Applicability Study of Ultrasonic Flaw Detector For Nuclear Grade Graphite Examination

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Abstract. The development of High Temperature Gas-cooled type Reactor obliges the usage of nuclear class graphite as essential structure of reactor core. Nuclear class graphite requires an in-service inspection of NDT ultrasonic process to determine the declining rate of properties due to the used up amount of time. Yet, up to this moment, NDT ultrasonic is merely used limited to metal, and therefore the purpose of this research is to analyze the capability of ultrasonic flaw detector as an in-service inspection for nuclear class graphite. The method used in this measurement is the contact method by using the ultrasonic flaw detector with 2 MHz and 5 MHz probe. The material used for this purpose was IG-110 type nuclear class graphite. The results of these measurements show that the ultrasonic flaw detector may be well-functioned for the nuclear class graphite in the velocity of 2,450 m/s and the attenuation of 0.93 dB/mm. Besides that, the simulation result shows that the maximum propagation distance of the ultrasonic flaw detector may only reach up to the distance of 50 mm with the intensity of 31.5 dB for 2 MHz probe and 49.5 dB for 5 MHz probe.

Keywords: HTGR, NDT, ultrasonic flaw detector, IG-110 graphite.

1. Introduction

The research on nuclear reactor aims to improve the safety and economical efficiency of reactor’s operation. One of promised nuclear reactor technology which is interesting to be developed further is the High Temperature Gas Cooled Reactor type (HTGR)[1,2]. In accordance to the reactor’s name, the outlet temperature of this reactor is beyond 600°C. Being such an extreme condition, metal as the main material component of reactor core clearly is not an option. Therefore, one of the main requirements as reactor core component is that being a material with the melting point well above the operation temperature.

Many research found out that the material which may fulfill such requirement is graphite[3]. Another requirement to be the reactor core component material, besides having high temperature resistance, is to fulfill other design requirements which related to mechanical properties, such as creep strength, fatigue strength, wear resistance, and fretting resistance. During the operational time of such a reactor, the material of reactor component may be undergoing a deterioration of mechanical character due to the aging mechanism. In order to ensure and maintain the integrity of reactor core component, it is needed to detect the ageing process.

To detect the deterioration of mechanical properties during its operation phase, the non-destructive detection method is necessary. One of NDT method is ultrasonic testing which is merely used for metallic components[4,5]. Intensive studies have been performed relating to the use of ultrasonic...
testing for various material characterization and/or inspection[6–11]. It is a challenge to use ultrasonic testing for graphite material. Characterizations of ceramic material, such as graphite, are successfully performed using ultrasonic testing[12]. The changes of propagation velocity of ultrasonic wave in material graphite, before and after creep condition, are confirmed[8]. An attempt to use ultrasonic flaw detector to detect defect in material graphite used in rocket, showed the capability of ultrasonic flaw detector for detecting graphite cracks[7]. A non-destructive testing of nuclear graphite material using other method also have been performed[13,14]. But, the study on the use of ultrasonic flaw detector to detect defect in nuclear grade graphite have not been performed, yet. Therefore, the aim of this study is to determine the applicability of ultrasonic flaw detector for detecting defect in nuclear grade graphite. In this study, nuclear grade graphite was used as a specimen for ultrasonic testing. After conducting ultrasonic testing, simulation were conducted to predict maximum distance of detection of conventional ultrasonic flaw detector.

2. Experimental
In this study, nuclear grade Isotropic graphite, IG-110, produced by Toyo Tanso was used for specimen material. Two types of specimens are prepared, that are step wedge and DS Block. These specimens were fabricated in accordance to Section 5 ASME. Ultrasonic testing was conducted using Epoch 4-Plus Ultrasonic Flaw Detector, manufactured by Panametric-NDT. Two longitudinal type ultrasonic transducers, which has 2 MHz and 5 MHz nominal frequency, respectively, were used in this study. Figure 1 showed the experiment equipment used in this study.

As characterization parameter, wave propagation velocity (further, called as ultrasonic velocity) and attenuation in graphite was measured. For the comparison, ultrasonic velocity and attenuation in SS 304 and AISI 1018 steel were measured.

2.1. Measurement of Ultrasonic Velocity
These measurements used the step wedges specimen, which has five different thicknesses and DS Block specimen. The measurements were conducted by using pulse echo method. Since all of the thickness is known, the measurements were conducted to measure Time of Flights (TOF) between pulse echoes. Then, ultrasonic velocity was determined using the following equation[15]:

$$V_L = \frac{2d}{\Delta TOF}$$ (1)
with $d$ is the material thickness and $\Delta TOF$ is the conjunction time between two pulse echoes. DS-block specimen was used in ultrasonic velocity measurement to investigate the isotropic properties of graphite material.

2.2. Measurement of Ultrasonic Attenuation Coefficient

Ideal materials have been assumed in which the sound pressure is reduced only by virtue of the spreading of the wave. A plane wave would thus show no reduction whatever of the sound pressure along its path, and a spherical wave, or the sound beam of a probe in its far-field, would merely decrease inversely with the distance from the source. Natural materials, however, all produce a more or less pronounced effect which further weakens the sound. These results from two basic causes that are scattering, and true absorption, which are both combined in the term attenuation\cite{15}. The decrease of ultrasonic intensity along it’s propagation in material is governed by the following equation.

$$I = I_0 e^{-ad}$$  \hspace{1cm} (2)

with, $I_0$ and $I$ are initial intensity and intensity after propagating a certain distance, respectively, $d$ propagation distance and $\alpha$ is attenuation coefficient. In the measurements, $I_0$ and $I$ represent the amplitude of each pulse echo. The unit of attenuation coefficient calculated using Eq.(2) is Np/mm. Commonly, in practice, attenuation coefficient of the intensity of ultrasonic intensity is in dB. There is a conversion value between Np/mm and and dB/mm, that are 1 Np = 8.686 dB.

2.3. Simulation of defect detection

Simulation was conducted in order to evaluate the maximum detectable distance of ultrasonic flaw detector in graphite material. Simulation procedure was described as follow. An initial condition used in simulation was set up using experimental equipment in Fig. 1, V1 calibration block and 5 MHz longitudinal transducer. The transducer was put on the V1 calibration in such a way that ultrasonic wave propagates toward 1inch hole (refer to Fig. 2). In this position, reflected pulse height was set into 80% FSH (Full Scale Height), and the gain controller value was recorded. After that, in the simulation gain controller was set up, as if it reaches into maximum value (maximum value of gain controller in Epoch4Plus is 100), and the FSH was calculated. Then, the FSH for maximum gain controller was defined as initial condition. According to this initial condition, wave propagation was simulated by attenuation coefficient found in the previous step to determine the distance where the pulse height decreases into 10% FSH. In the same way, simulation was conducted with graphite material.

![Figure 2. V1 Calibration block](image)

3. Result and Discussion

3.1. Ultrasonic Velocity Measurement Results

Figure 3 shows ultrasonic propagation velocity measurement results, for step wedge specimen and DS block specimen. For step wedge specimen, propagation velocity of ultrasonic wave was plotted for SS 304, 1018 steel and graphite material. A circle mark and triangle mark represents results by using 5
MHz and 2 MHz transducer, respectively. Whilst, open mark and solid mark represent results from 7.5 mm and 12.5 mm thickness, respectively. Besides, all values plotted in this graph are calculated using equation (1).

Figure 3(a) shows that the propagation velocity of ultrasonic wave in graphite has a lower value compare to two other materials (steel material). The velocity in graphite is approximately 2,400 m/s, while in SS 304 and 1018 Steel are approximately 5,800 m/s. It means that velocity in graphite has approximately half of those value in steel materials. This velocity measurement result from graphite material shows a good agreement with the previous study[8]. The difference of ultrasonic propagation velocity between materials are caused by the physical properties, such as density[16,17]. A higher density of material has a higher ultrasonic propagation velocity[16]. According to the physical properties of materials used in this study, steel materials has a density of about 7,800 kg/m$^3$ and graphite material is 1,760 kg/m$^3$, respectively[18,19]. By considering the measurement results and the physical property, it is known that there is a linear relationship between ultrasonic propagation velocity and density of material where the ultrasonic wave propagates.

![Graph showing propagation velocity measurement result.](image)

The results from different frequency of transducer (2 MHz and 5 MHz) show the same value of propagation velocity. A small difference observed for the results for steel material are less than 10%. This difference is still in the range of error limit in measurement. This difference is caused by the instrumentation used in this study. It means that the propagation doesn’t depend on the frequency of ultrasonic wave. The propagation velocity is determined by the material properties where the ultrasonic wave propagates. If the observation is subjected to the results from the difference thickness, there is no difference between them, for each material. It’s a consequence that for the same material will provide the same propagation velocity value.

The results from graphite material (Fig. 3(b)) show the same value of propagation velocity for different transducer frequency and travel of distance. Travel of distance in this graph has a different direction, where each direction is perpendicular to another. If we put 50 mm thickness on X-axis, so that the 100 mm and 150 mm thickness on Y-axis and Z-axis, respectively. By observing that the values of propagation velocity are the same, it means the graphite material used in this study is closely ideal isotropic material.

### 3.2. Attenuation Measurement Results

Figure 4 shows attenuation measurement results using step wedges for each material. The attenuation coefficients are measured using longitudinal transducer of 2 MHz and 5 MHz. The intensity of ultrasonic signals used for attenuation coefficient calculation, are setted up in such a way so that the pulse echo does not exceed 100% and thus affecting the FSH to be more accurate. Attenuation coefficients are calculated by using Eq. (2).
Figure 4 shows that attenuation coefficient has different value for each material. Steel material has slightly different attenuation coefficient, while graphite material has an attenuation coefficient four time higher compare to the steel material. As mentioned in previous part, attenuation is the energy loss due to the absorbing and scattering process. Attenuation may happen on any material due to many reasons, such as the material porosity, dislocation density, microstructure’s condition, etc. For steel material, since they have a similar density and chemical composition, they have a similar attenuation coefficient. The difference attenuation value between steel materials is caused by microstructure.

It is confirmed from this result that, for 2 MHz transducer, SS 304 has attenuation coefficient of 0.24 whilst 1018 steel has attenuation coefficient of 0.15. A large different in attenuation coefficient between steel material and graphite material is due to its density. It’s known that density of steel is approximately four times of that from graphite material. It reflects on attenuation coefficient, by which, the attenuation coefficient of graphite material (0.9 dB/mm) is approximately four times compare to the attenuation coefficient of steel material (0.2 dB/mm). These results show that, there is an inversely linear correlation between attenuation coefficient and material density. In the evaluation of frequency effect on ultrasonic attenuation, it can be known that a higher frequency of ultrasonic wave has a higher attenuation coefficient. Experimental results show that 5 MHz transducer provide a slightly higher attenuation coefficient compare to 2 MHz transducer. These results are consistence for all material. The frequency effect can be considered as follow. A higher frequency ultrasonic wave has a shorter wave length. As mentioned above, along the propagation path, ultrasonic wave experiences energy absorbing and scattering due to various matter such as material porosity and microstructure. A short wave length is affected easily by these matters, so that the energy loss is higher. This phenomenon have been formulated in the previous study[20]. According to the velocity measurement and attenuation coefficient results, it can be known that a conventional ultrasonic flaw detector could be used in graphite inspection.

3.3. The Simulation of Flaw Detection Distance
The simulation results were plotted in Fig. 5. The aim of this simulation is to predict the maximum distance of detection capability base on an artificial defect in V1 block by using conventional ultrasonic flaw detector. These results covered for 1018 steel and graphite material. As shown in this graph, it can be observed that, in graphite material, intensity of reflected wave decreased remarkably.
as increasing the wave propagation distance. Contrarily, in AISI 1018 steel material, the intensity of reflected wave decreased more gradually as increasing the wave propagation distance. These results agree with the result of attenuation coefficient measurement. Based on the simulation results, it is concluded that the ultrasonic wave could merely detect the flaw with the maximum size of 1 mm at the maximum distance of 200 mm (it means 100 mm thick) on the nuclear class graphite with maximum gain value. It is contrary with AISI 1018 Steel, which has the maximum propagation distance of 600 mm. This different circumstance is affected by various attenuations on every material. As above mentioned, nuclear class graphite possesses more porosity, which affects the required energy aimed for the propagated ultrasonic wave to become bigger. It also causes the propagation distance on nuclear class graphite to become shorter when being compared to AISI 1018 Steel. These results also confirmed by the testing of graphite material using DS Block. These results are shown in Table 1.

In HTGR design, such as HTR-10, the side reflector parts were made of graphite material, with 800 cm thickness[21]. Considering the maximum distance showed in Fig. 5, for inspection, small part of side reflector part only could be covered by the conventional ultrasonic flaw detector. Therefore, it is needed to develop a special ultrasonic flaw detector in graphite inspection.

![Figure 5. Simulation result for 1 mm diameter hole.](image)

| Table 1. Peak intensity of back wall echo as a function of distance and gain value |
|---------------------------------|---------------|---------------|---------------|
| 50 mm  | 100 mm | 150 mm |
| First echo | FSH dB | FSH dB | FSH dB |
| 70% | 40 | 27% | 58 | 40% | 64 |
| Second echo | 40% | 58 | 17% | 82 | 29% | 88 |

Table 1 shows the peak intensity of back wall echo from DS block as a function of distance and gain value in UFD equipment. Peak intensity of second echo for the distance of 150 mm is 29% when the gain control was set to 88 dB (the maximum gain control value is 100 dB). By considering this result, the results from simulations provided a good agreement.

4. Conclusion
An experimental study of applicability of ultrasonic flaw detector for graphite material has been conducted. Acoustic characteristics of graphite material were evaluated by ultrasonic flaw detector to determined ultrasonic propagation velocity and attenuation coefficient. Simulations were conducted to
predict the maximum distance of ultrasonic flaw detector to detect a defect below 1 mm in size. Experimental results show that ultrasonic propagation velocity in graphite material is approximately 2,400 m/s and the attenuation coefficient is 0.93 for 2 MHz frequency and 0.98 for 5 MHz frequency. The simulation results show that the maximum distance of ultrasonic flaw detector to detect a defect 1 mm or below is 200 mm. According to these results, a conventional ultrasonic flaw detector could be used to inspect graphite material, but the thickness of material to be inspected is very limited.

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