Defence Science Journal, Vol. 52, No. 1, January 2002, pp.27-32

Dry-coupled Pulse Echo Ultrasonic Inspection Methodology for Solid Graphite Products of Rocket Boosters

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ABSTRACT

High modulus solid graphite products are used in nozzle throats of solid rocket boosters. Functionally, nozzle throats are critical and hence require to be inspected thoroughly. Ultrasonic method can be utilised for detecting tight defects/cracks and estimating material properties, such as elastic modulus, grain size, uniformity of structure, etc. For ultrasonic energy to pass to the material, a liquid coupling medium is used conventionally, and hence, commercially available transducers are meant for usage with a liquid couplant. Such a liquid couplant is harmful to graphite products and hence cannot be used. Replaceable solid couplant transducer faces have been developed that can be used on conventional probes for inspection of any product. Studies were conducted to understand various aspects of ultrasonic inspection for critical applications. This paper details the experimentation conducted and analysis done on signals collected for evolving an application methodology and a procedure.

Keywords: Solid rocket boosters, nozzle throats, ultrasonic non-destructive evaluation, solid graphite, inspection methods, ultrasonic inspection

1. INTRODUCTION

Destructive testing techniques are mostly done on sample basis. In this procedure, actual part or volume of material used to realise products are not tested. Non-destructive testing (NDT) inspects cent per cent volume of the material used to realise products. It can also be used for testing products under use. Major testing techniques are: Ultrasonic technique, radiographic technique, magnetic technique, Eddy-current technique, infrared technique, etc. Unlike most of the NDT techniques, ultrasonic technique can also be used for estimating material properties. In ultrasonic technique, different methodologies, equipment and transducers are used.

Some important methodologies are: (i) pulse echo, (ii) transmission, and (iii) multiscattered sound. In all these methodologies, ultrasound energy produced by the transducer is to be transmitted to the material/product under evaluation. Some sort of coupling medium is used for this purpose. For testing and evaluating the material or product, NDT professional should be aware of the features of ultrasound interaction with the specific material/product. Users requirements and problems are also to be studied and understood. Conventionally, ultrasonic inspection is quite common in production centres of metallic materials. Materials like solid graphite are not common materials that are tested using conventional NDT facilities. Users of solid graphite for rocket boosters are also very few worldwide. Hence, studies are required to be conducted on ultrasonic inspection of solid graphite[1].

Received 03 November 2001

2. DRY-COUPLED PULSE ECHO ULTRASONIC TEST FACILITY

Graphite is a porous material; it absorbs liquids. Hence, conventional liquid coupling medium (liquid couplant) should not be used. Ultrasonic pulse echo transducers available in the NDT facilities and in the commercial markets are meant for use with liquid couplant. Due to this, these transducers cannot be used without modification for testing graphite products used in rocket boosters. Usage of solid coupling medium and its implications are reported widely[2]. Solid coupling media are to be used when other liquid couplants cannot be used. Since solid couplant probe faces are not available in the commercial market, studies were conducted to understand this technology[3,4]. An experimental method was devised to identify key material features suitable for dry couplant faces. It has been found that modulus, compressibility and ability to stick to surfaces are the material features which are to be optimised.

Few compositions were tailor-made and few others were selected from readily available compositions. These compositions were based on silicon rubber. Some compositions were used in cured condition and some in uncured condition. For practical reasons, easily replaceable probe faces (Fig. 1) have been developed by fabricating suitable moulds.

For certain applications (say when concave surfaces are to be tested), cured thick couplant sheets (Fig. 2) were used. For concave surfaces, thickness has to be more for getting adjusted to the surface contour. Cured, low modulus composition was used for this application.

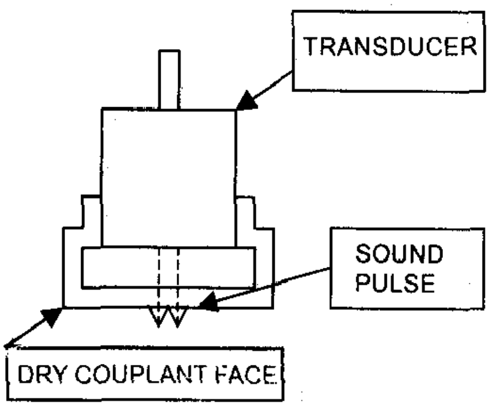

Figure 1. Transducer fitted with replaceable dry couplant face

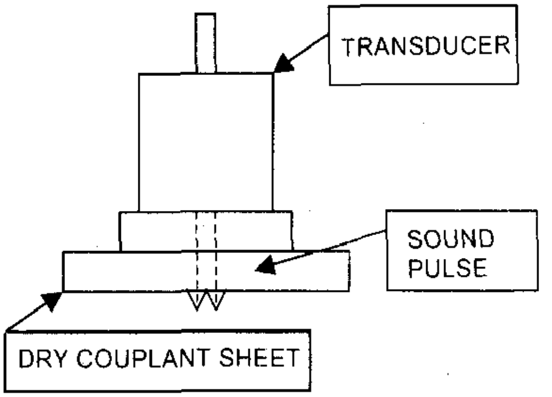

Figure 2. Transducer used with cured dry couplant sheets

One composition in an uncured condition was made into freely sticking probe faces (Fig. 3). In an uncured condition, sticking property of the composition is more, and hence it freely sticks to the probe face.

Using this couplant face, it is now possible to move the probe as freely as in liquid couplants. On graphite, this is possible because the graphite powder on the surface of the product is acting as a lubricant which enables free movement without rupturing the couplant face.

3. ULTRASONIC FREQUENCY & TRANSDUCER SELECTION

For good results, optimum ultrasonic frequency and transducer selection are to be made. It is well

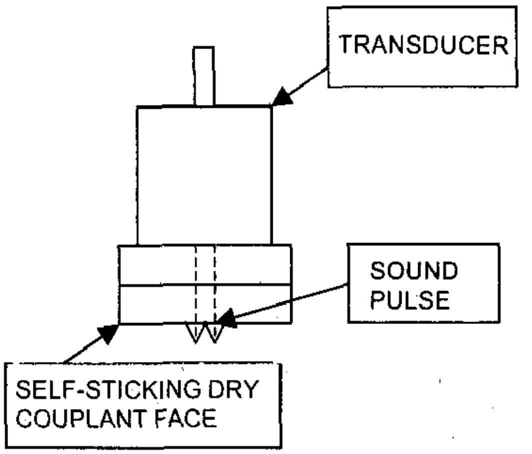

Figure 3. Transducer used with dry couplant face

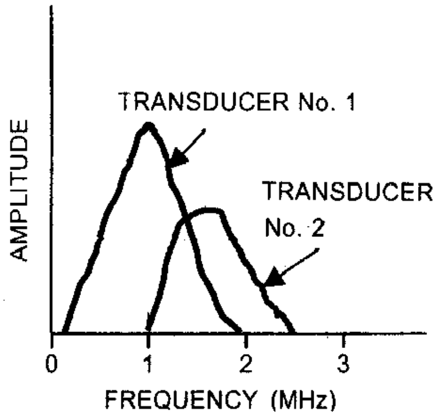

Figure 4. Ultrasonic spectroscopic response comparison on 100 mm graphite block using 1 MHz and 2 MHz transducers.

known that for the detection of smaller defects, higher transducer frequency is required. Selection of this depends on maximum material thickness to be inspected and ultrasonic characteristic of the material. Transducer type also influences the sensitivity. Signals were collected using transducers of frequency 0.5 MHz, 1.0 MHz and 2.0 MHz from blocks of heights 50 mm, 60 mm, 100 mm, 200 mm and 400 mm. Results were evaluated and signals were analysed. Transducers of 24 mm diameter and 1 MHz frequency gave better response as compared to transducers of 2 MHz frequency. Also, spectrum of the transducers of 2 MHz frequency shifted heavily towards transducer of 1 MHz frequency even for 100 mm block (Fig. 4). The above studies indicate that the transducers of 24 mm diameter of 1 MHz frequency are optimum for graphite inspection when the products thickness is 100 mm to 400 mm.

4. ULTRASONIC FEATURES TO BE MONITERED

Properties and characteristics of the material can be extracted from the following features[5] of ultrasound:

(a) Velocity of transmission of sound energy

(b) Features of reflected sound pulse

- Strength (amplitude) of reflection from defect and back wall of material
- Location of reflection in the material
- Its shape and dynamic behaviour
- Spectral features.

Velocity is useful for estimating Young's modulus of the 100 per cent volume of material using the following relation:

$$\text{Young's modulus} = (\text{Velocity})^2 \times \text{Specific gravity}$$

Modulus estimation is useful for this material, because it is an important property for the application. Experiments were conducted to measure its variations. Velocity measurements were carried out at 20,000 locations on large number of products. It was found that general variation is 2 per cent. Maximum local variation is 15 per cent. Variation of this order is a cause for rejection of the material on the basis of low modulus. Thus, this feature (sound velocity) is to be monitored to identify locations of low modulus and give feedback to the user.

Reflected sound from the defects within the material and from the back wall of a large number of specimens and few number of products were monitored initially. After examining these initial results, it was found that for monitoring reflections within the material, a reference of ϕ10 FBH is feasible. A detailed evaluation of the amplitudes of signals was done only after the sufficient number of products were inspected and their strength of reflections from the material measured.

Studies conducted on specimens revealed that reflection from back wall of material of thickness 100 mm generally varies 20 per cent. At certain locations, 50 per cent variations were seen. After inspecting few products, and measurements done at 5000 locations, it was found that 50 per cent variation at certain localised region is quite common in the material of thickness 100 mm. Thus, this feature was monitored on all products to identify general variation, evolve an acceptance standard, and give feedback to the users. In the case of material of 400 mm, variation of back wall echo amplitude was much more due to material variation in terms of velocity and porosity. However, monitoring the back wall echo is also useful to identify abnormal reductions at large regions. Locations of defects indications are to be recorded, because the presence of defects at different locations in the products have different effects and also the presence of defects at certain locations can be removed through machining.

The material grain size can be estimated through ultrasonic spectroscopy. A methodology was developed to estimate grain size using the signal analysis software developed in-house. The methodology is based on the scattering of ultrasound by material grain[6]. Scattering is highly dependent on the relation of grain size to ultrasonic wavelength. When the grain size is less than 0.01 times the wavelength, scattering is negligible. Scattering effects vary approximately with the third power of grain size and when the grain size is 0.1 times the wavelength,excessive scattering occurs. These effects can be located from the spectrum because the sound velocity, frequency and wavelength are related by the formula:

$$\text{Velocity} = \text{Frequency} \times \text{Wavelength}$$

When velocity is known in a material, wavelength can be obtained from the frequency. Frequencies at which sudden sound attenuation change occur can be obtained from the spectrum. Once the frequency is obtained, wavelength for this frequency can be computed using the above equation.

At present, this method is utilised only to detect gross variation in grain size in comparison with a reference (Fig. 5). In Fig. 5, two grades of graphites have been compared for grain size. Graphite grade No. 1 has smaller grain size as compared to graphite grade No. 2, because the spectrum for grade No. 1 terminates at high frequency. This information is highly useful because the reduction in grain size improves overall property of the material.

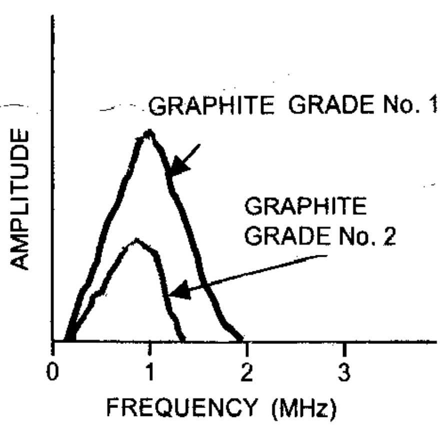

Figure 5. Ultrasonic spectroscopic response comparison on 100 mm graphite blocks (graphite grade No. 1 and grade No. 2) using 1 MHz transducers.

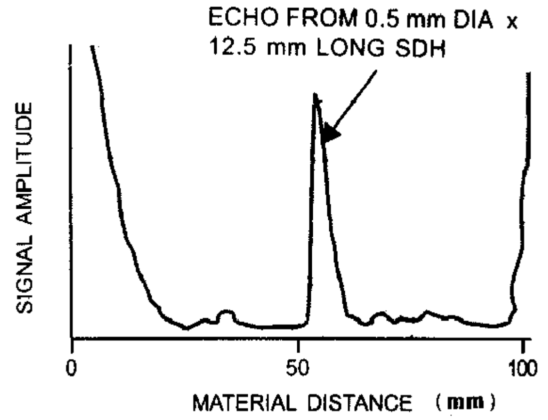

Figure 6. A-scan showing response of 0.5 mm diameter, 12.5 mm long) side-drilled hole made on 100 mm block.

5. DEFECT DETECTION SENSITIVITY

To create an awareness and understand the factors affecting detectability of defects by this method on this material, an experiment was conducted by drilling a side-drilled hole of 0.5 mm diameter with length 12.5 mm. Response of this side drilled hole is generally considered equivalent (in signal amplitude) to that obtained[7] from a ϕ2 FBH. Thus, the reflecting area of this defect is 3.14 mm^2. The reflecting area of 10 diameter FBH (i.e., reference) is 75 mm^2. It means that apparent reflecting area of 12.5 × 0.5 side-drilled hole is 4 per cent of reference (ϕ10 FDH). After inspecting 30 number of products, it was found that geometric mean of defects obtained so far is 5 per cent of reference. Thus, it can be seen that defects of ϕ2 FBH size is generally seen in this material. Measurements conducted on the above side-drilled hole showed that such a defect is giving SN ratio of the order 20 dB (Fig. 6).

For creating further understanding, X-ray inspection was done in the radial direction of the side-drilled hole (Fig. 7). This defect was detectable in X-ray too. Afterwards, this side-drilled hole was filled with graphite powder and the above non-destructive evaluation (NDE) inspections were repeated. Ultrasonic response was not affected by filling of the graphite powder. In the reX-ray inspection, this defect was not detectable. Though it is expected, it is a demonstration of difference between X-ray and ultrasonic inspection sensitivity.

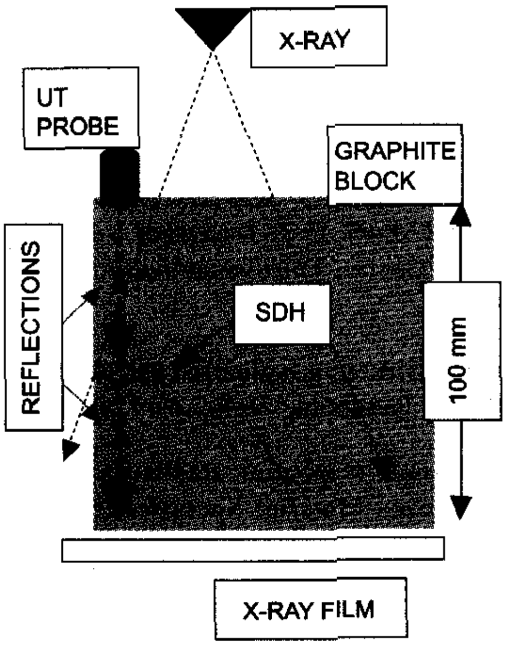

Figure 7. Side-drilled hole made on graphite block being inspected by ultrasonic technique and X-ray technique.

This demonstration also gave confidence that indication obtained during inspection of products are from defects present in the material.

6. STATICAL ANALYSIS OF DEFECTS

After inspection of 30 products, defects indications obtained were 300 numbers in total. To understand statistically, the amplitude of defects indications were compared with that of reference and geometric mean size of the defects was computed. It was found that mean size is 5 per cent of the reference (Fig. 8). With this background,

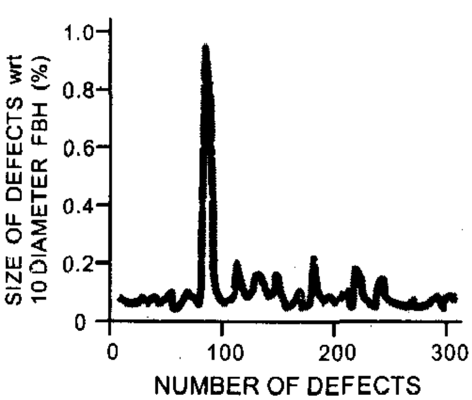

Figure 8. Equivalent size of defects observed on graphite products compared with 10 diameter FBH.

it is now possible for the NDE professional and user to identify abnormal defects, by considering conventional practices of accepting defects below 3 times standard deviation or likewise.

7. APPLICATIONS

Graphite is an important material used in rocket nozzles as nozzle throat inserts. It is customary that these products undergo several tests like static test, acoustic test, vibration test, etc. for verifying certain design and application-related factors. This dry-coupled pulse echo ultrasonic test (DCPEUT) method developed by the authors is the only method to monitor the impact of acoustic test of nozzle assembly. Inspection was carried at the Vikram Sarabhai Space Centre (VSSC) and indications observed were recorded. This nozzle was then transported to the National Aerospace Laboratory (NAL), Bangalore, for acoustic test and the ultrasonic testing inspection was repeated prior to acoustic test. After acoustic test, inspection conducted earlier was repeated. Also, indications observed earlier were closely monitored and found that there was no adverse impact on the material. This nozzle was used in a solid rocket booster which had undergone static test. It was observed that this nozzle has functioned normally. On number of occasions, this method was utilised in fabrication-related problems, such as to identify the extent of impact damages, defects locations for salvaging, etc. This method was also used to assess the overall quality of the sample solid graphite blocks obtained from the supplier prior to its bulk purchase and is continuously being used to inspect various graphite products at the identified stages of production.

8. CONCLUSION

After development, standardisation and initial application, DCPEUT is currently being employed on products for regular inspection as well as an investigating tool.

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