Effects of Specimen Size on The Flexural Strength and Weibull Modulus of Nuclear Graphite

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1. Introduction

Flexural strength and the Weibull modulus of porous graphite are key material data for the design, and safety and lifetime evaluation of VHTR graphite core components [1]. For brittle materials like graphite, it follows from the experiments that the mean strength of a set of large specimens is smaller than the mean strength of a set of small specimens since it is more likely to find a major flaw in a large than in a small [2]. This size effects of strength is the most prominent and relevant consequence of the statistical behavior of the strength of brittle materials.

Weibull was the first to develop a statistical theory of brittle fracture based on the weakest link hypothesis. Using some empirical arguments necessary to make a simple and good fitting of his experimental data he derived the Weibull distribution of the probability of failure, where the weibull parameter, m, is being used in the probabilistic methods in materials science and structure mechanics, for example, in the design and safety analysis of graphite core components in VHTR [2].

The purpose of the present study is to investigate the specimen size effects on the flexural strength and Weibull modulus of nuclear graphite of different coke particle sizes and different forming methods.

2. Experimental

2.1 Materials and specimen.

Four-point-1/3 point(4-1/3) loading flexural strength test specimens of three different sizes, i.e., 3.18 (Thick-ness) x 6.35 (Width) x 50.8 (Length), 6.50 (T) x 12.0(W) x 52.0 (L), 18.0 (T) x 16.0 (W) x 64 (L) (mm) (total: 212 specimens), were prepared from three nuclear graphite grades: IG-110, NBG-18 and PCEA differing in forming method and coke particle size.

Table 1. Summary of typical characteristics of IG-110, NBG-18 and PCEA nuclear grade graphites.

	IG-110	NBG-18	PCEA
Coke type	Petro	Pitch	Petro.
Forming method	Iso.Mold	Vib.mold	Extrusion
Ave. coke part. size	~25 ㎛	~ 300 ㎛	360 ㎛
Den. (g/cc)	1.77	1.85	1.85
Manufa.	Toyo	SGL	GrafTech

The number of specimens for each grade ranges 41 ~ 45 specimens of three different dimensions. Typical characteristics of the grades are summarized in **Table 1**. Anisotropy was considered during specimen machining for NBG-18 and PCEA: with grain (a) and against grain (c).

2. 2 Flexural test and Weibull modulus determination

Four-point-1/3 point (4-1/3) flexural tests were performed at 0.5 mm/min cross head speed at room temperature by using a screw type universal testing machine (model: Instron 5860, Load cell capacity: 30 K Newton). The Weibull modulus was calculated based on the flexural strength data obtained in the present study. To evaluate the changes in the Weibull modulus due to the specimen size (i.e., dimension) and the number of flexural strength data, the Weibull modulus was calculated three times for each grade: (1) for each specimen size of a grade, (2) for all three dimensions of a grade considering anisotropy, (3) for all flexural strength data of a grade.

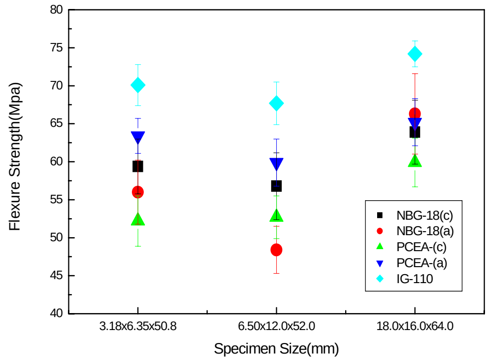
The Weibull modulus was calculated based on the flexural strength data by using the Excel program developed by Willium W. Dorner [3].

3. Results and discussion

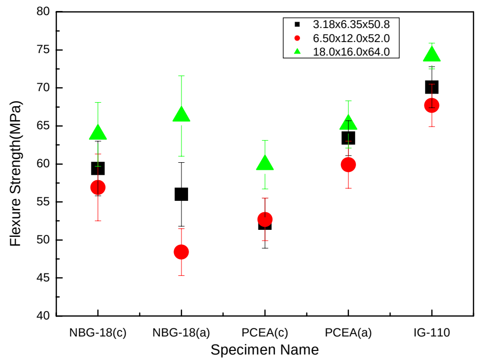
3.1 Specimen size effects on flexural strength.

Results on the specimen size effects on flexural strength can be evaluated based on the differences in specimen size and the graphite grade since the differ-ences in the particle size would affect the test results. **Figure 1 (a)** shows the former, i.e, specimen size effects, and **Figure 1 (b)** shows the latter, i.e., graphite grade effect.

Figure 1 (a) and **(b)** show that there are no large differences among the flexural strength obtained from specimens of three different sizes. Except NBG-18 (a) which shows 37% difference between the 3T and 18T, differences among the flexural strengths obtained from three sizes range 7.6 % (NBG-18(c)) ~ 15% (PCEA(c)). IG-110 (70.2 MPa) showed the highest, and the PCEA (C)(54.9 MPa) showed the lowest for all sizes except NBG-18. NBG-18 has been known to have the largest maximum coke particle size of 1600 ㎛. Even the differences are small, figure 1 (a) shows that the largest 18T appeared to show the highest, and 6T (not 3T) appeared to show the lowest strength value. If the comparatively small block size (volume) used for manufacturing the specimens, the observed non-linear volume dependency and the scattering of flexural strength may partly be attributed to the employed test loading system. It is also noted that, especially for small size specimens, the four contacts between the



(a)



(b)

Fig. 1**.** Specimen size effects on the flexural strength of IG-110, NBG-18 and PCEA nuclear grade graphites.

loading system. It is also noted that, especially for small size specimens, the four contacts between the specimen and loading fixture may accounts a large portion of the whole specimen surface area contributing to the scatter. The present observation may need further confirmation.

3.2 Specimen size effects on Weibull modulus.

Results of Weibull modulus calculation are shown in **Table 2**, where large differences in the Weibull modulus are shown among specimens of three different sizes. The differences between the largest and smallest Weibull moduli range from 9 % (NBG-18(a) ~ 48% (IG-110). Here, it is noted that the "Integrated a, c" refers to "the Weibull modulus based on all data of with-grain(a) or against-grain (c) of three different specimen sizes", and the "Integrated a + c" refers to the Weibull modulus based on all data regardless of anisotropy for each grade. **Table 2** shows that the Weibull moduli tend to decrease with an increasing number of data. The validity of the Weibull modulus obtained in the present study may be confirmed from comparisons with those obtained from standard size specimens for NBG-18, i.e., 11.24 [4] and 10 [5]. Li Hong-wei et al [4] obtained the Weibull parameter of NBG-18 as 11.24 from standard

Table 2 Specimen size effects on Weibull modulus.

Specimen dimension (mm)	NBG-18		PCEA		IG-110
	a	c	a	c	
3.18 x 6.35 x 50.8	14.5	16.2	31.9	17.9	29.1
6.50 x 12.0 x 52.0	14.0	11.5	20.9	20.5	25.0
18.0x 16.0 x 64.0	13.2	16.7	22.2	20.0	48.0
Integrated a/c	11.1	12.2	22.9	14.1	24.2
Integrated (a +c)	11.9		11.8		24.2

tensile strength experiments (DIN 51914-1985, specimen size: L:103, Dia:45.8 mm, room temperature), and SGL [5] obtained the Weibull modulus of NBG-18 as 10 from four points bending strength (ASTM C 651, DIN 51944, specimen size: Length: 110, Dia: 30 mm, room temperature). The differences between these two Weibull moduli obtained from the standard specimens and the modulus from non-standard small size specimens, i.e., 11.9 (Table 2, NBG-18, Integrated (a + c)) are 5.5 % and 16%, respectively.

4. Conclusion

Specimen size effects on flexural strength appeared grade dependent. While NBG-18 (a) showed a rather significant specimen size effects (37% difference between the 3T and 18T) with the largest relative error, the differences in IG-110 and PCEA were 7.6 ~ 15%.

In comparison to flexural strength, a large specimen size effects appeared in Weibull modulus, where, the differences range from 9 % (NBG-18(a) ~ 48%(IG-110). The Weibull moduli tend to decrease with an increasing number of strength data.

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