ANALYSIS OF RELATION BETWEEN ULTRASONIC TESTING AND MICROSTRUCTURE: A STEP TOWARDS HIGHLY RELIABLE FAULT DETECTION

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Abstract:

In conventional ultrasonic nondestructive condition monitoring, the testing personnel use their testing experience to interpret defects by analyzing the ultrasonic echo. Owing to the coarse material structure, the ultrasonic waves are more attenuated and from time to time they give a deceitful impression of defect and thus provide unreliable results. The conventional inspection method is too subjective to be used and highly relies on the effectiveness of testing personnel and consequently inspection reliability is very low. Therefore, to mitigate these limitations, a multi-interrogation ultrasonic technique and correlation of several parameters such as attenuation, acoustic velocity and grain size with material features are covered by this paper.

1 Introduction

Non Destructive Testing (NDT) is the testing of materials, surface or internal flaws or metallurgical condition, without rendering it unfit for service.
There are various NDT methods for inspecting the internal defects of complex surface parts, e.g., radiography, eddy flow, ultrasonic, etc. Among these testing techniques, ultrasonic testing has a paramount role attributable to strong penetration, favorable direction, high sensitivity, overall comparatively low-cost, and being harmless to the human body and the material of the parts. Furthermore, ultrasonic [1, 2, 3, 4] is a highly efficacious and a non destructive condition monitoring method that helps in detecting even incipient faults. Therefore Mean Time between Failure (MTBF) is increased and Mean Time to Repair (MTTR) is reduced by improving trouble shooting capabilities. Therefore, ultrasonic nondestructive testing methods [5] play a paramount role in the physical characterization of engineering materials and assess their quality and serviceability in structures. At present, a wide range of different NDT methods are available, although approaches to ultrasonic velocity have been extensively used to evaluate the density and the elastic constants of metals and alloys.
Ultrasonic evaluation enables us to determine [6] elastic modulus and acoustic properties even though a single technology cannot cover everything. Each of the condition monitoring techniques has both benefits and hindrances. Therefore, the recommendation is to be merged into two or more technologies to confirm reliable results.
The predominant parameters in attenuation measurement are the relationships between the

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wavelength of the ultrasonic wave and the grain size [7, 8, 9, and 10]. The relation is as follows:
High attenuation occurs when $\lambda < D$, where λ = wavelength, D = grain diameter. Low attenuation occurs when $\lambda > D$.
Also, high attenuation is associated with high level of damage and low attenuation to low-level of damage. Therefore, if the wavelength of the ultrasonic wave is not appropriately selected, then it will consequently give a deceitful impression of defects occurring in the material. Particularly, if we have the grain size (Using SEM) of the specimen, then it is possible to choose an appropriate testing wavelength.
The scanning electron microscopy [11] is a highly efficacious and accurate method. Therefore, it is possible to determine grain size more accurately by SEM. It consists of an electron gun producing an electron beam that is collected at a detector after being scattered from the molecules of the specimen and sent to a cathode ray tube for display.
The primary idea is to associate ultrasonic condition monitoring technique with grain size analysis to enhance the effectiveness and reliability of fault detection. The ideal aim is to keep up asset availability, reduce maintenance cost and improve safety conditions.

2 Experimental Approach

2.1 Material Selection

Mild Steel is the common form of steel due to its relatively low price although it provides material properties that are acceptable for multifarious applications. Mild steel has a relatively low tensile strength although it is cheap and malleable. In P355N, the tensile strength is significantly improved by normalizing. Particularly this material is best suited for high pressure applications such as spiral casing of the turbine. The density of material is d = 8030 kg/m3.

2.2 Chemical Composition of P355N as Determined by (Optical Emission Spectroscopy) OES

OES is used to determine chemical composition of the specimen. A cylindrical specimen of the diameter 0.01 m and length 0.015 m prepared for this analysis.

2.3 Sample Preparation

First of all, samples of the diameter 0.01 m have been prepared, and then Clock Finishing Machine used to obtain mirror finishing on the side of the specimen. This is necessary to eradicate scratches over the specimen.

2.4 Analysis by Imaging Microscopy and Scanning Electron Microscopy

The Imaging Microscopy instrument renders visible the micro structural images of the sample. It is necessary to review the specimen by Imaging Microscopy to ensure that the specimen is ready for SEM. The Scanning Electron Microscopy is a highly efficacious and accurate method that by employing an electron gun produces an electron beam that is collected at a detector and after being scattered it is sent to a cathode ray tube for display. Consequently, the value of grain size of specimen was analyzed.

Table 1. Chemical Composition of P355N EN 10028-3-2009 as Determined by OES

Element	By max%	Element	By max%
C	0.18	Cr	0.30
Si	0.50	Cu	0.30
Mn	1.10-1.70	Mo	0.08
P	0.025	Nb	0.05
S	0.015	Ni	0.50
Al	0.020	Ti	0.03
N	0.012	V	0.01

2.5 Grain Size Evaluation (As per ASTM) [12]

This method is better known as a planimetric method or Jeffries method. The steps are as follows:
(a). Inscribe a circle of the known area (*A)* on the image of magnification (*M)*. Here we inscribe a circle of the diameter $D = 79.8$ mm and the area $A = 5000$ mm^2 on the image of magnification $M = 1000$.
(b). Count the number of grains that are completely within the area.(c). Count the number of grains that are partly in the area. d). Divide the result from (c) by 2 i.e. 22 / 2 = 11
(e). Add the result from (d) to result from (b) i.e., 32 + 11 = 43
(f). Divide the result from (e) by area "*A"* i.e., 43/5000 = 0.0086 grain/mm^2.
(g). Convert the result from (f) to grain/m^2 @ 100X by multiplying it by $(M/100)^2$ i.e. 0.0086 $(1000/100)^2 = 0.86$
(h). Use the table provided below to find the diameter of the average grain section.

Figure 1. Sample Preparation.

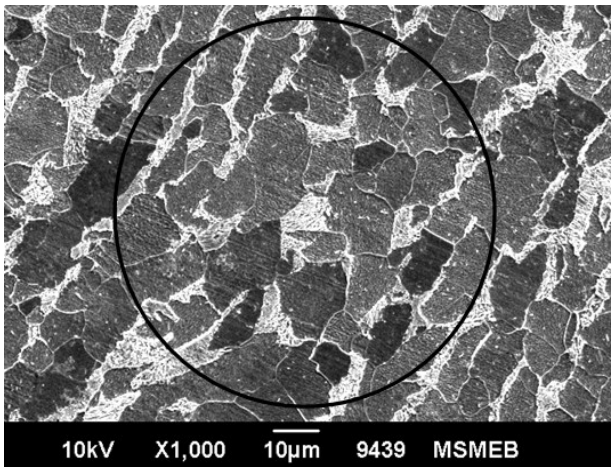

Figure 2. Circle Inscribed on SEM Image.

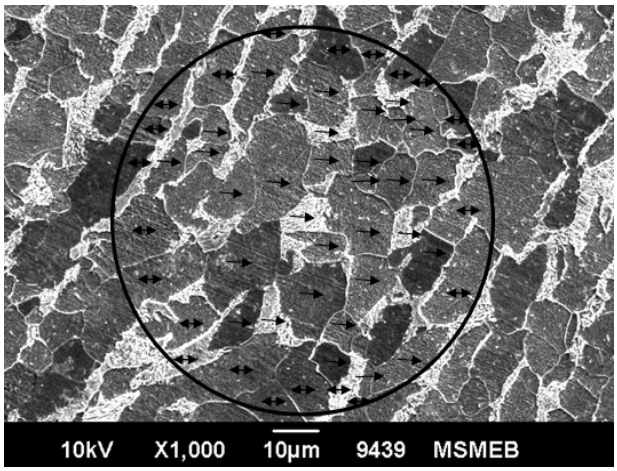

Figure 3. Grain Counting on SEM Image.

Table 2. Finding from SEM Image

Notation	Meaning	Total
→	Completely within circle	32
↔	Partially within circle	22

(i). Using the table below, we found that the value of grain per m^2 was 0.86 lying between two values, so that linear interpolation technique is therefore used to find an accurate value that is explained as follows: $d_p = d_1 + \{(d_2 - d_1) / (\mu_2 - \mu_1)\} (\mu - \mu_1)$, where d_p is an unknown data against quantity µ.
$d_1 = 11$; $d_2 = 10$; $\mu_2 = 1$; $\mu_1 = 0.79$ and $\mu = 0.86$
$d_p = 11 + \{(10 - 11) / (1 - 0.79)\} (0.86 - 0.79)$
$= 10.66$ µm or 0.00001066 m

Table 3. Micro Grain Size Relationships computed for Uniform Randomly Oriented Equiaxed Grains [12]

ASTM micro grain size no. (G)	Diameter of average grain section		Average Intercept Distance (D) mm	Intercept count n/l per mm	Area of average grain section mm^2	Calculated number of grains per mm^3	Average grains per mm^2 1X@ (n/a)*
	Nominal (d_m) mm	Feret's (d_t) mm					
00^E	0.51	0.570	0.453	2.210	0.258	6.11	3.88
0	0.36	0.403	0.320	3.125	0.129	17.3	7.75
0.5	0.30	0.339	0.269	3.716	0.0912	29.0	11.0
1.0	0.25	0.285	0.226	4.42	0.0645	48.8	15.50
1.5	0.21	0.240	0.190	5.26	0.0456	82	21.9
$(1.7)^F$	0.200	0.226	0.177	5.64	0.0400	100	25
2.0	0.18	0.202	0.160	6.25	0.0323	138	31
2.5	0.15	0.170	0.135	7.43	0.0228	232	43.8
	µm	µm	µm		$mm^2 . 10^{-3}$		
3.0	125	143	113	8.84	16.1	391	62
$(3.2)^F$	120	135	106	9.41	14.4	463	69.4
3.5	105	120	95	10.51	11.4	657	87.7
$(3.7)^F$	100	113	89	11.29	10.0	800	100
4.0	90	101	80	12.5	8.07	1105	124
4.5	75	85	67.3	14.9	5.70	1859	175
$(4.7)^F$	70	79	62	16.1	4.90	2331	204
5.0	65	71	56.6	17.7	4.03	3126	248
$(5.2)^F$	60	68	53.2	18.8	3.60	3708	278
5.5	55	60	47.6	21.0	2.85	5258	351
$(5.7)^F$	50	56	44.3	22.6	2.50	6400	400
6.0	45	50	40	25	2.02	8842	496
$(6.4)^F$	40	45	35.4	28.2	1.60	12500	625
6.5	38	42	33.6	29.7	1.43	14871	701
$(6.7)^F$	35	39	31.0	32.2	1.23	18659	816
7.0	32	36	28.3	35.4	1.008	25010	992
$(7.2)^F$	30	34	26.6	37.6	0.900	29630	1111
7.5	27	30	23.8	42	0.713	41061	1403
$(7.7)^F$	25	28	22.2	45.1	0.623	51200	1600
	µm	µm	µm		$mm^2 . 10^{-6}$	$x10^6$	$x10^3$
8.0	22	25	20.0	50	504	0.0707	1.98
$(8.4)^F$	20	23	17.7	56.4	400	0.1000	2.50
8.5	19	21	16.8	59.5	356	0.1190	2.81
9.0	16	18	14.1	70.7	252	0.200	3.97
$(9.2)^F$	15	17	13.3	75.2	225	0.237	4.44
9.5	13	15	11.9	84.1	178	0.336	5.61
10.0	11	13	10.0	100	126	0.566	7.94
$(10.3)^F$	10	11.3	8.86	113	100	0.800	10.00

@ Table 3 contains the value of grain/m^2 at magnification 1X therefore to obtain grains/m^2 at 100X multiply this value by 10^{-4} as per standard ASTM procedure for measurement of grain size.

* n/a stands for number of grains per unit area.

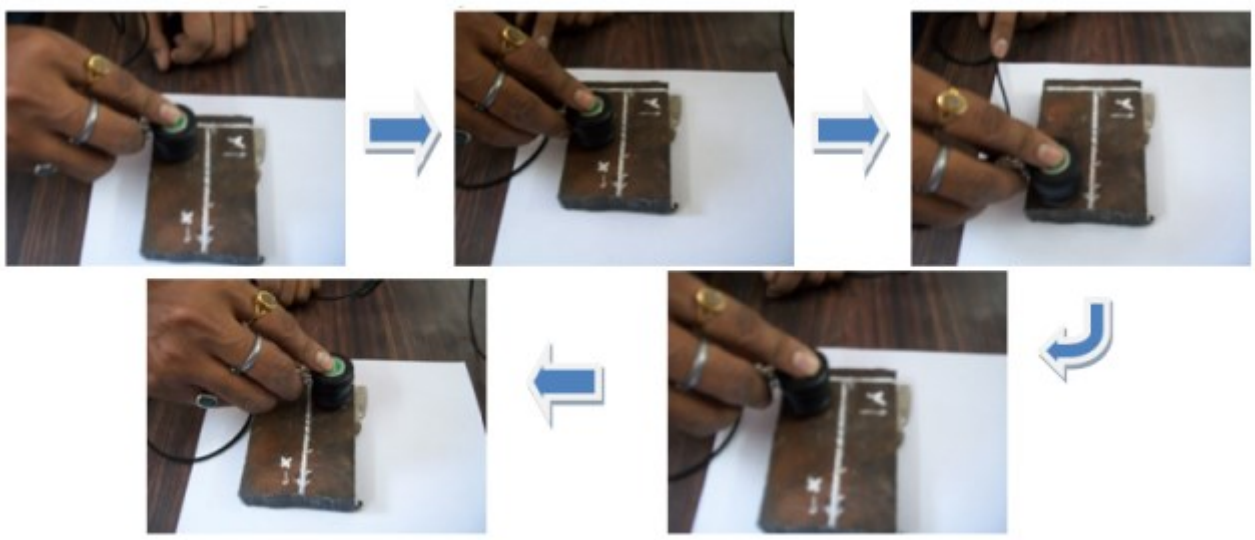

Figure 4. Measurement of Longitudinal Velocity.

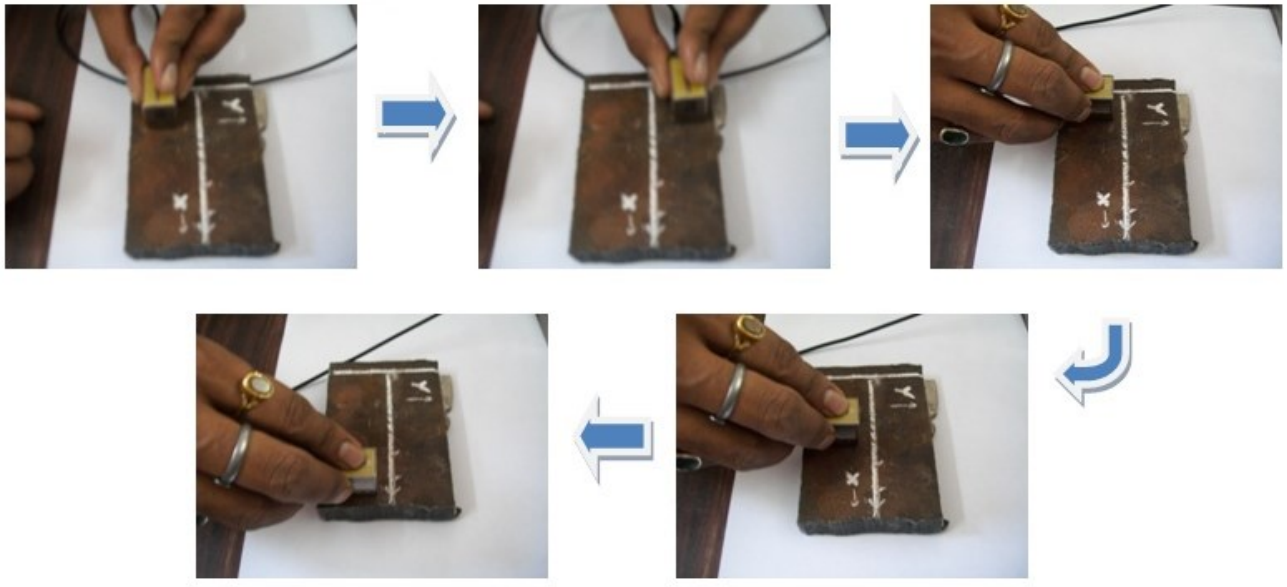

Figure 5. Measurement of Shear Velocity.

2.6 Ultrasonic Testing and Evaluation

The instrument suitable for this analysis is Epoxh-XT flaw detector. First, made two axes on a specimen, and then do the testing by moving the probe of flaw detector along the axis. With this flaw detector and by following parameters measured Longitudinal Velocity and Shear Velocity Measurements - there are basically [13, 14, 15] two modes of wave propagation, namely, the longitudinal and transverse (or shear) ones. If the waves propagate in the same direction as the Particle motion, then it is a longitudinal wave and corresponding velocity is longitudinal velocity. If the waves propagate at the right angle or transverse to the particle oscillation, then it is a shear wave and corresponding velocity is shear velocity.

Firstly, the vernier caliper is used to measure the thickness of the sample. An ultrasonic probe with an angle 0° and frequency 5 MHz is used to measure longitudinal velocity, then a probe is placed at different locations over the specimen for determining the time of flight (TOF), which is shown in Figure 4. Finally, Equation 1 is used to calculate the longitudinal velocity.

An ultrasonic probe with an angle of 70° and frequency of 2 MHz is used for measuring shear velocity, and a probe is placed at different locations over the specimen for determining the time of flight (TOF), which is shown in Figure 5. Next, Equations 2 and 3 are used to calculate the shear velocity:

$$V_{Logitudinal} = 2T/t, \quad (1)$$

$$Cos\theta = T/d, \quad (2)$$

$$V_{shear} = 2d/t, \quad (3)$$

where, T = Thickness of Sample, t = TOF, d = Sound Path, θ = Angle of Transducer.

Ultrasonic attenuation measurement - When sound travels through a medium, the sound intensity diminishes with distance. This weakening is the result of scattering and absorption of the waves. Scattering is a sound reflection in directions different from the original direction of propagation. On the other hand, absorption is the sound energy conversion into other forms of energy. The attenuation is the combined result of scattering and absorption [14]. Therefore, the micro-structure of the material exhibited an influence on the ultrasonic wave propagation.

$$\alpha l = ln\ (A_{final}/A_{initial}), \quad (4)$$

where, α = attenuation coefficient in Nepers, A = amplitude in volts, A_{final} = max or initial amplitude, $A_{Initial}$ = min or final amplitude.

Evaluation of Elastic Constants- It is possible to determine elastic constants of a material [16] by putting sound velocities and density of the specimen in following relation:

$$C = (c_{11}/\rho)^{1/2}, \quad (5)$$

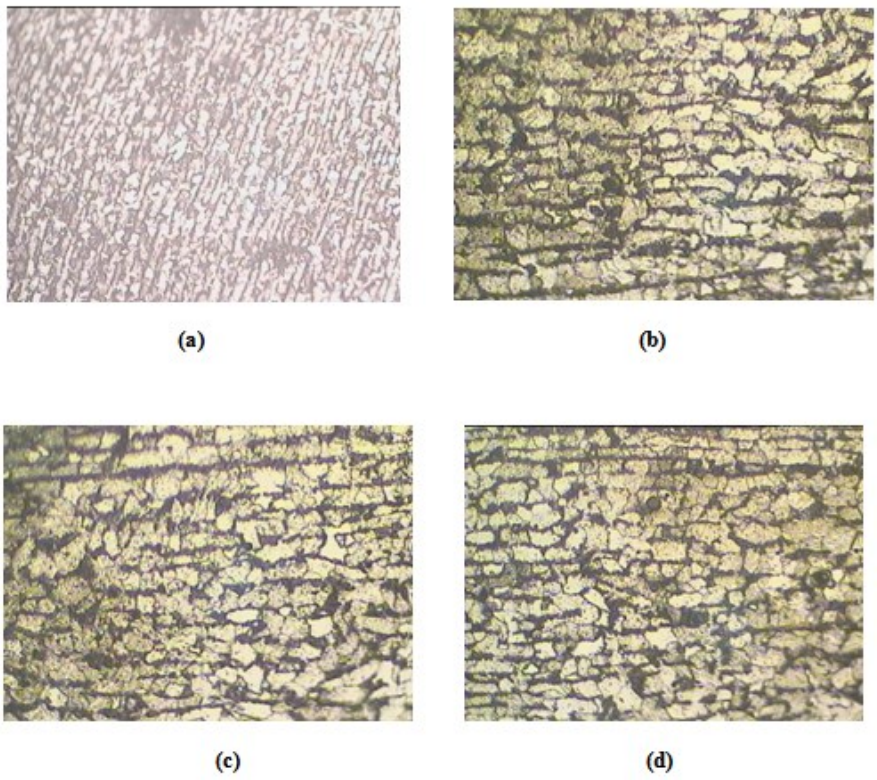

Figure 6. Microstructural Images of Specimen by Imaging Microscopy

3. Results

As discussed in sections 2.3 and 2.4, the sample is prepared and then done after clock finishing micro-structural analysis by using imaging microscopy and scanning electron microscopy. Consequently, the imaging microscopy images of the specimen (Figure

6) show that the specimen is scratch free and therefore ready for micro structural analyses.

Furthermore, the SEM images of the specimen (Figure 7) provide following information's-

- It is clear from these images that the specimen is free from defects.
- The SEM images clearly show that the material has pearlite and ferrite. The dark areas show that the pearlite exists and the light regions show that the ferrite exists.
- These images help in predicting grain size. We know that high decay of the ultrasonic wave occurs when $\lambda / D < 1$ and low attenuation occurs when $\lambda / D > 1$ (Where λ = wavelength, D = grain diameter). It means that if we have a grain size, then for enough penetration, the value of the wavelength (λ) should be greater than the value of the grain diameter (D).
- Here we evaluated the diameter of grain for material MS P355N as 10.66 μm or 0.00001066 m. Now if we know the diameter, it is particularly possible to select the ultrasonic wave frequency in such a way that $\lambda / D > 1$. An ultrasonic flaw detector is used to measure time of flight and maximum and minimum amplitudes. Equations 1, 2, 3, 4 and 5 are used to measure longitudinal velocity, shear velocity, the attenuation coefficient and elastic constants.
- Attenuation Coefficient (α) = -0.027 Nepers/mm
  = -27 Nepers/m.

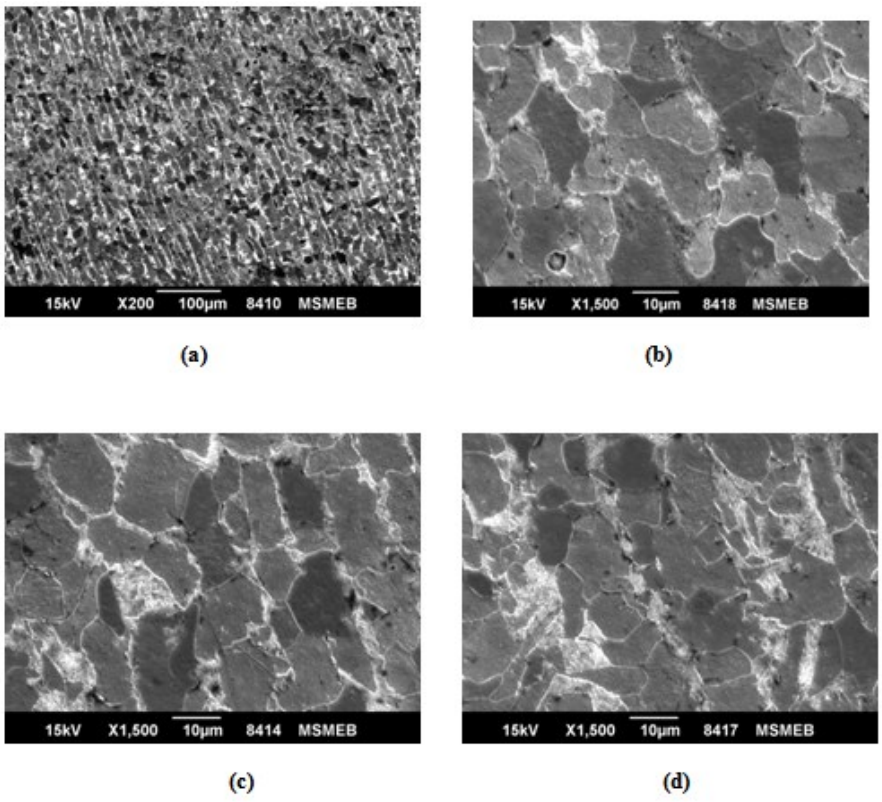

Figure 7. Microstructural Images of Specimen by Scanning Electron Microscopy.

Table 4. Evaluation of Attenuation Coefficient

X-axis-

Position	$A_{Initial}$	A_{final}
1	89.50	1.25
2	89.50	1.25
3	89.50	1.25

Table 4. Evaluation of Attenuation Coefficient (Continued)

Y-axis

Position	$A_{Initial}$	A_{final}
1	89.50	1.25
2	89.50	1.25

Elastic Modulus:

Table 5. Evaluation of Longitudinal Velocity and Elastic Modulus

X-axis-

Position	Longitudinal Velocity (m/s)	Elastic Modulus (GPa)
1	4778	183.3
2	4786	183.9
3	4764	182.2

Y-axis

Position	Longitudinal Velocity (m/s)	Elastic Modulus (GPa)
1	4778	183.3
2	4757	181.7

Shear Modulus:

Table 6. Evaluation of Shear Velocity and Shear Modulus

X-axis-

Position	Shear Velocity (m/s)	Shear Modulus (GPa)
1	2288	42.03
2	2408	46.56
3	2473	49.11

Y-axis

Position	Shear Velocity (m/s)	Shear Modulus (GPa)
1	2288	42.03
2	2408	46.56

Cost of analysis:

a) The table below shows the Cost of Testing (In Indian Currency Rupees) per Sample at Maulana Azad National Institute of Technology, India where the above analysis and testing done.
b) Sample Preparation Cost - Rs 400 /-
c) Total Cost - Rs 5,671/-

Table 7. Cost of Analysis

Testing/Equipment	Cost of Testing (Rs) / Sample in Maulana Azad National Institute of Technology, India
Clock Finishing	400
Imaging Microscopy	1000
SEM	3371
Ultrasonic Testing	500
Total	5271

4. Conclusion

In traditional ultrasonic non destructive testing (NDT) performed according to the ultrasonic echo, the testing personnel judges internal defects by his or her own experience. Due to the material coarse structure, a qualitative assessment could occasionally yield unreliable results. Since the traditional inspection method is too subjective, inspection reliability and efficiencies are low. Particularly, to enhance the effectiveness and reliability of ultrasonic testing, it is necessary to decide on the ultrasonic wavelength by keeping in mind the grain size.

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