

## Structural and Property Changes in Glass-like Carbons Formed by Heat Treatment and Addition of Filler

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**Abstract:** Glass-like carbon precursors shrink significantly during curing and carbonization, which leads to crack formation and bending. Cured furan resin powder and ethanol were added to furan resin to diminish the weight loss, to suppress the shrinkage and bending, and to readily release the gases evolved during polymerization and curing. Curing and carbonization were controlled by pressure and slow heating to avoid damage to the samples. The effect of the filler and ethanol on the fabrication process was examined by measuring the properties of the glass-like carbon, such as the specific gravity, bending strength, electrical resistivity, and microstructural change. The specific gravities of the filler-added glass-like carbons were higher than those of the ethanol-added samples because of the formation of macropores from the vaporization of ethanol during the curing and polymerization processes. Although the ethanol-added glass-like carbons exhibited lower bending strengths after carbonization than did the filler-added samples, the opposite result was observed after aging at 2,600 °C. We found that the macropores created from ethanol were contracted and removed upon heat treatment. The electrical resistivity of the glass-like carbon aged at 2,600 °C was lower than those of the samples carbonized at 1,000 °C. We attribute this phenomenon to the fact that aging at high temperature led to well-developed microstructures, the removal of macropores, and the reduction of the surface area.

**Keywords:** glass-like carbon, mechanical properties, electrical properties.

### Introduction

Glass-like carbons have been developed as commercially available products in the early 1960's under the designations of "Glassy Carbon" and "Vitreous Carbon".<sup>1-4</sup> Fractured surfaces are glass-like in appearance. The glass-like carbons, which can be obtained from the pyrolysis of diverse materials such as cellulose, phenolic resins, polyfurfuryl alcohol, and polyvinylidene chloride, are well known for their structural stability at high temperature.<sup>3,5-7</sup> This high temperature structural stability displays a strong resistance against graphitization and crystallite growth.<sup>3,9,10</sup> Even though the preparation process is undoubtedly different, glass-like carbons from various sources represent similar characteristics.<sup>3,8</sup> Glass-like carbons are widely used for aerospace, medical,

chemical and semiconductor industries,<sup>5,11-18</sup> which require various physical properties such as low density, closed porosity, thermal stability, impermeability of gases and liquids, and electrical conductivity including glass-like isotropic properties.

Although glass-like carbon artifacts can be obtained in complex shapes, the fabrication of monolithic glass-like carbon presents two processing restrictions. Firstly, the thickness of the artifact limits the heating rate to a critical value in order to avoid tensions and discontinuity in the final material.<sup>11</sup> Mesopores and macropores, secondly, are created during the resin cure. These are caused by the trapping of the decomposition products released during carbonization.<sup>11,19,20</sup> In order to overcome these restrictions, fillers are added to fabricate glass-like carbon, resulting in effectiveness to diminish weight loss, to suppress shrinkage, and to release the gases evolved at the polymerization and curing stages.<sup>21</sup> Very fine natural graphite powders are generally used as

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ordinary filler material.<sup>1,21</sup> However, since the natural graphite is not well mixed with the furan resin, the graphite material as filler tends to deteriorate the properties of glass-like carbon. This problem is overcome if the graphite particles are carefully blended under vacuum capable of removing trapped gases.<sup>21</sup> In other words, the ultimate performance and the properties of the glass-like carbon are mainly influenced by material processing which often involves the addition of fillers.

In this study, a cured furan resin was chosen as a filler material for fabricating glass-like carbon composite, instead of natural graphite that deteriorates the properties of glass-like carbon properties. Ethanol was used as another additive to control viscosity of glass-like carbon during fabrication. The cured furan resin filler and/or ethanol were added to furan resin to diminish weight loss, to suppress shrinkage and to release the gases evolved during the polymerization and curing. The effects of the cured furan filler and/or ethanol on physical properties of fabricated glass-like carbon were investigated using several characterizing tools. The evaluations of the glass-like carbons were carried out every fabrication process, *i.e.*, polymerization, curing, carbonization, and aging at 2,600 °C. The relation of microstructural changes of the glass-like carbons, such as pore distribution and crystalline characteristics, to addition of filler/ethanol were found as a function of heat treatment temperature.

## Experimental

**Sample Preparations.** A commercial furan resin, KC-5302 ( $M_w = 2,150$ ,  $M_n = 190$ , and viscosity at 25 °C = 170 cPs, Kangnam Chemical Co., Korea), was selected as the carbon precursor. The furan resin samples were catalyzed by adding 0.5 wt% of *p*-toluenesulfonic acid monohydrate (PTSA,  $\text{CH}_3\text{C}_6\text{H}_4\text{SO}_3\text{H}\cdot\text{H}_2\text{O}$ , Shinyo Pure Chemical Co. Ltd., Japan), and, then, homogenizing in the resin by mechanical stirring for 30 min. The catalyzed samples were poured into a borosilicate glass mold of  $\Phi 100 \times 2$  mm, and, subsequently, polymerized under a pressure of 460 kgf/m<sup>2</sup> for five days at room temperature. Curing was, then, performed at 100 °C for 96 h in a drying oven under a pressure of 460 kgf/m<sup>2</sup>.

The filler material was prepared with furan resin and PTSA

of 0.5 wt% by the same method described in the above. The cured furan resin was milled to 44  $\mu\text{m}$ .

To control the viscosity, ethanol was added to resin/PTSA and resin/PTSA/filler mixtures, and, further, mechanically stirred for 30 min at room temperature. The fabrication conditions of the samples used in this study are shown in Table I.

The resin mixed with filler only and filler/ethanol were poured into the glass molds, and placed in a drying oven at room temperature for 5 days to proceed polymerization under a pressure of 460 kgf/m<sup>2</sup>. The samples were placed in a convection oven for curing, and heated up to 100 °C at a heating rate of 0.1 °C/min under a pressure of 460 kgf/m<sup>2</sup>. The samples were held for 1 h after every 50 min during the curing step. The cured samples were removed from the glass molds for heat treatment. All of the samples were pyrolyzed in N<sub>2</sub> atmosphere by slow heating from room temperature up to 1,000 °C at a heating rate of 1 °C/min, and keeping at this temperature for 1 h. The samples were held for 1 h at each 60 °C increment in 10 steps up to 600 °C and then in a single step up to 1,000 °C to give sufficient time for releasing the gases formed during carbonization. The samples were buried into fine coke particles under a N<sub>2</sub> flow of 500 mL/min during carbonization, and, finally, aging was performed at 2,600 °C for 1 h in Ar atmosphere.

**Characterizations of Samples.** The samples polymerized, cured, carbonized at 1,000 °C, and aged at 2,600 °C were characterized. Weight loss and shrinkage of the samples were measured using an analytical balance (0.1 mg) and calipers, respectively. An electronic densimeter (MD-200S, Mirage Trading Co. Ltd., Japan) was utilized to measure specific gravity at room temperature. Ten specimens were prepared for each sample, and the average values were reported. In order to examine the variation of crystalline characteristics at each heat treatment, X-ray diffraction (XRD,  $\lambda = 1.542 \text{ \AA}$ , XD-D1, Shimadzu Corporation, Japan) on the powders of the samples was carried out. The (002) diffraction profiles from high purity silicon powder were used as an internal standard. The sub-surface of the sample was observed at the acceleration voltage of 20 kV using a scanning electron microscopy (SEM, Hitachi S-3500N). Each sample obtained at each heat treatment stage was cut into small pieces of 5 mm  $\times$  5 mm with low speed diamond saw, and burned-off

**Table I. Fabrication Conditions for Glass-like Carbon Samples Used in This Study**

Series	Symbol	Sample Fabrication Condition
F	F0	Furan Resin + PTSA 0.5 wt% + Filler 0 wt%
	F5	Furan Resin + PTSA 0.5 wt% + Filler 5 wt%
	F10	Furan Resin + PTSA 0.5 wt% + Filler 10 wt%
EF	EF0	Furan Resin + PTSA 0.5 wt% + Ethanol 10 wt% + Filler 0 wt%
	EF5	Furan Resin + PTSA 0.5 wt% + Ethanol 10 wt% + Filler 5 wt%
	EF10	Furan Resin + PTSA 0.5 wt% + Ethanol 10 wt% + Filler 10 wt%

for 10 sec. The samples were coated with Pt/Pd alloy. In order to measure the porosity of the samples, the images observed were analyzed through image processing (Image-Pro Plus, Version 4.5, Copyright 2001 Media Cybernetics, Inc., Carlsbad, California). Three point bending tests were performed over the samples of 30 mm span at room temperature under a crosshead speed of 40 mm/min using an Instron (PGD-IIR, Marubishi Scientific Instrument MFG Co., Japan). The dimensions of the samples were  $40 \times 10 \times 1.2$ – $1.5$  mm. Five specimens were tested for each sample. Electrical resistance was measured using a digital multimeter (34401A Multimeter, Hewlet Packard, U.S.A.) using four probe method. The samples carbonized and aged at  $2,600^\circ\text{C}$  were tested, respectively, to verify the variation of electrical resistance.

## Results and Discussion

### Weight Loss, Shrinkage and Density Measurements.

Table II represents variation of the weight loss of the samples measured after each heat treatment process. The weight losses were calculated with the ratio of reduced weight with respect to initial weight. The weight of the sample F0 decreased to 13.7% during the polymerization, whereas the sample F10 showed the weight loss of 10.6%. At curing step, the weight losses of the samples F0 and F10 were 22.2 and 15.5%, respectively. It indicates that the addition of filler reduced the weight loss after the polymerization and curing. In the case of the EF series of samples, the weight losses, overall, were greater than those of the F series of samples. Such results are due to the evaporation of ethanol in the EF series of samples during the polymerization and curing. Meanwhile, the weights of the samples EF0 and EF10 were reduced by 22.3 and 17.5% after the polymerization, and by 29.4 and 21.7% after curing, respectively. From these results, it was found that the addition of filler led to the reduction of the weight loss in the EF series of samples during the polymerization and curing as represented in the F series of samples. Among the consecutive heat treatment steps, the largest weight loss in both series of samples took place during the carbonization where the organic compounds presenting in the furan resin were decomposed. The weight losses of the samples F10 and EF10 with 10% of

filler, measured after carbonization, were lower than those of the samples F0 and EF0 without filler. Moreover, while the difference in weight loss between the samples F10 and F0 was 3.1%, it was 4.4% between the samples EF10 and EF0. Unlike the curing, the carbonization reduced the difference in the weight loss of the samples. It is attributed to the fact that the cured furan resin used as fillers was thermally decomposed during the carbonization. Therefore, the use of a cured furan resin as filler may not be an effective way to fabricate the glass-like carbon providing the higher yield after carbonization process. During the aging at  $2,600^\circ\text{C}$ , the weight loss in both series of samples was about 0.3%. This small weight loss is due to the decomposition of residual hydrogen contained in the carbonized samples.

The linear shrinkages of the samples after the consecutive heat treatment process are varied as shown in Table III. The linear shrinkage measured by calipers was dependent upon the temperature of heat treatment rather than the addition of filler and/or ethanol. Addition of filler at the F series sample reduced the linear shrinkage of about 0.3% in the curing step. EF series of samples, which were added with a filler and ethanol, showed the lower linear shrinkage than F series of samples in curing step. Similar to the change of the weight loss, the linear shrinkage significantly increased with the carbonization process. Furthermore, the carbonization gave rise to somewhat larger linear shrinkage in the EF series of samples, compared to the F series of samples. The lengths in all the samples aged at  $2,600^\circ\text{C}$  were negligibly varied in the range of experimental errors of 0.01%, implying that the

**Table III. Linear Shrinkage of Samples after Consecutive Heat Treatments**

Series	Sample	After Curing (%)	After Carbonization (%)	After HTT at $2,600^\circ\text{C}$ (%)
F	F0	2.39	21.97	21.97
	F5	2.13	21.57	21.56
	F10	1.94	21.80	21.80
EF	EF0	1.89	21.88	21.87
	EF5	1.82	21.78	21.77
	EF10	1.74	21.76	21.77

**Table II. Weight Losses of Samples after Consecutive Heat Treatments**

Series	Sample	After Polymerization (%)	After Curing (%)	After Carbonization (%)	After HTT at $2,600^\circ\text{C}$ (%)
F	F0	13.7	22.2	53.7	54.0
	F5	11.9	16.9	51.2	51.5
	F10	10.6	15.5	50.6	51.0
EF	EF0	22.3	29.4	58.8	59.2
	EF5	19.2	22.8	54.8	55.1
	EF10	17.5	21.7	54.4	54.7

length of the sample did not change even after heat treatment at 2,600 °C.

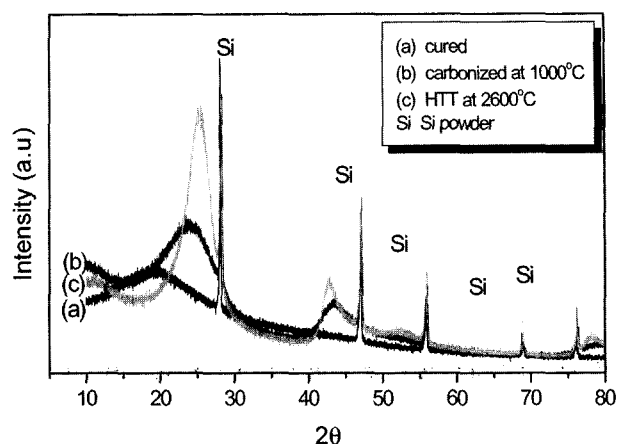
Table IV shows the specific gravities of the samples varied as the consecutive heat treatment proceeds. After the curing process, the EF series of samples exhibited most likely lower specific gravities than the F series of samples. It is known that the specific gravity of the cured sample is closely related to the porosity, which was dependent upon the viscosity of resin systems.<sup>11</sup> This is due to the fact that the sample with lower viscosity favors the easy release of the volatile products at the beginning of the polymerization reaction. Such low viscosities of the samples were accomplished by adding the ethanol to the resin/PTSA and resin/PTSA/filler mixtures to prepare the EF series of samples in this study. Fine bubbles dispersed in the mixtures were not suppressed during polymerization, because their size was too small. In spite of the carbonization and aging at 2,600 °C, the bubbles were not completely removed and/or suppressed. As a result, the bubbles were remained as pores in the interior of the glass-like carbon.

On the other hand, the specific gravity increased in the samples F10 and EF10 with the addition of 10% of the filler. It is likely that the filler affected the reduction of the bubbles in the mixture after the curing process. The interface of filler and resin in the mixture, presumably, worked as a channel facilitating escape of the gas bubble during the polymerization and curing. The abrupt improvement of the specific gravity of the samples carbonized was also shown in Table IV. This seems to arise from the shrinkage occurred during carbonization that depends upon the decomposition of resin. The further linear shrinkage was not taken place with the aging at 2,600 °C (see Table III), and, accordingly, the specific gravity did not change at the same stage.

**X-ray Diffraction and SEM Measurements.** The crystalline characteristics of the samples varied with the consecutive heat treatment were examined using X-ray diffraction. Although several reflections appeared in all the samples (Figure 1), the present study has analyzed the peak reflecting from the (002) planes. The comparison of other reflections was not only improper from the unclear peak shape, but,

**Table IV. Specific Gravity of Samples after Consecutive Heat Treatments**

Series	Sample	After Curing (g/cm <sup>3</sup> )	After Carbonization (g/cm <sup>3</sup> )	After HTT at 2,600 °C (g/cm <sup>3</sup> )
F	F0	1.27	1.49	1.49
	F5	1.27	1.50	1.50
	F10	1.29	1.51	1.51
EF	EF0	1.24	1.47	1.48
	EF5	1.24	1.48	1.49
	EF10	1.27	1.48	1.49



**Figure 1.** X-ray diffraction profiles of glass-like carbons after the consecutive heat treatment.

with the consideration of (002) reflection only, it is also enough to explain how crystalline structure of the glass-like carbon develops. Curve-fitting by Microcal Origin, Version 6.0 was carried out to obtain the interplanar spacing of (002) reflection,  $d_{(002)}$ , and the full width at half maximum (FWHM) representing the correlation length of (002) planes. Table V shows how  $d_{(002)}$  in the samples with the heat treatment was altered, whereas Table VI does the variation of the FWHM. Based on the Figure 1 and Tables V and VI, with an increase

**Table V. Change of  $d_{002}$  Measured after the Consecutive Heat Treatments**

Series	Sample	After Curing (Å)	After Carbonization (Å)	After HTT at 2,600 °C (Å)
F	F0	4.643	3.799	3.468
	F5	4.643	3.721	3.468
	F10	4.592	3.721	3.463
EF	EF0	4.626	3.810	3.452
	EF5	4.642	3.810	3.485
	EF10	4.432	3.678	3.463

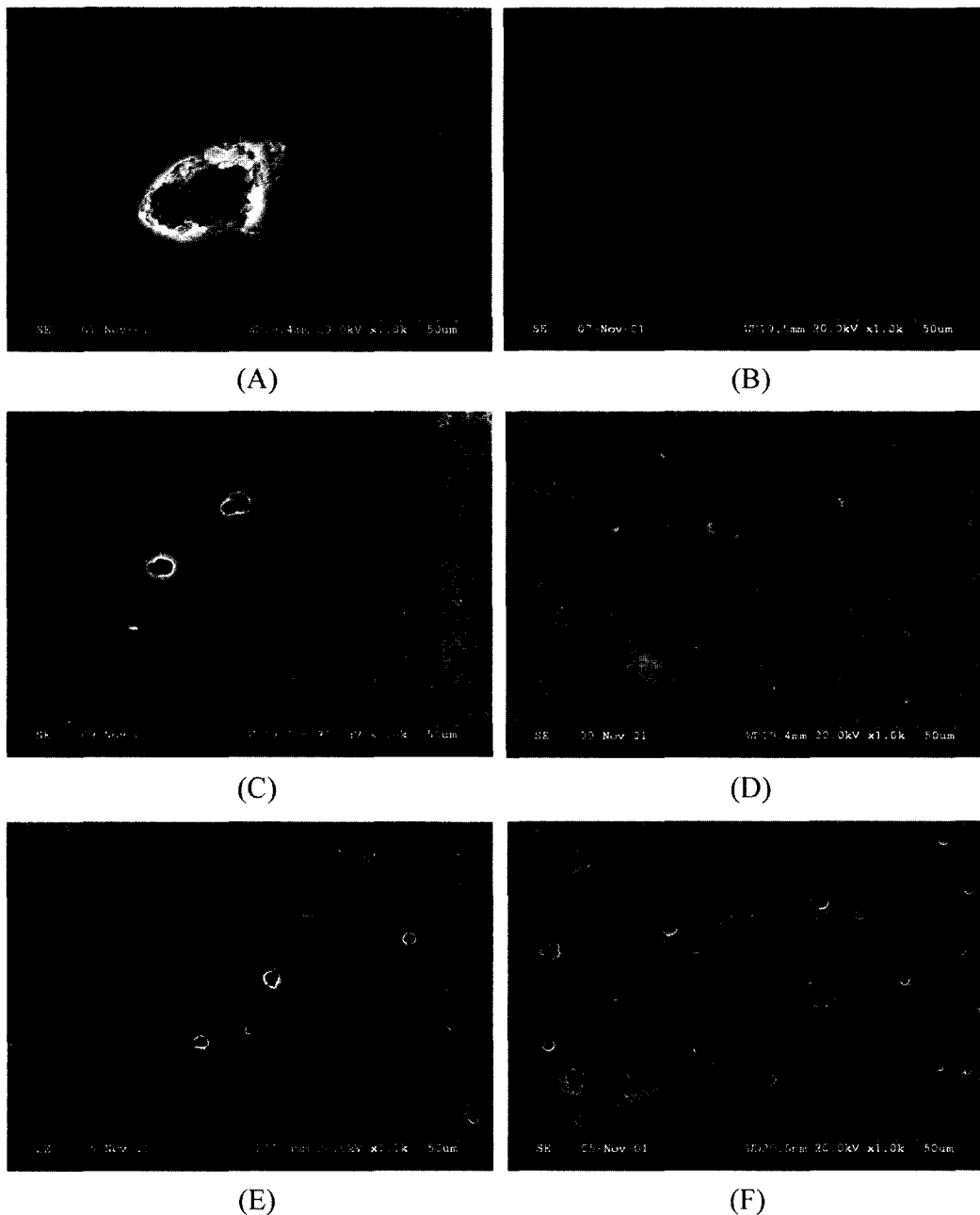
**Table VI. Change of Width at (002) Peak Measured after the Consecutive Heat Treatments**

Series	Sample	Cured (degree)	Carbonized (degree)	HTTed at 2,600 °C (degree)
F	F0	6.348	3.575	2.649
	F5	6.385	4.321	2.646
	F10	5.531	5.207	2.663
EF	EF0	5.879	5.189	2.503
	EF5	6.470	5.719	2.643
	EF10	5.299	5.812	2.636

of the heat treatment temperature, the (002) reflection from the fabricated glass-like carbon gradually becomes sharper with simultaneous shift to a higher angle, *i.e.*, decrease of  $d_{(002)}$ . The integrated intensity, apparently, increased with the temperature of the heat treatment. The decrease of  $d_{(002)}$  implies the development of compact periodic registry, whereas the sharpness of the XRD peak represented as the FWHM indicates the development of crystalline structure in glass-like carbons. From the change of integrated intensity, the volume of the crystal-like materials has increased inside

the glass-like carbon as heat treatment proceeds. The crystallinity of the samples, unfortunately, could not be measured, because the broadness of the peak is far from the crystalline materials as seen in Figure 1. However, it is clear that the development of the crystalline structure in the glass-like carbon proceeds with the consecutive heat treatment. These affected variation of specific gravity and bending strength of the samples to be explained in the later part.

Figure 2 is SEM photographs representing the distribution of the internal pores at sub-surface of the samples F10 and



**Figure 2.** SEM observation of sub-surface of the samples cured, carbonized and aged at 2,600°C. (A) Cured F10, (B) cured EF10, (C) carbonized F10, (D) carbonized EF10, (E) heat treated F10 at 2,600°C, and (F) heat treated EF10 at 2,600°C.

EF10 cured, carbonized and aged at 2,600°C. As a matter of fact, the samples were burned off for 10 sec because the pores were not observed near surface. For the sample F10, the pores in the range of 25-30  $\mu\text{m}$  after curing were reduced to 3-6  $\mu\text{m}$  after carbonization. The heat treatment at higher temperature improved the number of pores, but the size of pores decreased. The sample EF10 exhibits a smaller pore of about 20  $\mu\text{m}$  in comparison to the sample F10 with about 25-30  $\mu\text{m}$  after curing (Figures 2(A) and 2(B)). After carbonization, the sizes of internal pores in both samples were reduced. It is presumed that the bend strength of the samples abruptly increases with the carbonization. While the sample F10 has lots of internal pores with heat treatment at 2,600°C, a small number of internal pores are distributed in the sample EF10 (Figures 2(E) and 2(F)). Porosity of the fabricated glass-like carbon was measured by analyzing with SEM images. Here, the area fraction of pores was obtained, assuming that the area fraction corresponds to the volume fraction of the pores in the samples. This is a usual way to calculate the volume fraction of a special object in the two-dimensional micrograph. As shown in Table VII, the fraction of the pores abruptly decreased after the carbonization, whereas the porosity increased after at aging at 2,600°C. This implies that after heat treatment at 2,600°C, the HTTed at 2,600°C samples has lower bend strength than that of carbonized sample. Based upon the distribution of internal pores from the SEM observations, it is clearly expected that the bend strength of the carbonized samples should abruptly increase, and, further, the heat treatment at 2,600°C lead to the lower bend strength of the sample F10 than the sample EF10.

The results from XRD and SEM measurements confirmed the change in the specific gravity of the glass-like carbons undergoing heat treatment. From X-ray scattering profiles shown in Figure 1, the apparent crystallinity of the samples increased with heat treatment temperature. It corresponds to the continuous increase of the specific gravity with the development of the crystalline structure of the glass-like carbon. At this point, it should be reminded that the specific gravity was significantly improved with the carbonization, while the change in specific gravity was negligible after aging at 2,600°C. The improvement of specific gravity in the carbonized sample is really due to the development of

crystalline structure of glass-like carbon as well as the reduction of porosity inside samples. In spite of the improvement of the apparent crystallinity, however, the specific gravity did not increase with heat treatment at 2,600°C. This phenomenon is attributed to the slight increase of porosity after heat treatment at 2,600°C (see Table VII). The crystallization caused to increase the specific gravity, whereas the creation of the internal pores reduced the specific gravity. The more accurate measurement of crystallinity and porosity may provide the way to improve and/or reduce the specific gravity through heat treatment.

**Three-point Bending Strength.** Table VIII shows the variation of three-point bending strength in the samples undergoing the consecutive heat treatments, and the results are in accordance with the internal pore distribution shown in Table VII and Figure 2. The bending strength was highest in the samples carbonized, and, subsequently, reduced with the aging at 2,600°C. This implies that the strength of glass-like carbons was affected by the existence of pore: the narrower distribution of the small pores provides the better mechanical properties of glass-like carbons. In the cured samples, the bend strengths of the EF series of sample was, in overall, higher than those of the F series of sample without ethanol. This is due to the fact that the porosity, as shown in Table VII and Figure 2, was lowered with the reduced viscosity of the resin mixture by the addition of ethanol. That is, the addition of filler caused the bending strength to be lowered by means of the increase of the porosity in the cured sample.

For the carbonized samples, the addition of both ethanol and filler provoked a significant decrease of the bending strength in the EF series of samples, compared to the F series of samples. During carbonization, the F series of samples showed the larger increase in the strength than the EF series of samples; the strength of the F and EF series of samples increased by 44-61 MPa and 22-37 MPa, respectively. This indicates that the ethanol plays an important role as pore creator during the carbonization. After heat treatment at 2,600°C, the EF series of samples, in contrast, showed higher strength than F series of samples, since the

**Table VII. Porosity of the Samples Measured through Image Processing after the Consecutive Heat Treatments**

Sample	Cured (%)	Carbonized (%)	HTTed at 2,600°C (MPa)
F0	5.6	0.9	2.1
F10	7.8	1.2	2.5
EF0	4.7	0.8	1.5
EF10	4.4	1.2	1.8

**Table VIII. Bending Strength after the Consecutive Heat Treatments**

Series	Sample	Cured (MPa)	Carbonized (MPa)	HTTed at 2,600°C (MPa)
F	F0	138.5	182.5	151.2
	F5	130.6	181.8	133.4
	F10	113.9	175.1	121.7
EF	EF0	146.1	183.1	173.9
	EF5	136.2	171.1	160.4
	EF10	134.2	156.2	131.8

**Table IX. Electrical Resistivity of Samples after Various Heat Treatments**

Series	Sample	Carbonized ( $\mu \cdot \Omega\text{m}$ )	HTTed at 2,600°C ( $\mu \cdot \Omega\text{m}$ )
F	F0	73.3	42.3
	F5	68.1	42.9
	F10	69.1	41.4
EF	EF0	74.0	42.7
	EF5	77.3	37.0
	EF10	79.2	42.8

EF series of samples have relatively smaller pores and lower porosity, and well-distributed pores, compared to the F series of samples. In a consequence, the size of pores and their porosity were directly related to the variation of the strength of brittle materials.

**Electrical Resistivity Measurement.** Table IX represents the variation of the electrical resistivities of the samples obtained after carbonization and heat treatment at 2,600°C. The EF series of samples had higher electrical resistivity than that of F series samples after carbonization. It is likely that the higher electrical resistivity in the EF series is due to the pores introduced by the addition of ethanol in the resin, since the electrical resistivity is proportional to the amount of macropores.

The electrical resistivity should increase with the heat treatment at 2,600°C due to the increase of the porosity (Table VII). Nonetheless, the lower electrical resistivity appeared in the glass-like carbon aged at 2,600°C rather than in the carbonized sample. The high temperature heat treatment at 2,600°C has, probably, induced well-developed microstructure, removal of micropores, and reduction of surface area. The insignificant increase of the porosity, in addition, does not tend to affect the change of the electrical resistivity. At any rate, the electrical resistivity after heat treatment at 2,600°C was almost similar, except for the sample EF5, implying that the F and EF series of the glass-like carbon samples may have almost the similar microstructure after the heat treatment at 2,600°C.

## Conclusions

The samples, prepared with addition of filler and/or ethanol, were polymerized, cured, carbonized, and finally aged at 2,600°C. The glass-like carbons were sampled out of each heat treatment, and their properties were measured. The addition of filler reduced the weight loss of the samples after polymerization and curing, and, further, carbonization caused a dramatic weight loss in both F and EF series of samples. The weight losses, overall, were greater in EF series of samples, resulting from the evaporation of ethanol in the

EF series of samples during polymerization and curing. Similar to the change of the weight loss, the linear shrinkage significantly increased with carbonization process. Furthermore, the carbonization gave rise to somewhat large linear shrinkage in the EF series of samples. Significant change in specific gravity was observed upon 10% addition of filler during curing for the F and EF series of samples. It is presumed that the interface between filler and resin mixture worked as an escape channel of the gas bubbles during curing. For the samples carbonized and aged at 2,600°C, however, the specific gravity was not affected by the filler addition. Adding ethanol to the resin mixtures decreased the viscosity, and influenced the release of the volatile products at the beginning of the polymerization reaction. The bubbles were still maintained in the resin mixture, and were not suppressed even after polymerization, since their size was too small. The bend strength and electrical resistivity of the glass-like carbons were higher in the samples carbonized rather than the samples aged at 2,600°C, resulting from the increase of the porosity during heat treatment at 2,600°C. In a consequence, the properties of the glass-like carbons were significantly related to existence of pores and development of crystalline phase, and, thus, it is suggested that the two factors should be controlled to manufacture the glass-like carbon adapted to demand in a circumstance.

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