interesting in view of the report in Ref. 24 that glassy carbon does graphitize when heat-treated under a hydrostatic pressure of the order of 10 kbar. It also graphitizes when it is melted (Ref. 25). This behavior is probably characteristic of all carbons.

The electron micrographs of the fractured surfaces (Fig. 3 and 4) reveal a difference in mode of fracture as a function of grade and temperature. However, the absence of similar structural differences in polished deformed samples and the possible presence of replication artifacts make it difficult to identify the structural components responsible for this difference.

C. Strength and Tensile Behavior

The tensile strength of glassy carbon is exceptionally high for an isotropic polycrystalline carbon. Although a detailed understanding of the strength is not yet possible, the cross-link bonding must be considered an important factor. This bonding may be expected to increase the intercrystalline boundary and layer-plane shear and cleavage strengths, which are probably the primary sources of weakness in polycrystalline carbons and graphites. The small crystallite size may also contribute to the high strength on a microscopic scale. This strength is transferred to the bulk sample by processing methods that retain a very small pore size. The excellent high-temperature tensile properties realized in glassy carbon indicate that further development of the technology of specially prepared nongraphitizing carbons could lead to superior materials for specialty applications.

There are a number of striking similarities in the tensile behavior of pitch-coke graphite, pyrolytic carbon, and glassy carbon. Figure 5 shows the strength versus the temperature data for these materials. At all temperatures glassy carbon is stronger than pitch-coke graphites but not as strong as pyrolytic carbon parallel to the substrate. The two grades of glassy carbon show the same strength behavior as pitch-coke graphite; i.e., an increase in strength with test temperature reaching a peak at approximately 2500°C, followed by a decrease with increasing temperature. It is likely that the increase in strength for glassy carbon is due to an increase in ductility and plastic

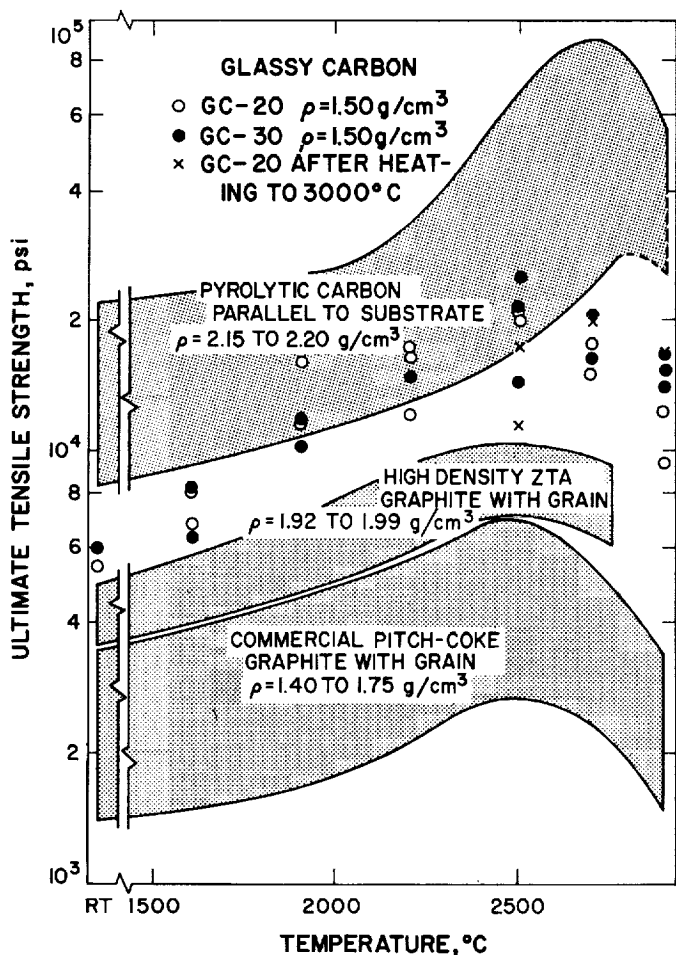


Fig. 5. Ultimate tensile strength vs temperature

flow (both of which allow for relief of stress concentrations) as in pitch-coke graphite (Ref. 9, 17, and 18).

The data in Table 1 show that there are large differences in a number of room temperature properties of GC-20 and GC-30, although the densities of the two grades are nearly the same. The density and hardness data shown in the table are consistent with the present results, but no significant difference in the tensile strength at temperatures below 2700°C was found for the two grades. Striking differences in the ductility were observed at temperatures above about 2200°C. It is not clearly understood why the properties of GC-20 and GC-30 are so different. The high-temperature ductility difference is of particular interest here. The amount of structural change that occurs in GC-20 in the range of maximum ductility, 2500–2700°C, seems too small to account for the observed effect. Nevertheless, the difference between GC-20 and GC-30 is definitely associated with the additional heat treatment received by GC-30. This suggests that microcracks and internal stresses resulting from dif-

ferential thermal expansion and stress relaxation at high temperatures, as suggested by Mrozowski (Ref. 17) for pitch-coke graphite, may play an important role. This mechanism is consistent with the large modulus, thermal conductivity, and hardness differences, and with the negligible density difference. However, it is difficult to reconcile with the lack of difference in tensile strength. Moreover, appropriate structural features, such as microcracks, have not been observed in GC-30. Another possibility is that the process of impurity volatilization affects the properties. There is some evidence from magnetic susceptibility measurements and chemical analyses that considerable loss of impurities (especially Si, Al, Fe, Ca, and Ba) occurs in the temperature range of the ductility maximum. There are no data on the loss of oxygen, or on other factors that could affect the ductility.

For many high-temperature applications, the strength-to-density ratio is an important characteristic. Figure 6

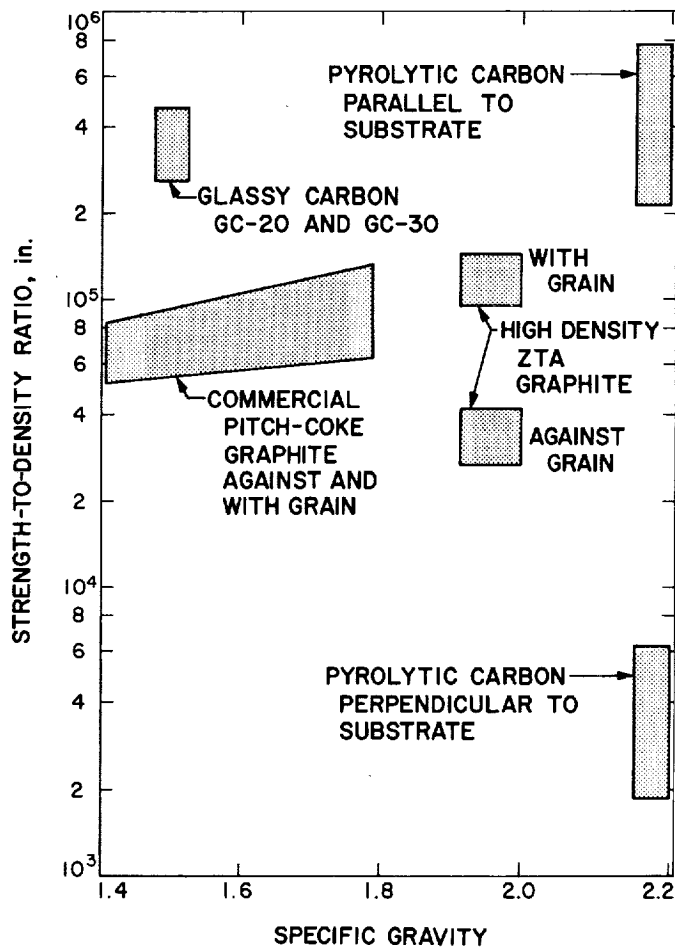


Fig. 6. Strength at 2500°C to density ratio vs specific gravity

shows the ratio of tensile strength (at 2500°C) to density versus specific gravity for various carbons and graphites. On this basis, the strength of glassy carbon is equal to that of pyrolytic carbon parallel to the substrate, and is approximately twice that of the highest strength pitch-coke graphite. This figure also illustrates another impor-

tant characteristic of glassy carbon. Hot-pressed recrystallized ZTA pitch-coke graphite and pyrolytic carbon show a marked degree of anisotropy in their strength. The initial structure of glassy carbon shows no anisotropy, and, therefore, no anisotropy in the tensile strength would be expected.

VI. CONCLUSIONS

The results presented here are from a limited number of tests on glassy carbon and, while they are typical for the two grades tested, they should not be considered as representative of all glassy and nongraphitizing carbons. The lack of processing knowledge is a serious handicap in understanding the detailed behavior of glassy carbon in terms of structure and starting material, and could be an important factor in the property differences reported herein. The limitation in thickness to approximately $\frac{1}{8}$ in. for flat plates and shaped objects, and the limitation in size of fabricated components could impede the engineering interest in this material. Despite these limitations, these results show that glassy carbon has many favorable characteristics that make it potentially useful for certain high temperature applications. The conclusions reached in this investigation are summarized below:

1. Glassy carbon is approximately two to four times stronger than conventional pitch-coke graphites over the room temperature to 2900°C range. Like pitch-coke graphite, glassy carbon shows a maximum in strength at 2500°C.
2. Over the range 2200 to 2500°C, glassy carbon is almost as strong as pyrolytic carbon in the direction parallel to the substrate.
3. On a strength-to-density ratio basis at 2500°C, glassy carbon is as strong as pyrolytic carbon in the direction parallel to the substrate.
4. Undeformed glassy carbon does not show any structural anisotropy, and, therefore, no anisotropy in strength would be expected.
5. Unlike pyrolytic carbon and pitch-coke graphite, which graphitize upon deformation and heat treating at 3000°C and above, glassy carbon does not graphitize upon 1-hr heat treating at 3200°C or upon 33% deformation at 2700°C.
6. Glassy carbon becomes softer with heat treatment and deformation.
7. An increase in open porosity accompanies deformation of glassy carbon as observed in pyrolytic carbon and pitch-coke graphite.
8. Electron micrographs indicate a difference in fracture mode between the two grades of glassy carbon. However, electron microscopic examination of unetched polished sections reveals no extensive microcracks or other structural features that can account for the differences in behavior.
9. It is suggested that strong cross-link bonding in glassy carbon is responsible for its nongraphitizing behavior, high strength, and lack of anisotropy.

REFERENCES

1. Martens, H. E., and Kotlensky, W. V., *Structural and High Temperature Tensile Properties of Special Pitch-Coke Graphites*, Technical Report No. 32-181, Jet Propulsion Laboratory, Pasadena, Calif., November 30, 1961.
2. Kotlensky, W. V., and Martens, H. E., *Tensile Properties of Pyrolytic Graphite to 5000°F*, Technical Report No. 32-71, Jet Propulsion Laboratory, Pasadena, Calif., March 10, 1961.
3. Kotlensky, W. V., and Martens, H. E., "Tensile Behaviour of Pyrolytic Boron Nitride to 2200°C," *Nature*, Vol. 196, pp. 1090-1091, 1962.
4. Kotlensky, W. V., and Martens, H. E., *Structure and High Temperature Tensile Properties of Boron Pyrolytic Graphite*, Technical Report No. 32-299, Jet Propulsion Laboratory, Pasadena, Calif., December 16, 1963.
5. Kotlensky, W. V., and Martens, H. E., "Tensile Properties of Glassy Carbon to 2900°C," Paper V-2, in *Symposium on Carbon*, Carbon Society of Japan, Tokyo, Japan, July 1964. Also published in *Nature*, Vol. 206, pp. 1246-1247, 1965.
6. Yamada, S., and Sato, H., "Physical Properties of Glassy Carbon," *Nature*, Vol. 193, p. 261, 1962.
7. Yamada, S., Sato, H., and Ishii, T., "Eigenschaften und verwendung von glasartigen kohlenstoff," *Carbon*, Vol. 2, pp. 253-260, 1964.
8. Tsuzuku, T., and Kobayashi, H., "Internal Friction of Carbon Materials," in *Proceedings of the Fifth Conference on Carbon*, Vol. 2, pp. 539-543, Pergamon Press, Ltd., London, England (distributed by the Macmillan Co., New York, N. Y.), 1963.
9. Martens, H. E., Jaffe, L. D., and Jepson, J. O., "High-Temperature Tensile Properties of Graphites," *Proceedings of the Third Conference on Carbon*, pp. 529-542, Pergamon Press, Ltd., London, England (distributed by the Macmillan Co., New York, N. Y.), 1959.
10. Stover, E. R., *Improvement of Pyrolytic Graphite Properties by Heat-Treating and Hot-Working—Initial Evaluation of Structure and Properties*, Report No. 62-RL-2991M, General Electric Co., Research Laboratory, Schenectady, N. Y., May 1962.
11. Fischbach, D. B., "The Magnetic Susceptibility of Pyrolytic Carbons," in *Proceedings of the Fifth Conference on Carbon*, Vol. 2, pp. 27-36, Pergamon Press, Ltd., London, England (distributed by the Macmillan Co., New York, N. Y.), 1963.
12. Noda, T., and Inagaki, M., "The Structure of Glassy Carbon," *Bulletin of the Chemical Society of Japan*, Vol. 37, pp. 1534-1538, 1964.
13. Poquet, E., Lumbroso, N., Hoarau, J., Marchand, A., Pacault, A., and Soule, D. E., "Etude du Diamagnetisme du Monocristaux de Graphite," *Journal de Chimie Physique et de Physicochimie Biologique*, Vol. 57, pp. 866-872, 1960.
14. Fischbach, D. B., "Effect of Plastic Deformation on Preferred Orientation of Synthetic Carbons," in *Space Programs Summary No. 37-27*, Vol. IV, pp. 29-31, Jet Propulsion Laboratory, Pasadena, Calif., June 30, 1964.
15. Franklin, R. E., "Crystallite Growth in Graphitizing and Nongraphitizing Carbons," *Proceedings of the Royal Society, Series A*, Vol. 209, pp. 196-218, 1951.

REFERENCES (Cont'd)

16. Kakinoki, T., "A Model for the Structure of Glassy Carbon," *Acta Crystallographica*, Vol. 18, p. 578, 1965.
17. Mrozowski, S., "Mechanical Strength, Thermal Expansion and Structures of Cokes and Carbons," in *Proceedings of the Conferences on Carbon, 1st and 2nd Conferences*, pp. 31-45, University of Buffalo Press, Buffalo, N. Y., 1956.
18. Smith, M. C., "Effects of Temperature and Strain Rate on Transverse Tensile Properties of H4LM Graphite Tested in Helium and in Vacuum," *Carbon*, Vol. 1, pp. 147-153, 1964.
19. Pappis, J., *The Mechanical Properties of Pyrographite*, TM T-216, Raytheon Company, Research Division, Waltham, Mass., March 1960.
20. Stover, E. R., *Mechanisms of Deformation and Fracture in Pyrolytic Graphite*, Report No. 61-RL-2745M, General Electric Co., Research Laboratory, Schenectady, N. Y., June 1961.
21. Kotlensky, W. V., and Martens, H. E., *Structural Transformation in Pyrolytic Graphite Accompanying Deformation*, Technical Report No. 32-360, Jet Propulsion Laboratory, Pasadena, Calif., November 1, 1962.
22. Bragg, R. H., Crooks, D. D., Fenn, R. W., Jr., and Hammond, M. L., "The Effect of Applied Stress of the Graphitization of Pyrolytic Graphite," *Carbon*, Vol. 1, pp. 171-179, 1964.
23. Losty, H. H. W., and Orchard, J. S., "The Strength of Graphite," *Proceedings of the Fifth Conference on Carbon*, Vol. 1, pp. 519-532, Pergamon Press, Ltd., London, England (distributed by the Macmillan Co., New York, N. Y.), 1962.
24. Noda, T., and Kato, H., "Heat Treatment of Carbon under High Pressure," Paper III-19, in *Symposium on Carbon*, Carbon Society of Japan, Tokyo, Japan, July 1964.
25. Noda, T., and Inagaki, M., "The Melting of Glassy Carbon," *Bulletin of the Chemical Society of Japan*, Vol. 37, pp. 1709-1710, 1964.