A STUDY ON THE IRRADIATED STRENGTH AND STRESS EVALUATION OF NUCLEAR GRAPHITE MATERIAL

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ABSTRACT

In this study, the isotropic graphite IG-110 of Toyo Tanso was investigated. Shore hardness test, compressive test, bending test and fracture toughness test were conducted. Compressive test, bending test and fracture toughness test were performed by MTS- 810. Test velocity of compressive and bending test were 0.5 mm/min and fracture toughness test were 0.1 mm/min. The results were compared with manufacturer data of Toyo Tanso. Through irradiation test using HANARO research reactor, hardness and strength of nuclear graphite IG-110 was examined. Generally, strength and hardness of irradiated steel is higher than non-irradiated it. But nuclear graphite IG-110 declined unlike steel. To search for characteristic change of nuclear graphite IG-110 under the amounts of neutron, Once again the experiment changed amounts of neutron was conducted.

INTRODUCTION

Nuclear graphite has a good thermal conductivity, high melting point, high chemical stability, and with excellent resisting on both irradiation and corrosion. It is chemically inert, highly conductive, and resistant to corrosion, is easily machined, and has good mechanical properties at high temperature, graphite has been used widely in reactors. Nuclear graphite also has a superior ability to withstand neutron investigation than any other metal or ceramic materials. The graphite is used as a moderating material, a structure material, a reflector material and a fuel element matrix material.

Kim[1] and Koo[2] studied thermal shock fracture toughness for graphite. Han[3] studied the fracture characteristics of nuclear graphite IG-110. Cho [4,5] studied oxidation behavior under surface roughness and the influence of specimen geometry under oxidation behavior of nuclear graphite. Kim[6,7] studied development of oxidation model and test and reaction between nuclear graphite IG-110 and carbon oxides. Chi[8] studied oxidation and graphitization of nuclear graphite IG and NBG series. Shibata[9] studied non-destructive evaluation method of IG110 and IG-430 for loss. Joyce[10] studied microscopic deformation and damage observation of nuclear graphite. Babout[11] studied three-dimensional characterization and thermal property modeling of nuclear graphite. Srinivasan[12] studied expectation of fracture possibility of nuclear graphite. Fuller[13] studied a reaction of air and kinetic structure of nuclear graphite IG-110. These studies help to forecast accident during reactor operation. In this study, hardness test, compressive test, four point bending test and fracture toughness test of isotropic graphite IG-110 were conducted. Irradiation test was conducted to find a characteristics as well as non-irradiated test. Furthermore to search for characteristic change of nuclear graphite IG-110 under the amounts of neutron, Once again a experiment to change amounts of neutron was conducted.

NON-IRRADIATED TESTS OF NUCLEAR GRAPHITE MATERIAL

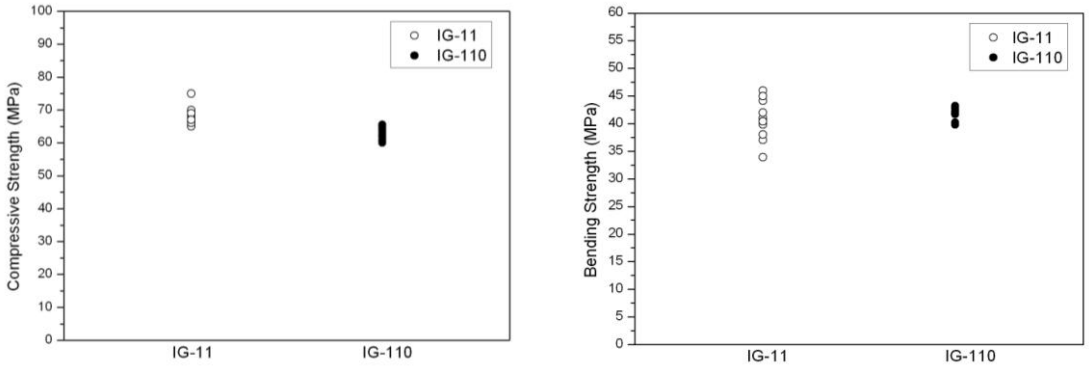
Properties comparison of graphite IG-11 with IG-110

The material properties of graphite IG-11 and IG-110 are shown in Table I. These have brought to this place by ToyoTanso[14] was investigated. The material property of IG-110 is good against IG-11. Because of IG-110 is upgraded to get to high purity by specific tempering. Typically, IG-110 is more used than IG-11 in reactor. The material properties of isotropic graphite IG-110 get the density of 1.78 g/cm^3, Young's modulus of 8.93 GPa, Shore hardness of 51, bending strength of 37.4 MPa and compressive strength of 76.8 MPa. To compare with IG-11

and compressive strength of IG-110 and four points bending test was conducted. IG-110 has almost constant value of compressive strength and bending strength unlike IG-11 as shown in Fig. 1. Here the IG-110 is only for this study.

Table 1: Properties of Nuclear Graphite IG-11 and IG-110.[14]

Material	Density (g/cm^3)	Hardness Shore	Bending Strength (MPa)	Compressive Strength (MPa)	Tensile Strength (MPa)	Young's Modules (MPa)
IG-11	1.77	51	39	78	25	9.8
IG-110	1.76	51	37.4	76.8	25	8.93



(a) Compressive strength (b) bending strength

Fig. 1 The test results of graphite IG-11 and IG-110

Hardness Test

In order to measure the shore hardness of graphite IG-110, shore hardness tester of Japan SATO was used. The cylindrical specimens with 26 mm diameter and 6mm length were prepared. And the test was done with 10 specimens.

Compressive Test

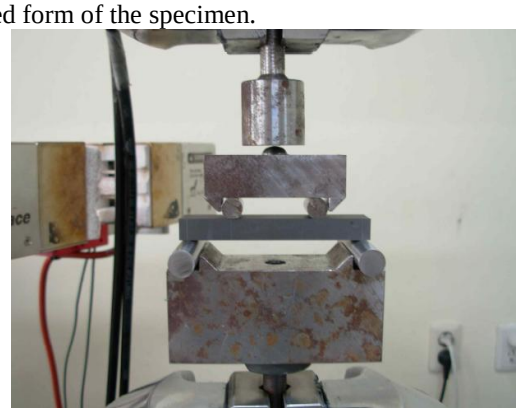
In order to measure the compressive strength of graphite IG-110, the cylindrical specimens along ASTM C695-91[15] standard with 19 mm diameter and 38 mm length were prepared. Fig. 2 (a) shows the isotropic graphite mounted in the load frame for testing using the MTS-810. Each test spent 3 minutes and in order to prevent the specimen to spring out using the thick paper wrap the specimen. Fig. 2 (b) shows the fracture form of the specimen. The tests were done with 10 specimens.

(a) Compressive specimen mounted MTS-810. (b) Fracture shape of graphite IG-110

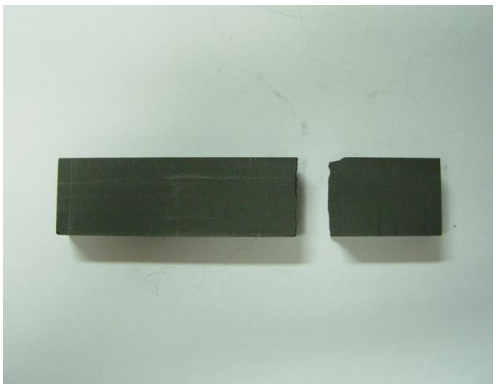
Fig. 2 Compressive test using MTS-810.

Bending Test

In order to measure the bending strength of graphite IG-110 four point bending test was done. According to ASTM C651-91[16] standard, the beam specimens with 90 mm length, 20 mm width and 10 mm thickness were prepared. Span gap was 82 mm Fig. 3 (a) shows the mounted IG-110 specimen in the load frame under four point bending test. Test velocity was 0.5 mm/min and after 2 minutes the specimen was fractured. Fig. 3 (b) shows the fractured form of the specimen.



(a) Four points bending test using MTS-810.



(b) Fracture shape of graphite IG-11 and IG-110

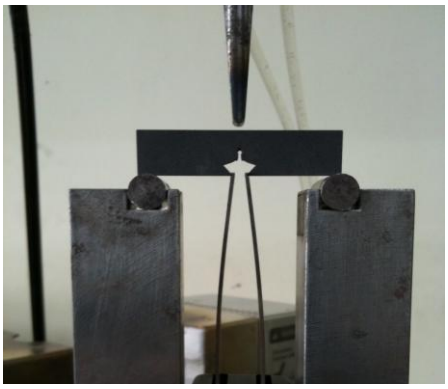
Fig. 3 bending test using MTS-810.

Fracture toughness test

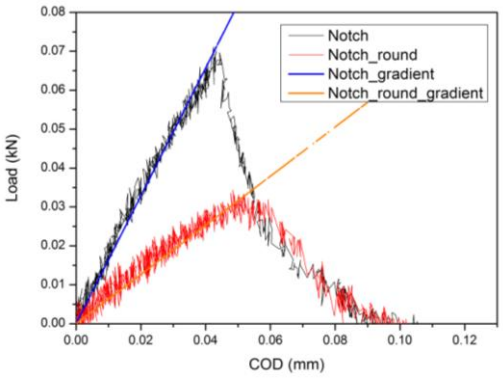
In order to measure the fracture toughness of graphite IG-110, three point bending specimens are prepared. The tests were done 10 times using COD gage and MTS-810 having displacement control 0.1mm/min speed according to ASTM E399[17] standard as shown in Fig. 4 (a). Fracture time was faster than four points bending because three points bending specimens have notch. Fig. 4 (b) shows the peaked load point under displacement. Fracture toughness was calculated using equation (1) which is selected by load-displacement. These have average 0.90 MPa $m^{1/2}$

$$K_Q = \left(\frac{P_Q S}{B W^{\frac{3}{2}}} \right) f\left(\frac{a}{W} \right)$$

$$f\left(\frac{a}{W} \right) = \frac{3\left(\frac{a}{W} \right)^{\frac{1}{2}} \left[1.99 - \left(\frac{a}{W} \right)\left(1 - \frac{a}{W} \right)\left(2.15 - \frac{3.93a}{W} + \frac{2.7a^2}{W^2} \right) \right]}{2\left(1 + \frac{2a}{W} \right)\left(1 - \frac{a}{W} \right)^{\frac{3}{2}}} \quad \text{.....(1)}$$



(a) Three point bending test of IG-110 graphite by MTS-810.



(b) Result of three point bending fracture toughness test.

Fig. 4 fracture toughness test results.

Table 2: Fracture toughness value under variation specimen thickness using FEM

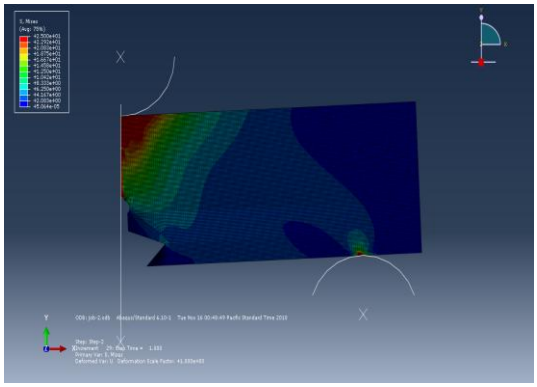
Width (mm)	Load (kN)	Fracture toughness, K_{IC} (MPa $m^{1/2}$)
5	0.072	1.20
6.35	0.091	1.19
10	0.143	1.19
15	0.215	1.19

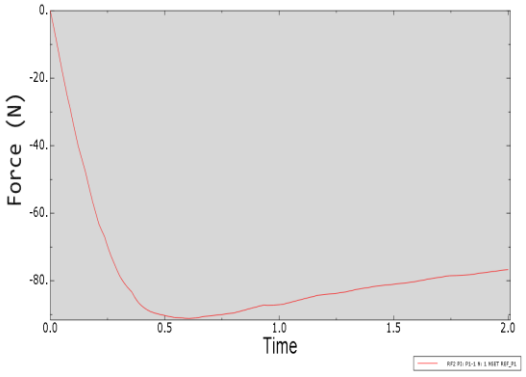
Jang[18] was studied the difference of fracture toughness under specimens thickness change of nuclear graphite IG-11. To simulate the experimental results of test a finite element analysis is carried out using commercial program ABAQUS. A two-dimensional mesh composed of 1135 eight-node elements and 3732 nodes is built as shown in Fig. 5 (a) and the material properties E = 8.93 MPa, ρ = 1.76 g/cm^3 and Poisson'ratio ν = 0.29 are input. The solution from ABAQUS is given in Table 2, which are in good agreement with the measured results of test. To seek for a reaction force, the punch moved down along vertical direction and the results as shown in Fig. 5 (b)

In order to measure the fracture toughness of graphite IG-110, the 10 CT specimens along ASTM E399 standards were prepared as well as above the test. Fig. 6 (a) shows the specimen shape and Fig. 6 (b) shows the test results. The test was used by MTS-810 of 0.1 mm/min speed. The equation (2) was used to calculate the fracture toughness for CT specimen. Fig. 6 (a) shows test by MTS-810. Fig. 6 (b) shows the fracture toughness graph of displacement-load. Using equation (2) in this graph the value of the fracture toughness was 0.85 $MPa^{1/2}$ among 10 data.

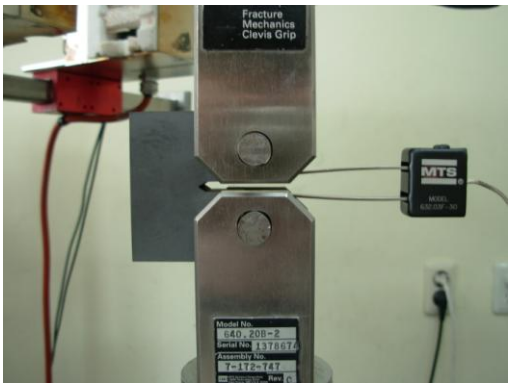
$$K_Q = \left(\frac{P_Q}{BW^{\frac{1}{2}}}\right) f\left(\frac{a}{W}\right)$$

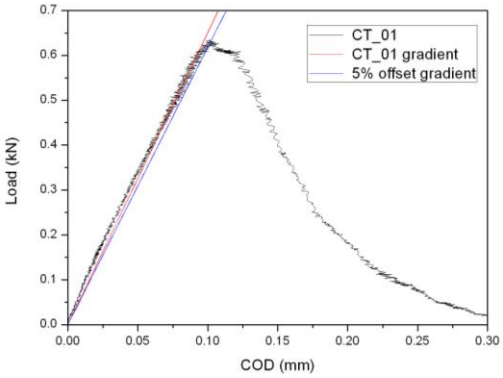
$$f\left(\frac{a}{W}\right) = \frac{\left(2+\frac{a}{W}\right)\left(0.886+\frac{4.64a}{W}-\frac{13.32a^2}{W^2}+\frac{14.72a^3}{W^3}-\frac{5.6a^4}{W^4}\right)}{\left(1-\frac{a}{W}\right)^{\frac{3}{2}}} \quad \text{.....(2)}$$





(a) Simulation result with width 6.35 mm. (b) Reaction force of punch specimen with 6.35 mm width.
Fig. 5 simulation using ABAQUS.





(a) CT test of IG-110 graphite by MTS-810. (b) Result of CT fracture toughness test.

Fig. 6 Fracture toughness test using CT specimen.

IRRADIATED TESTS OF NUCLEAR GRAPHITE MATERIAL

In order to neutron irradiation test of graphite IG-l10, the eight cylindrical compressive specimens with 7 mm diameter and 14 mm length and the six cylindrical Shore hardness specimens with 15 mm diameter and 8 mm length were prepared. Four compressive specimens and three hardness specimens were neutron irradiated at LH irradiation test hole with 1.42~5.52 x l0^-7 mrem/hr and 24 days. Fig. 7 (a) shows the nuclear graphite IG-ll0 before neutron irradiation and Fig. 7 (b) shows loaded in the capsule 10M-25U made of aluminum. These irradiated specimens were tested by IMEF(Irradiated Materials Examination Facility) in HANARO research reactor.

(a) Graphite specimens IG-110 for irradiation test. (b) Graphite specimens IG-110 loaded in the capsule 10M-25U.

Fig. 7 nuclear graphite IG-110 for neutron irradiation

Shore hardness test

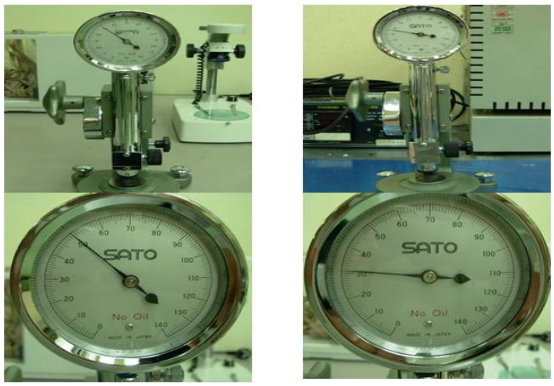
Shore hardness test was conducted by SATO shore hardness tester as shown in Fig. 8 (a) and Fig. 8 (b). Test was performed l0 times each specimen. The shore hardness test results of irradiated and non-irradiated graphite specimen are shown in table 3. Generally, strength and hardness of irradiated steel is higher than non-irradiated it but nuclear graphite was different with steel as shown Table 3 and Fig. 9 (a). Jang[16]'s research shows that strength and hardness of irradiated steel is higher than non-irradiated it under 450℃ but suddenly down over 550 ℃. This is the research results that irradiated still is intensified strength and hardness. In order to compare with a hardness characteristic of irradiated nuclear graphite IG-110 under amounts of the neutron, experiments were carried out once again. In the primary irradiation test, the shore hardness decrease from 49.6 to 35.5 during the irradiation and reduction rate was 29%. In the secondary irradiation test which is irradiated 12 times, the shore hardness decrease from 49.1 to 42.6 during the irradiation and reduction rate was 14%. Although the reduction of the hardness was confirmed through primary and secondary tests, a correlation of the results is difficult to find in the study.

Table 3: Shore hardness test results of irradiated nuclear graphite IG-110.

No	Amount of irradiation (n/cm^2)	Non-irradiation	Irradiation	Note
Case 1	3.17E+17	49.6	35.5	29% down
Case 2	40.17E+17	49.1	42.6	14% down

Table 4: Strength test results of irradiated nuclear graphite IG-110.

No	Amount of irradiation (n/cm^2)	Non-irradiation	Irradiation	Note
Case 1	3.17E+17	70	61.6	12% down
Case 2	40.17E+17	70	122.3	74% up

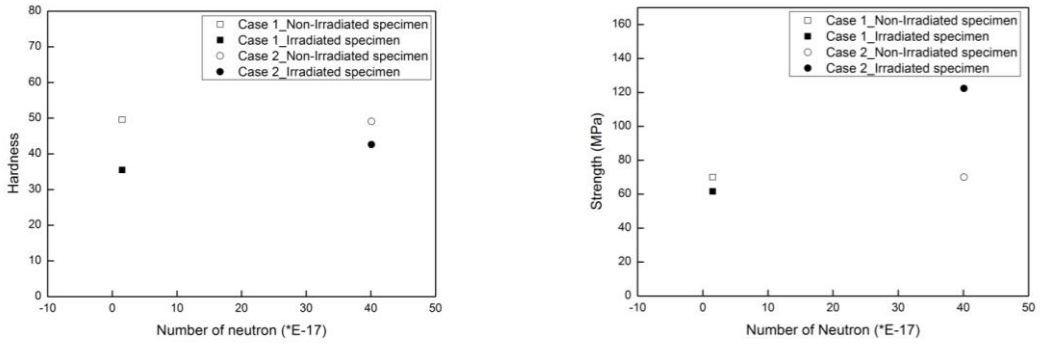


(a)Non-irradiated specimen (b)Irradiated specimen

Fig. 8 Shore hardness test of graphite IG-110.

Compressive test

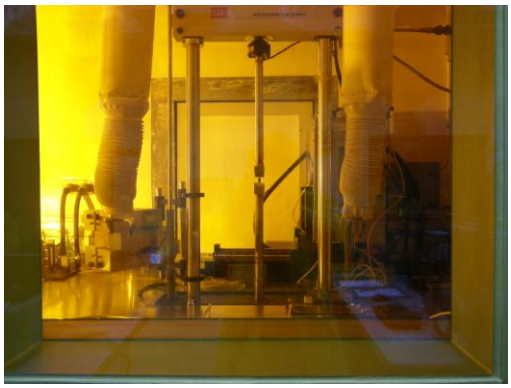
In order to compare with a strength characteristic of irradiated nuclear graphite IG-110 under amounts of the neutron, experiments were carried out once again as shown in Fig 10 (a), (b), (c), and (d). And Fig. 9 (b) shows the compressive strength test results. In the primary irradiation test, the strength decrease from 70 MPa to 61.6 MPa during the irradiation and reduction rate is 12% as shown in Table 4. In the secondary irradiation test which is irradiated 12 times, the compressive strength increase from 70 MPa to 122.3 MPa during the irradiation and rate of increase is 14%. Primary test with nuclear graphite IG-110 reduced the compressive strength with 12% down, the secondary test confirmed that 74% of the cases but rather increased. The primary and secondary research through tests of irradiated nuclear graphite IG-110 confirmed that the reduction of the strength but its correlation is hard to find under reduced range in this study.



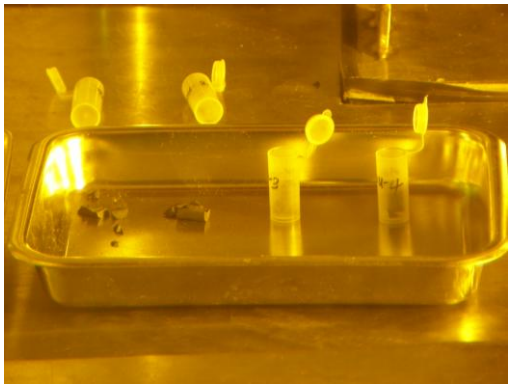
(a)Hardness of graphite IG-110 under amounts of neutron

(b) compressive strength of graphite IG-110 under amounts of neutron

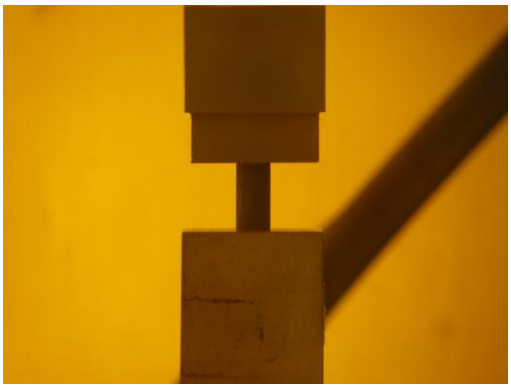
Fig. 9 Test results of IG-110 under irradiation



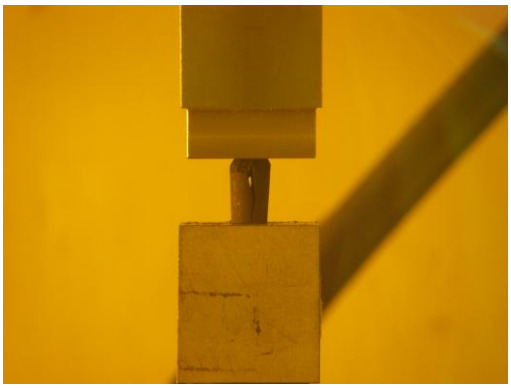
(a) Test machine MTS-810 for irradiated specimens compressive test



(b) Fractured shape of irradiated graphite IG-110 of



(c) Non-irradiation specimen of graphite IG-110



(d) Irradiation specimen of graphite IG-110

Fig. 10 compressive test of nuclear graphite IG-110

CONCLUSION

In this study, used in nuclear graphite IG-110 for the mechanical and fracture properties were studied. To understand the basic mechanical properties shore hardness test, compressive strength test, four-point bending test and fracture toughness test was conducted. Fracture toughness test was conducted three different test methods that three point bending test have round and V-notch and CT specimen each other. The experimental results of fracture toughness specimens with different thickness are compared with simulation using finite element analysis. Through irradiation test using HANARO research reactor, hardness and strength of nuclear graphite IG-110 was researched. Furthermore to search for characteristic change of nuclear graphite IG-110 under the amounts of neutron, Once again the experiment to change amounts of neutron was conducted. In this study the results are as follows,

1) Shore hardness was 49.6, compressive strength was 70 MPa, and bending strength was 41.1 MPa.

2) Fracture toughness tests were carried out with different notch and CT specimens fracture toughness using three point bending was 0.90 MPa $m^{1/2}$ and 0.86MPa m1/2 about CT specimens. Especially simulation to verification the experimental results, a finite element analysis have a two-dimensional mesh composed was carried out using commercial program ABAQUS. Experimental results show that fracture load 0.07 ~ 0.08 kN but simulation was 0.091 kN variation. The fracture toughness was 1.19 MPa $m^{1/2}$ using FEM. Analysis of 4 cases under variation of thickness had 1.19 ~ 1.20 MPa $m^{1/2}$.

3) Neutron irradiation test was conducted using capsule in HANARO research reactor. The primary nuclear graphite IG-110 specimens have exposed amounts of neutron 3.17E+17 and the secondary was about 12 times more than primary irradiated that it was 4.01E+18. The twice tests are have more than energy level of 0.821MeV. In order to compare with a hardness characteristic of irradiated nuclear graphite IG-110 under amounts of the irradiation, experiments were carried out once again. In the primary irradiation test,

the shore hardness decrease from 49.6 to 35.5 during the irradiation and reduction rate was 29%. In the secondary irradiation test which is irradiated 12 times more, the shore hardness decrease from 49.1 to 42.6 during the irradiation and reduction rate was 14%.

4) For the primary compressive strength test, the strength decrease from 70 MPa to 61.6 MPa during the irradiation and reduction rate was 12%. In the secondary irradiation test which is irradiated 12 times more, the compressive strength increase from 70 MPa to 122.3 MPa during the irradiation and rate of increase was 14%. For these tests, as neutron of irradiation increases, the hardness and compressive strength is increased but irradiation reduce the hardness and compressive strength of nuclear graphite IG-110.

5) It is difficult to find a quantitative correlation between amounts of neutron and hardness and compressive strength but it can be useful data for those who study nuclear graphite IG-110.

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