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Effect of Prestresses on the Fracture Behavior of Nuclear Graphites

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1. Introduction

When nuclear graphites are used for HTGR (High Temperature Gas-cooled Reactor) components, the graphite blocks are subjected to various stresses resulted from a irradiation-induced dimensional change, thermal gradient, dead weight and external loads such as an earthquake [1-2]. Consequently, in order to evaluate the integrity of a graphite block it is important to know how the mechanical properties change when the graphite materials for a HTGR are subjected to stresses. In this study, the fracture toughness and Young's modulus of two nuclear graphites, IG-110 and NBG-18, which were compressively prestressed perpendicular to the loading axis were examined.

2. Experimental

2.1 Materials and Compressive Tests

Two kinds of candidate nuclear graphite for a HTGR, IG-110 and NBG-18, were used for this study. Typical properties are summarized in Table 1. The dimensions of a test specimen were 15 mm square and 100 mm long. Based on the results of the preliminary compressive test performed at room temperature, the compressive prestresses of $0.2\sigma_c$, $0.3\sigma_c$, $0.5\sigma_c$, $0.9\sigma_c$ were applied in the longitudinal direction at the crosshead speed of 0.1mm/min using a universal testing machine of a 30kN load capacity. The specimens were kept for 10 min at the predetermined stress levels.

Table 1 Typical properties of IG-110 and NBG-18.

Grade	IG-110	NBG-18
Coke	Petroleum	Coal-tar
Manufacturing process	Iso-moulding	Vibro-moulding
Avg. grain size (μm)	10	Max. 1600
Apparent density (g/cm^3)	1.77	1.85
Porosity (%)	18	8.3
Young's modulus (GPa)	9.7	11.4

2.2 Fracture Toughness Tests

After the compressive prestressing and residual stain measurements, the square rods were notched to three point bending specimens. Fracture tests were carried out at the crosshead speed of 0.1mm/min. Fracture toughness, K_{Ic}, at the maximum load and strain energy release rate, G_I, were calculated according to the tentative ASTM fracture test method for a nuclear graphite. The Young's modulus in the transverse direction was obtained by measuring the sonic velocity of a 2.25MHz wave according to ASTM C769-98.

3. Results and Discussion

3.1 Residual Strain after Compressive Prestressing

The residual strains after the compressive prestressing are summarized in Table 2. It was observed that the residual strains are produced in the direction parallel to the loading axis and increase with the applied compressive stress for both grades.

Table 2 Residual strains of IG-110 and NBG-18 after compressive prestressing.

Grade	σ_{com} (MPa)	$\sigma_{Prestress}$ (MPa)	ΔL/L (%)
IG-110	78.5	0.2	-0.0374
		0.3	-0.0612
		0.5	-0.1157
		0.9	-0.3096
NBG-18	69.5	0.2	-0.0306
		0.3	-0.0408
		0.5	-0.0816
		0.9	-0.1463

3.2 Fracture Behaviors of Prestress-Free Specimens

It was found that the value of K_{Ic} for the prestress-free NBG-18 (1.34 MPam$^{1/2}$) is much higher than that for the prestress-free IG-110 (0.95 MPam$^{1/2}$). As shown in Fig. 1, the critical G_I is also much higher in NBG-18 (95.8 J/m^2) than in IG-110 (63.5 J/m^2) and the differences of G_I between IG-110 and NBG-18 increase with a crack extension.

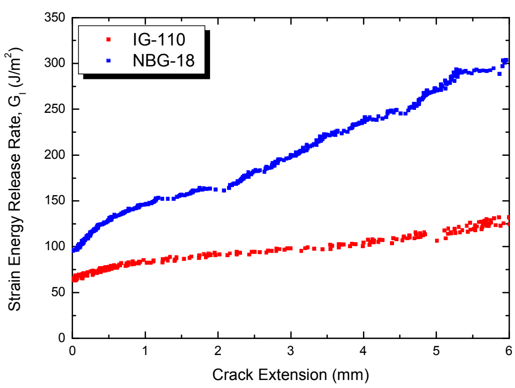

Figure 1. Strain energy release rate, G_I, curves as a function of crack extension for prestress-free IG-110 and NBG-18.

The higher values of K_{Ic} and G_I for NBG-18 compared with IG-110 may be related to the fewer inherent cracks such as pores and internal microcracks, and the higher irreversible processes occurring during cracking in a coarse microstructure [3].

3.3 Relationship between Fracture Toughness and Compressive Presress

Fig. 2 shows the change in the fracture toughness of IG-110 and NBG-18 as a function of the normalized prestress. The fracture toughness increased by about 5 % between the compressive prestress levels from $0.2\sigma_c$ to $0.5\sigma_c$, and then it decreased by about 1.2 % above the stress level.

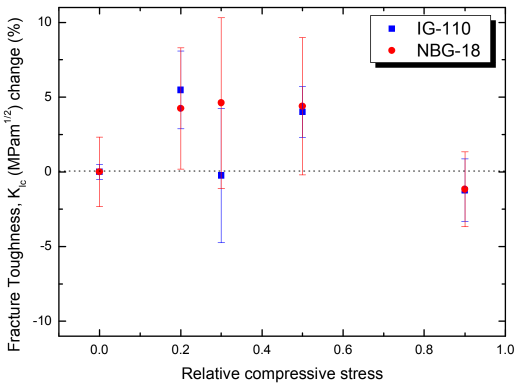

Figure 2. Relationship between fracture toughness and compressive prestress for IG-110 and NBG-18.

As shown in Fig. 3, the Young's modulus of IG-110 perpendicular to loading axis remained almost unchanged up to $0.5\sigma_c$. However, above $0.5\sigma_c$ the Young's modulus decreased by about 2.8%. It is well known that the Young's modulus of graphites decreases with increasing prestress level [4].

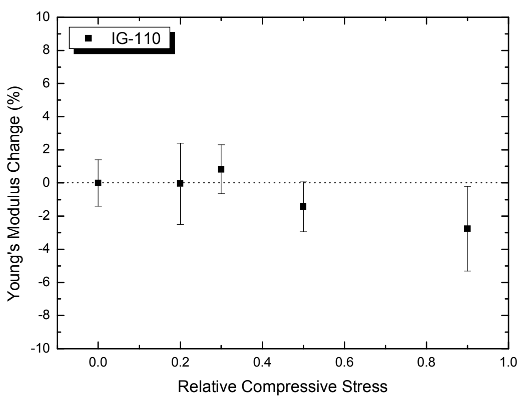

Figure 3. Relationship between Young's modulus and compressive prestress for IG-110 perpendicular to prestress axis.

When a compressive stress is applied and then removed, it is expected that the inherent pores or microcracks in the filler grains whose basal planes are nearly perpendicular to the loading axis will remain closed or shrunk since the filler grains are surrounded by the compressively deformed grains. In the case of filler grains whose basal planes are parallel to the loading axis, delamination between the basal planes is expected to occur easily since lateral plastic flow around the grains results in a resolved tensile stress applied at the planes. However, it is difficult for the grains to deform plastically since the resolved shear stress in a grain is even small [5].

It is expected that the closure or the shrinkage of the inherent pores and microcracks in perpendicular direction to crack propagation could decrease the region where crack initiation occurs and increase the resistance against the crack propagation up $0.5\sigma_c$. Above $0.5\sigma_c$, the decrease in the fracture toughness corresponds to the increase in the microcracks formed by a prestress which are enough to make the specimen fracture easily.

3. Conclusion

Changes in the fracture toughness and Young's modulus in the direction perpendicular to a compressive prestress axis were measured for IG-110 and NBG-18. The residual strain increased with an increase in the compressive prestress in both graphites. The Young's moduli of IG-110 remained unchanged up to $0.5\sigma_c$ and then decreased above this stress level. The fracture toughness perpendicular to compressive prestress axis increased with compressive prestress up to $0.5\sigma_c$ and then it decreased above this stress level. The effects of prestress on the fracture behavior can be attributed to the closure or shrinkage of the inherent pores or microcracks and the formation of microcracks parallel and nearly perpendicular to the loading axis.

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