Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Preliminary Investigation on the In-Service Inspection of Graphite Components in the HTTR Using Ultrasonic Testing

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ABSTRACT

Since an oxidation reduces graphite strength remarkably, one of important subjects to maintain the structural integrity of graphite components in the high temperature engineering test reactor as an in-service inspection is the measurement of the oxidation damage. To detect the damage with nondestructive way a preliminary analytical investigation on ultrasonic wave propagation was carried out taking account of the reflection and/or detour wave owing to pores created in the graphite body during the oxidation process. Furthermore, the harmful flaw size was evaluated based on the fracture mechanics approach. From both analytical results applicability of the ultrasonic testing for the detection of the oxidation damage produced in the graphite components is discussed in the paper.

1. INTRODUCTION

The high temperature engineering test reactor (HTTR) is a kind of gas-cooled and graphite moderated test reactor with thermal output of 30 MW and core outlet coolant temperature of 950 ℃ at the maximum plant operating condition[1]. The first criticality has be attained successfully in November 1998. The core internals are made of graphite material due to its excellent thermal resistivity. Two kinds of graphite components are installed in the HTTR as shown in Fig.1. The core graphite components, fuel graphite block, control-rod guide block etc., are to be replaced at regular intervals. The core support graphite blocks, however, are installed during a lifetime of the HTTR. From a viewpoint of in-service inspection the core support graphite component is more important rather than the core graphite component, since it is necessary to maintain a long-term structural integrity. Several in-service inspection methods have been studied [2-4], and are planned to conduct in order to maintain its structural integrity; i.e. a visual inspection using a TV camera and/or material tests using surveillance test specimens.

There are two kinds of damages to be detected as the in-service inspection in the HTTR. One is an accumulated residual strain damage in the graphite body; the graphite has a creep deformation as well as a dimensional change under an irradiation condition. These strains are produced irreversibly and accumulated with the plant operation. The other is an oxidation induced damage; the oxidation makes pores acting as initiation and/or extension of cracks within the graphite body, then the strength decreases remarkably with increasing oxidation damage. For the latter damage inspection the applicability of an ultrasonic testing (UT) was studied from analytical approach. Takatsubo et al. proposed a pore reflection model of the UT propagation wave, which is applicable to the porous ceramic materials [5].

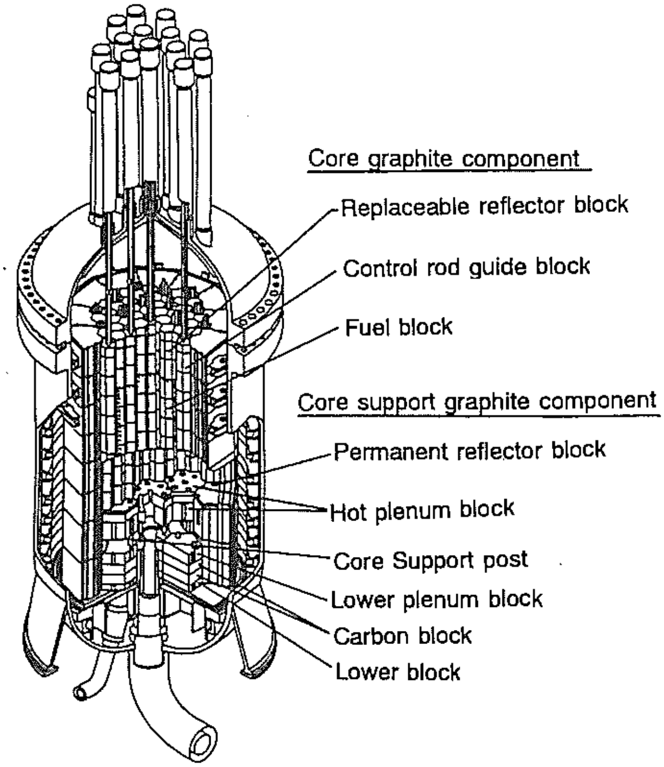


Fig.1 Core and core support graphite components in the HTTR.

Some of authors were improved the model to be applicable to the graphite material with pulse-echo technique [6], and applied to the strength estimation from the ultrasonic wave signal on the basis of the fracture mechanics approach. Since it is thought that the ultrasonic wave signal would change by the oxidation induced pores, the applicability of the oxidation damage measurement using the UT was studied to promote the in-service inspection technology for the core internal graphite component. The characteristics of the ultrasonic wave propagation were analyzed based on the pore reflection model. Moreover, a harmful flaw size was estimated based on the fracture mechanics approach to clarify the applicability of the UT as an in-service inspection.

2. ANALYSIS

2.1 ULTRASONIC WAVE PROPAGATION

A ultrasonic wave propagation model in porous ceramics body has been proposed by Takatsubo et al. taking account of the wave interaction with the pore[5]. If the ultrasonic wave comes into collision with the spherical shaped pore, the wave would be scattered by the pore or propagated through the pore edge as shown in Fig.2. At that time the detour wave has a time delay, Δt, in comparison with the direct wave, and the Δt is given by

$$\Delta t = \frac{\frac{2\pi r}{4}}{V_d} - \frac{r}{V_p} \qquad (1)$$

where V_d and V_p are the velocities for detour and direct waves, and r is the radius of the pore.
If pores with radius r are located homogeneously at a regular interval p in the body with thickness L, the propagation waveform, $P_w(t)$, through a great number of pores is given by following equation.

$$P_w(t) = F \cdot e^{-(t-t_p)^2/2t_w^2} \tag{2}$$

where

$$t_p = \{a + \sigma^2 \log(c)\} \cdot \Delta t$$

$$t_w = \sigma \cdot \Delta t$$

$$F = \frac{c^{a+(\sigma^2/2)\log(c)}}{\Delta t \cdot \sigma\sqrt{2\pi}}$$

$$a = \frac{L\pi r^2}{p^3}$$

$$\sigma^2 = \frac{L\pi r^2}{p^3}\left(1 - \frac{\pi r^2}{p^2}\right)$$

and c is a detour wave rate.
Here, we take following assumptions in the pore reflection model for the pulse-echo technique.

1) In roughly, it is expected that the mean reflection length from the plane of incidence would be a mean depth in the body.
2) Probability of reflection by the pore is proportional to the pore cross section.
3) Number of the reflection wave is also proportional to the pore cross section.

By taking them into consideration the reflection wave form, $R_w(t)$, is given as follows.

$$\begin{aligned} R_w(t) &= A \cdot (\pi r^2)^2 \cdot F \cdot e^{-(t-t_p)^2/2t_w^2} \\ &= F' \cdot e^{-(t-t_p)^2/2t_w^2} \end{aligned} \tag{3}$$

where A is a geometric constant defined by the propagation distance.

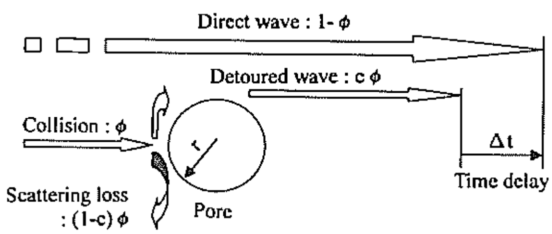


Fig.2 Ultrasonic wave propagation model in a porous body.
(ϕ is a probability of ultrasonic wave incident on a pore ($= \pi r^2/p^2$))

2.2 HARMFUL FLAW EVALUATION

The harmful flaw size for the core support graphite component was estimated from finite element analysis based on a fracture mechanics approach applying an influence function method [7]. Since many kinds of flaw meshes are necessary to evaluate a stress intensity factors in general, this method has an advantage of mesh modeling in the analysis, i.e. only the stress analysis mesh without flaw is necessary to evaluate the stress intensity factors. If the stress distribution, $\sigma(\xi)$, on the flaw surface along the y-axis in Fig.3 is determined as equation (4), the stress intensity factor for mode I, K_{IS}, is given by equation (6).

$$\sigma(\xi) = (A\xi^3 + B\xi^2 + C\xi + D)\sigma_0 \qquad (4)$$

where A,B,C and D are the fitting parameter, σ_0 is a maximum stress, and ξ is a normalization parameter defined by equation (5).

$$\xi = 1 - y/a \quad (0 << \xi << 1) \qquad (5)$$

$$K_{IS} = AK_3 + BK_2 + CK_1 + DK_0 \qquad (6)$$

where K_3, K_2, K_1 and K_0 are stress intensity factors for four kinds of basic stress modes, $\sigma(\xi)/\sigma_0$=1.0, ξ, ξ^2 and ξ^3, respectively.

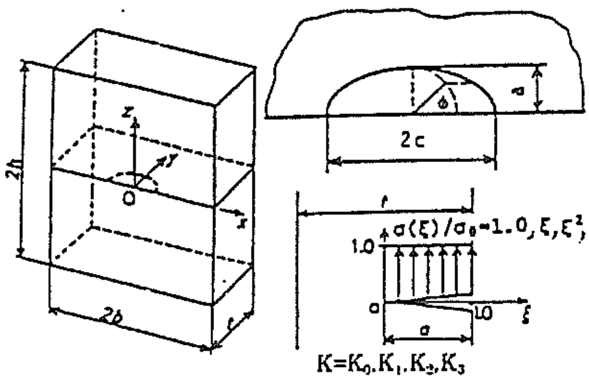


Fig.3 Influence function method to evaluate the stress intensity factor.

3. RESULTS AND DISCUSSIONS

3.1 ULTRASONIC WAVE PROPAGATION

Mainly core support graphite components, permanent reflector block, hot plenum block etc. in Fig.1 , are made of coarse-grained PGX graphite, and core support post of fine-grained IG-110 graphite. Typical mechanical properties are listed in Table 1. The following were parameters used in the analysis of the ultrasonic wave propagation in this study.

- direct wave velocity Vp= 2000 m/s
- detoured wave velocity Vd=0.71Vp [9]

- specimen thickness L=150 mm (IG-110 graphite)
  L=1000 mm (PGX graphite)
- interval length is determined by following equation.

$$p = \sqrt[3]{\frac{\frac{4\pi r^3}{3}}{\frac{2.26-\rho}{2.26}}} \tag{7}$$

here, ρ is a density (g/cm^3) .

The propagation wave form was analyzed as a function of the pore radius, r, and analyzed maximum signal was normalized by that of mean pore radius [8]. The analytical results are plotted in Fig.4. From this figure it is found that the propagation signal changes largely below around 0.2 mm for IG-110 graphite and 1 mm for PGX graphite.

Table 1 Typical mechanical properties of graphites.

Property	IG-110	PGX
Grain size(μm)	20(ave.)	800(max.)
Density(g/cm^3)	1.78	1.74
Young's modulus(GPa)	10.1	6.6 (L),8.5 (T)
Tensile strength(MPa)	28	8.3 (L),9.2 (T)
Compressive strength(MPa)	81	31 (L),30 (T)

*L: across grain direction, T: with grain direction

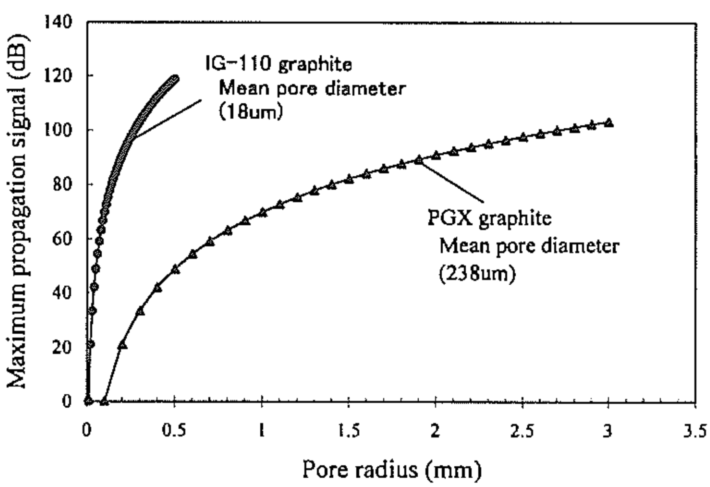


Fig. 4 Maximum propagation signal as a function of pore radius.

3.2 HARMFUL FLAW SIZE

The stress intensity factor was estimated as a function of circular flaw radius using the stress distribution obtained by the FEM stress analysis. Since it is well known that the mode-I fracture toughness is smaller than the mode-II and/or mode-III fracture toughness, the mode-I stress intensity factor was analized. In the analysis the flaw radius is gradually increased as shown in Fig.5 untill the stress intensity factor becomes greater than the minimum mode-I fracture toughness. The minimum mode-I fracture toughness was determined by equation (8) with 99% survival probability with 95% confidence level [10].

$$K_{IS} = K_{IC} - (k_{99} + \frac{k_{95}}{\sqrt{n}})S_{\sigma} \tag{8}$$

where K_{IS}: minimum mode-I fracture toughness,

K_{IC} :mode-I fracture toughness

κ_{99}, κ_{95} : statistical parameter (κ_{99}=2.326, κ_{95}=1.645)

n: number of specimen

S_{σ}: standard deviation of data

The estimated circular-shaped harmful flaw sizes are;

- 1.8 mm for spherical contact region of the core support post (IG-110 graphite)
- 21 mm for key-way region of the hot plenum block (PGX graphite)

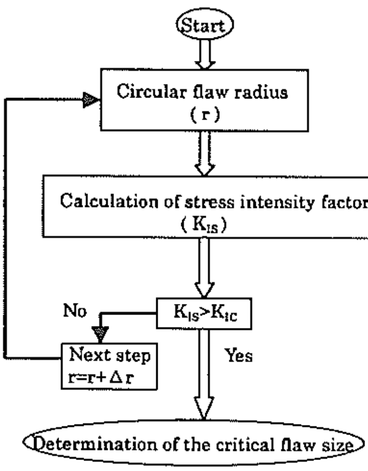
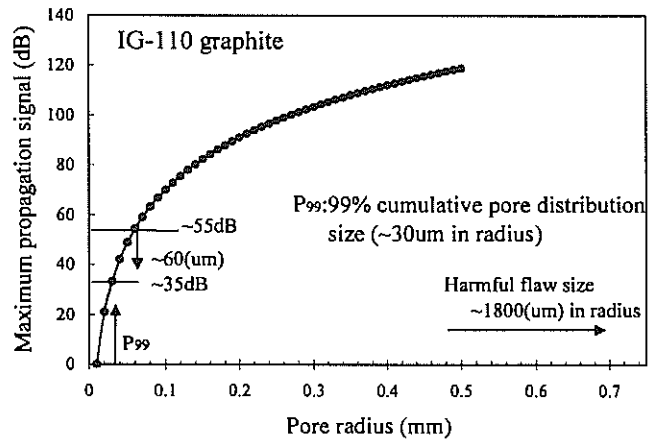


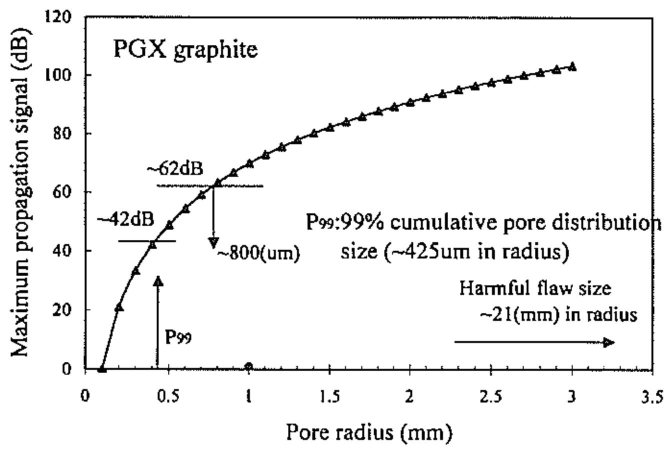
Fig.5 Analytical flow of stress intensity factor.

3.3 APPLICABILITY OF UT

In the UT for the graphite material the maximum background noise is determined from a preliminary scanning test with the same kind of reference specimen, and then the specimen's signal is compared with the pass/fail criteria determined from a structural integrity standpoint [11]. It is thought that the background noise would be mostly caused by the pores in the graphite and the maximum noise would be by the maximum pore within scanning section. Consequently, the maximum pore is not always detected in the preliminary scanning test. In the analytical study it is, therefore, assumed that the maximum background noise would be determined by the pore size with 99% cumulative probability. From a cumulative pore size distribution obtained by Nakanishi et al. in a morphological grain/pore statistical investigation, the 99% pore size is about 60 μ m and 850 μ m in diameter for IG-110 and PGX graphite, respectively [8]. The maximum background noise is, therefore, estimated to be 35dB and 42dB for IG-110 and PGX graphites as shown in Fig.6. If a meaningful magnitude of signal is thought to be 20dB from an industrial viewpoint, the detectable oxidation induced pore size is estimated to be about 60 μ m and 800 μ m in radius for IG-110 and PGX graphites, respectively. Since these estimated sizes are far below ten times as large as the critical flaw sizes, it could be thought that the UT is one of potential methods to detect the oxidation induced pores of graphite component.



(1) IG-110 graphite



(b) PGX graphite

Fig. 6 Estimation of the detectable pore radius by the ultrasonic testing.

4. CONCLUSIONS

In order to detect the oxidation damage of the core internal graphite component the applicability of the ultrasonic testing method was studied analytically. The ultrasonic wave propagation was analyzed based on the pore reflection model, and the harmful flaw size was also estimated by the fracture mechanics approach with influence function method. From comparison between them it was found that the detectable oxidation-induced pore size is small enough to the harmful one. It is concluded from this study that the ultrasonic testing has a potential as the in-service inspection technique for graphite components. Since the ultrasonic wave propagation would depend more on the equipment, specimen and/or testing condition, the experimental study on the detection ability of oxidation induced damage will be necessary to define a detail testing condition and so on.

ACKNOWLEDGEMENTS

The authors express their gratitude to Mr. T.Tanaka, Mr. H.Mogi and Mr. T.Iyoku, HTTR project of JAERI, for their useful suggestions and comments in this work.

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