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Ultrasonics: A Technique of Material Characterization

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1. Introduction

The material science and characterization is a field concerned with inventing new materials and improving previously known materials by developing a deeper understanding of properties under different physical conditions. The properties of materials depend upon their composition, structure, synthesis and processing. Many properties of materials depend strongly on the structure, even if the composition of the material remains same. This is why the structure-property or microstructure property relationships in materials are extremely important.

On the basis of different physical properties, the materials are classified mainly into five categories: (a) metals and alloys, (b) semi-metals and semiconductors, (c) ceramics, glasses and glass-ceramics, (d) polymers, and (e) composite materials. Functional classification of materials includes aerospace, biomedical, electronic, energy and environmental, magnetic, and optical (photonic) materials. The structural classification of materials are of two types as (a) crystalline (single crystal and polycrystalline), and (b) amorphous.

The selection of a material and the potential to be manufactured economically and safely into useful product is a complicated process. It requires the complete knowledge of constituent material not only after production but also in processing. Increased competition and need of higher productivity and better products from material producing industries are creating more stringent requirements for process and quality control. This demands the characterization of materials. The topic material characterization essentially includes the evaluation of elastic behaviour, material microstructure and morphological features, associated mechanical properties etc. The destructive, semi-destructive and non-destructive testing (DT & NDT) techniques are available for the complete characterization. These characterization techniques are the basic tool for the quality control and quality assurance of the material or component or product.

Ultrasonics, which is a sub category of acoustics deals with acoustics beyond the audio limit. The application of ultrasonics falls into two categories as high frequency- low intensity and low frequency – high intensity. The low intensity application carries the purpose of simply transmitting energy through the medium in order to obtain the information about the medium or to convey information through the medium. High intensity application deliberately affects the propagation medium or its contents. So, the low intensity and high

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intensity application of ultrasonic wave belongs in non-destructive and destructive techniques of characterization respectively.
The quantities, ultrasonic velocity and attenuation are the important parameters, which are required for the ultrasonic non-destructive technique of material characterization. The ultrasonic velocity is related to the elastic constants and density of material. Hence, it gives the information about the mechanical, anisotropic and elastic properties of medium through it passes. It is also important in low temperature physics because it is involved in the evaluation of Debye average velocity and Debye temperature. Ultrasonic velocity in nanofluid depends on the concentration of nano-particles of material dispersed in polymer matrix, thus it is not only important at bulk scale but also at nanoscale. When the ultrasonic wave propagates through the medium, its some part of energy is attenuated through the different mechanism like thermal loss, scattering, absorption, electron-phonon interaction, phonon-phonon interaction, and magnon-phonon interaction etc., called as ultrasonic attenuation. The coefficient of ultrasonic attenuation correlates several physical properties like elastic constants, guruneisen parameter, thermal conductivity, thermal relaxation time, acoustic coupling constant, thermal energy density, specific heat, particle size, density, Debye average velocity, and concentration etc. Thus, the material can be characterized with the knowledge of ultrasonic parameters under different physical conditions.
Normally, the ultrasonic NDT of material characterization are used for the determination of (a) elastic constants (Shear modulus, Bulk modulus, Young modulus and lame modulus), (b) microstructure (grain size, texture, density etc.), (c) discontinuity (porosity, creep damage, fatigue damage etc.), and mechanical properties (tensile strength, shear strength, hardness etc.). The new work in this field also provides the characterization of advanced and smart materials like GMR etc. Now a day, the synthesis and characterization of nanomaterials and nanofluids are also in touch of ultrasonic NDT&E.
In this chapter, ultrasonic material property characterization has been considered. Initially, it covers information about the ultrasonic wave, its mode of propagation and characteristic properties. After this, a brief study of ultrasonic velocity and attenuation in solid has been discussed, which covers the theoretical evaluation and experimental measurements of these ultrasonic parameters. Later on, the characterization of different material (metals, alloys, platinum group metals, nanomaterials, nanofluid, semiconductor etc) has been discussed on the basis of these ultrasonic quantities and related parameters.

2. Ultrasonic wave

As a sub category of acoustics, ultrasonics deals with the acoustics above the human hearing range (the audio frequency limit) of 20 kHz. Unlike audible sound waves, the ultrasonic waves are not sensed by human ear due to the limitations on the reception of vibrations of high frequency and energies by the membrane. Ultrasonic wave exhibits all the characteristic properties of sound. Ultrasonic vibrations travel in the form of wave, similar to the way light travels. However, unlike light waves, which can travel in vacuum, ultrasonic wave requires elastic medium such as a liquid or a solid. The wavelength of this wave changes from one medium to another medium due to the elastic properties and induced particle vibrations in the medium. This wave can be reflected off with very small surfaces due to having much shorter wavelength. It is the property that makes ultrasound useful for the non-destructive characterization/testing of materials. The knowledge of generation/detection of ultrasonic wave and its characteristics is important for its precise and suitable application.

2.1 Sources of ultrasonic wave

The ultrasonic wave (UW) can be generated with the mechanical, electrostatic, electrodynamic, electromagnetic, magnetostrictive effect, piezoelectric effect, and laser methods.

Mechanical method or Galton Whistle method is an initial method for the generation of ultrasonic wave. This uses mechanical shock or friction for the generation of wave in frequency range of 100 kHz to 1 MHz. A high frequency of ultrasonic wave (10 to 200 MHz) can be generated using electrostatic method. The magneto inductive effect is used in electrodynamic method for the production of ultrasound. The mechanical deformation in ferromagnetic material in presence of magnetic field is called as magnetostriction. This phenomenon is most pronounced in metals such as nickel, iron, cobalt and their alloys. Magnetostriction effect is used for generation of ultrasonic wave in magnetostrictive effect method. Most common method for generation of ultrasound is the Piezoelectric effect method. In this method, inverse Piezoelectric effect is used for generation of UW. When a laser light incident on the surface of suitable material, its some portion of energy is absorbed at the surface with in the skin depth and rest get reflected. The absorbed energy produces tangential stress and then bulk strain through transient surface heating; as a result UW is produced in concerned medium.

2.2 Transducers for ultrasonic wave

The device that converts one form of energy to another form is called as transducer. An ultrasonic transducer converts electrical energy to mechanical energy, in the form of sound, and vice versa. The main components are the active element, backing, and wear plate (Fig.1).

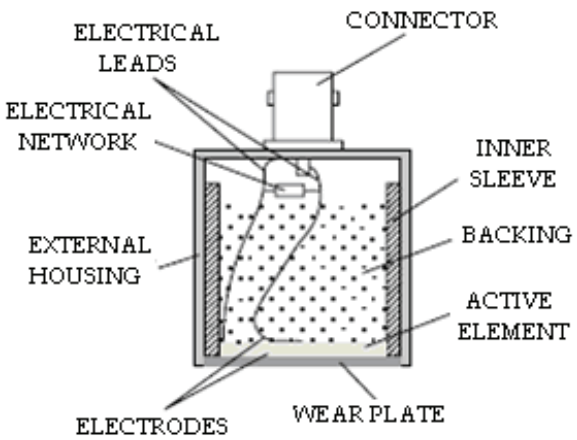


Fig. 1. Basic figure of an ultrasonic transducer

a. The Active Element

The active element, which is piezo or ferroelectric material, converts electrical energy such as an excitation pulse from a flaw detector into ultrasonic energy. The most commonly used materials are polarized ceramics which can be cut in a variety of manners to produce different

wave modes. New materials such as piezo polymers and composites are also being employed for applications where they provide benefit to transducer and system performance.

b. Backing

The backing is usually a highly attenuative, high density material that is used to control the vibration of the transducer by absorbing the energy radiating from the back face of the active element. When the acoustic impedance of the backing matches with the acoustic impedance of the active element, the result will be a heavily damped transducer that displays good range resolution but may be lower in signal amplitude. If there is a mismatch in acoustic impedance between the element and the backing, more sound energy will be reflected forward into the test material. The end result is a transducer that is lower in resolution due to a longer waveform duration, but may be higher in signal amplitude or greater in sensitivity.

c. Wear Plate

The basic purpose of the transducer wear plate is to protect the transducer element from the testing environment. In the case of contact transducers, the wear plate must be a durable and corrosion resistant material in order to withstand the wear caused by use on materials such as steel. For immersion, angle beam, and delay line transducers, the wear plate has the additional purpose of serving as an acoustic transformer between the high acoustic impedance of the active element and the water.

Now a days, following type of transducers are in use for different applications.

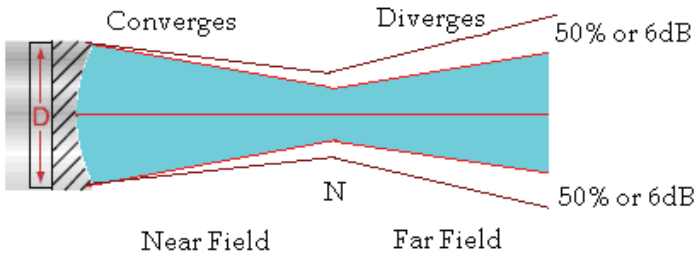
1. Normal beam or single element or delay line transducer
2. Dual element transducer
3. Angle beam transducer
4. Immersion transducer
5. Mechanical focous transducer
6. Electronic time delay focouing or array transducer
7. Capacitive transducer

In most of applications piezoelectric transducers are used for generating and receiving the ultrasonic waves.

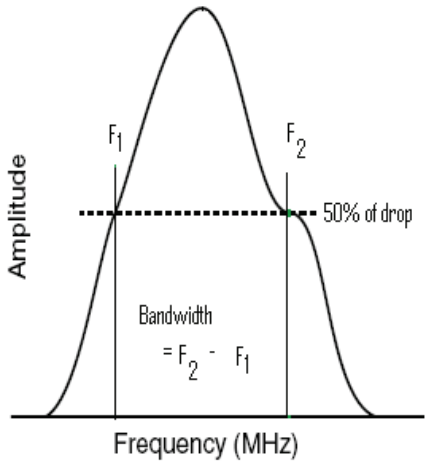
2.3 Characteristics of ultrasonic wave

For the appropriate choice of ultrasonic wave with suitable frequency and intensity, the knowledge of some essential parameters related to transducer is important. The characteristic parameters of ultrasonic wave are:

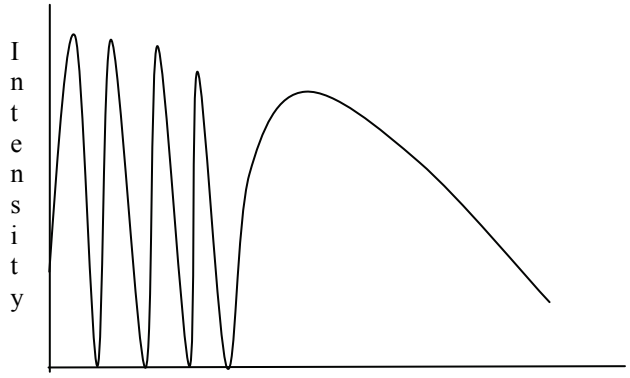
1. Sound Field (Near field and far field): The sound field of a transducer is divided in two two zones; the near field region or Fresnel zone and far field region or Fraunhofer zone. In the near field region the ultrasonic beam converges and in the far field it diverges. The near field is the region directly in front of transducer where echo amplitudes goes through a series of maxima and minima and ends at the last maximum, at the distance N ($N = D^2v/4C = D^2/4\lambda$; N: near field distance, D: Element diameter, v: frequency, c: material sound velocity, and λ: wavelength) from the transducer (Fig.2). The intensity variation along and across the axial distance up to near field region is approximately constant and after which it decreases. The beam boundary defines the limits of the beam to the point where the disturbance ceases to exist or falls below the threshold value. The beam intensity at the boundary is reduces to one half (6dB) of the intensity at the beam axis (Fig.2).



(a)



(b)



(c)

Fig. 2. (a) sound field of transducer, (b) amplitude verses frequency of UW, (c) intensity of UW verses axial distance from transducer.

2. Focal zone: The starting and ending points of the focal zone on axis of transducer are located where pulse echo signal amplitude drops to -6dB of the amplitude at the focal point. If Z_B and Z_E are the beginning and end of the focal zone from the transducer then, then focal zone will be difference of them. The length of focal zone (F_Z) is equal to $NS_F^2[2/(1+0.5S_F)]$; where S_F: Normalized focal length=F/N, F: focal length, N: near field distance.
3. Beam diameter: It is a parameter, which defines the transducers sensitivity. Smaller the beam diameter, the greater amount of energy is reflected by the flaw. At -6dB drop of intensity, the beam diameter (BD) at the focus is equal to $0.2568DS_F$ or 1.02FC/vD. For the flat transducer, normalized focal length have value one. The Fig.3 represents the clear picture of focal zone and beam diameter.

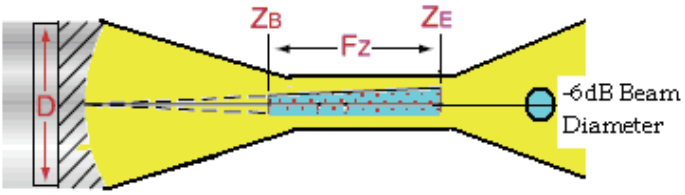


Fig. 3. Focal zone of transducer and beam diameter

4. Beam spread or half angle: The spreading of ultrasonic beam always take place as the wave travel from the transducer. In the near field, the beam has a complex shape that narrows, while in the far field it diverges. The divergence angle or beam spread angle (θ) is equal to $\sin^{-1}(K\lambda/D)$ or $\sin^{-1}(KC/\nu D)$. Where K is a constant which depends on shape of transducer, edge of beam and method used to determine the beam spread.It is clear that beam spread from a transducer can be reduced by selecting a transducer with higher frequency or larger element diameter or both. Fig.4 shows a simplistic understanding of beam spread angle.

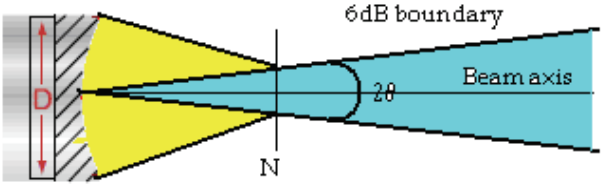


Fig. 4. Ultrasonic beam divergence and angle of divergence

2.4 Detection of ultrasonic wave

There are various methods for the detection of UW. The methods are based on the principle of piezoelectric, electrostatic and magnetostriction effects. The classical methods like mechanical and optical methods are also used for the detection of UW. Normally the devices based on piezoelectric effect are used commercially for the detection of UW, these devices comes in electrical method of detection.

The prime division of detection in electrical method are the Interferometer or continuous wave (CW) and Pulse technique (PT) methods. In CW method, the UW generated by the

source is passed through the concerned medium/specimen, which is reflected from the reflecting plate. The reflecting plate is adjusted towards the source such that the current in the oscillator of the source changes periodically in maxima or minima. The maximum in current corresponds to the half of wavelength interval due to the formation of standing wave between source and plate. This method is preferred in low frequency region for the measurements of ultrasonic parameters in liquids.
The Pulse technique is utilized for detection or measurement of transit time in both liquids and solids. It uses piezoelectric transducer with and without delay lines for the production and detection of UW. In this method short duration electric pulses generates the UW with the broadband piezoelectric transducer. The generated longitudinal or shear wave are transmitted to the specimen. The reflected wave or echo by the medium are detected by the transducer on the principle of direct piezoelectric effect and echo pattern is obtained. Using this pattern, the exact transit time needed for a signal to travel between the front and back surface of the specimen or concerned medium is determined, that is used for determination of ultrasonic velocity and attenuation. The different pulse techniques for precise measurements or detection of UW are Sing around, Pulse superposition, Pulse echo overlap, Cross-correlation, Phase slope and Pulse transmission method. Hydrophones are also piezoelectric transducer that generates electrical signal when subjected to pressure change or UW under water. It can detect UW in air, but will be less sensitive due to its design as having a good acoustic impedance match with water.

3. Material characterization techniques (NDT & DT)

The two major classification of material characterization technique are non-destructive testing (NDT) and destructive testing (DT). Under destructive technique (such as: tensile testing, creep testing, impact testing, torsion testing, hardness testing etc.) of characterization the tested material or product can not be used again. The destruction of test object usually makes this type of test more costly. Non-destructive testing technique is a specific procedure whereby the service ability of materials or components is not impaired by testing process. The various methods like visual testing, liquid penetrant testing, magnetic particle testing, eddy current testing, radiographic testing, ultrasonic testing, leak testing, thermography and neutron radiography are the NDT technique of material characterization. Among the various non-destructive testing and evalution (NDT&E) plays a key role in material characterization.Ultrasonic properties provide important diagnostic for microstructural properties as well as deformation processes in a material, controlling material behaviour based on the physical mechanism to predict future performance of the materials.

4. Classification of ultrasonic application and testing

The ultrasonic testing involves both the low intensity and high intensity ultrasonic wave for the characterization, that belongs in non-destructive and destructive techniques of characterization respectively. Uses of high intensity and low frequency ultrasonic wave includes medical therapy and surgery, atomization of liquids, machining of materials, cleaning and wielding of plastics and metals, disruption of biological cells, and homogenization of materials. The low intensity and high frequency ultrasonic waves are applied for medical diagnosis, acoustical holography, material characterization etc. The low

intensity ultrasoud measurements provides a good diagnosis of material property and process control in industrial apllication (Alers, 1965; Green,1973; Lowrance, 1975; Renolds, 1978; Teagle, 1983; Smith, 1987; Varry, 1987; Thompson,1996; Jayakumar, 1998; Kumar, 2001; Raj, 2003; Roth, 2003; Blodgett, 2005).

5. Ultrasonic NDT as a material characterization

There are four mode of propagation by which an ultrasonic wave can propagate in a medium, as: longitudinal or compressnal wave, transverse or shear wave, surface or Rayleigh wave and plate or lamb wave. The most common methods of ultrasonic examination utilize the longitudinal waves or shear waves.

Ultrasonic velocity or attenuation are the parameters that correlate to structural inhomogenities or flaw size atomistic (interstitials), elastic parameters, precipitates, dislocations, ordering of molecules in liquid crystals, phase transformations, porosity and cracks, concentration of different components of alloys or mixed crystal system, vacancies in lattice sites, size of the nanoparticles in nano-structured materials, electrical resistivity, specific heat, thermal conductivity and other thermophysical properties of the materials depending upon the different physical conditions like temperature, pressure, crystallographic orientation, magnetization etc. Thus, ultrasonic study of a material provides information about elastic constants, microstructure, discountinuty, and mechanical properties under different condition.

5.1 Ultrasonic velocity

On the basis of mode of propagation there are four types of ultrasonic velocities, as longitudinal, shear, surface and lamb wave velocity. Longitudinal and shear wave velocities are more important for the material characterization because they are well related to elastic constants and density. However, it is independent of frequency of wave and dimension of the given material. The mechanical behaviour and anisotropic properties of the material can be well defined on the knowledge of ultrasonic velocity. The mathematical formulations and measurement techniques for ultrasonic velocity are detailed in following heads.

5.1 A Ultrasonic velocity, related parameters and its theoretical evaluation

The mechanical properties of the solids differ from those of fluids in two important respects. Firstly, greater binding forces exist between their constituent atoms so that they support shear stress. Secondly, anisotropy may occur, especially in single crystal, in which the atoms form regular lattice. The velocity of ultrasonic wave of any kind can be determined from the elastic moduli (Y: Young's modulus, G: modulus of rigidity, and σ: poisson's ratio) and density (d) of the material. The logngitudinal and shear wave velocities (V_L and V_S) can be determined with following expressions.

$$V_L = \left[\frac{Y(1-\sigma)}{d(1+\sigma)(1-2\sigma)}\right]^{1/2} \text{ and } V_S = \left[\frac{Y}{2d(1+\sigma)}\right]^{1/2} = \left[\frac{G}{d}\right]^{1/2} \quad (1)$$

In terms of lame's moduli (λ and μ) , the ultrasonic velocities can be expressed as;

$$V_L = \left[\frac{\lambda + 2\mu}{d}\right]^{1/2} \text{ and } V_S = \left[\frac{\mu}{d}\right]^{1/2} \quad (2)$$

The stress strain relationships for anisotropic crystals vary with the direction. Thus velocity of ultrasonic wave varies with the direction of propagation of wave and mode of polarization. There are three type of ultrasonic velocity (one longitudinal and two shear wave) for each direction of propagation of wave in cubic (Mason, 1958; Singhal 2003) and hexagonal structured materials (Mason,1969; Alers,1958; Rosen,1970; Yadawa,2009). The expressions for the velocities are given in Table (1) and Table (2). In Tables 1-2, the V_1 is longitudinal and V_2 & V_3 are the shear wave velocities of ultrasonic wave. The C_{11}, C_{12}, C_{44}, C_{33} and C_{66} are the second order elastic constants.

The Debye theory of specific heat has proven its usefulness because it is a single –parameter theory which describes the observation remarkebly well. Its one parameter, Debye temperature (T_D) need not to be determined by any heat capacity measurements but can be calculated from the elastic moduli. Once this parameter has been determined from the elastic moduli, the Debye theory specifies the lattice contribution to the specific heat only to an accuracy of about 10 or 20% over most of temperature range. Because of this, the theoratical model assumes the solid to be an elastic continuum in which all sound waves travel at the same velocity independent of their wavelength. This model is satisfactory only in the limit of long wavelengths or low temperatures. The expression for the T_D can be given as:

$$T_D = \frac{\hbar \, V_D \, (6\,\pi^2 \, n_a)^{1/3}}{K_B} \quad (3)$$

Here, $\hbar$ is quantum of action and is equal to Planck's constant divided by 2π ; K_B is Boltzmann Constant; n_a is atom concentration. This Debye average velocity is important

Direction of propagation	Direction of polarization	Type of wave	Velocity expression	Velocity notation
100	100	Long.	$(C_{11}/d)^{1/2}$	$V_1=V_L$
	010	Shear	$(C_{44}/d)^{1/2}$	$V_2=V_{S1}$
	001	Shear	$(C_{44}/d)^{1/2}$	$V_3=V_{S2}$
110	110	Long.	$((C_{11}+C_{12}+2C_{44})/2d)^{1/2}$	$V_1=V_L$
	001	Shear	$(C_{44}/d)^{1/2}$	$V_2=V_{S1}$
	$1\,\bar{1}\,0$	Shear	$((C_{11}-C_{12})/2d)^{1/2}$	$V_3=V_{S2}$
111	111	Long.	$((C_{11}+2C_{12}+4C_{44})/3d)^{1/2}$	$V_1=V_L$
	Any direction in 111 plane	Shear	$((C_{11}-C_{12}+C_{44})/3d)^{1/2}$	$V_2= V_3$ $V_{S1}=V_{S2}$

Table 1. Ultrasonic velocities for cubic structured materials

Direction of propagation	Direction of polarization	Type of wave	Velocity expression	Velocity notation
001 (Along unique axis or z-axis)	001	Long.	$\left(C_{33}/d\right)^{1/2}$	$V_1=V_L$
	Any direction in 001 plane	Shear	$\left(C_{44}/d\right)^{1/2}$	$V_2= V_3$ $V_{S1}=V_{S2}$
100 (or any other direction perpendicular to 001)	100	Long.	$\left(C_{11}/2d\right)^{1/2}$	$V_1=V_L$
	001	Shear	$\left(C_{44}/d\right)^{1/2}$	$V_2=V_{S1}$
	010	Shear	$\left((C_{11}-C_{12})/2d\right)^{1/2}$	$V_3=V_{S2}$
At angle θ with the unique axis of the crystal		Long.	$[\{C_{33}Cos^2\theta + C_{11}Sin^2\theta + C_{44} + \{[C_{11}Sin^2\theta - C_{33}Cos^2\theta + C_{44} (Cos^2\theta - Sin^2\theta)]^2 + 4\,Cos^2\theta\, Sin^2\theta\,(C_{13}+C_{44})^2\}^{1/2}\}/2d]^{1/2}$	$V_1=V_L$
		Shear	$[\{C_{33}Cos^2\theta + C_{11}Sin^2\theta + C_{44} - \{[C_{11}Sin^2\theta - C_{33}Cos^2\theta + C_{44} (Cos^2\theta - Sin^2\theta)]^2 + 4\,Cos^2\theta\, Sin^2\theta\,(C_{13}+C_{44})^2\}^{1/2}\}/2d]^{1/2}$	$V_2=V_{S1}$
		Shear	$[\{C_{44}Cos^2\theta + C_{66}Sin^2\theta\}/\ d]^{1/2}$	$V_3=V_{S2}$

Table 2. Ultrasonic velocities for hexagonal structured materials

parameter in the low temperature physics because it is related to elastic constants through ultrasonic velocities. The Debye average velocity (V_D) in the materials is calculated using the following equation (Oligschleger, 1996).

$$V_D = \left(\frac{1}{3} \sum_{i=1}^{3} \int \frac{1}{V_i^3} \frac{d\Omega}{4\pi} \right)^{-1/3} \tag{4}$$

Here the integration is over all directions and summation is over the type of ultrasonic velocities. Along the [100], [111] (for cubic crystal) and [001] (for hexagonal structured crystals) direction of propagation of wave, the equation (4) reduces as:

$$V_D = \left[\frac{1}{3} \left(\frac{1}{V_1^3} + \frac{2}{V_2^3} \right) \right]^{-1/3} \tag{4a}$$

and along the [110] (for cubic) and any angle with the unique axis of hexagonal structured crystal, direction of propagation, the equation (4) reduces as:

$$V_D = \left[\frac{1}{3} \left(\frac{1}{V_1^3} + \frac{1}{V_2^3} + \frac{1}{V_3^3} \right) \right]^{-1/3} \quad (4b)$$

On the knowlewdge of elastic constants, the theoretical evaluation of ultrasonic velocity and Debye average velocity in cubic and hexagonal structured materials can be done with help of expressions written in Table (1), Table (2) and equations (4a)-(4b). There are several theories (Ghate,1965; Mori,1978; Rao,1974; Yadav AK, 2008) for the calculation of elastic constants. The elastic constants depend on the lattice parameters of structured materials. The elastic constants and elastic moduli can be calculated with the knowledge of lattice parameters.

5.1 B Measurement techniques of ultrasonic velocity

The study of the propagation of ultrasonic waves in materials determines the elastic constants, which provides better understanding of the behaviour of the engineering materials. The elastic constants of material are related with the fundamental solid state phenomenon such as specific heat, Debye temperature and Grüneisen parameters. The elastic constants in the materials can be determined by measuring the velocity of longitudinal and shear waves. Elastic constants are related to interatomic forces, co-ordination changes etc., and also with the impact shock, fracture, porosity, crystal growth and microstructural factors (grain shape, grain boundaries, texture and precipitates etc.). So, the study of ultrasonic velocity is useful not only for characterization of the structured materials, engineering materials, porous materials, composites, glasses, glass ceramics but also bioactive glasses, nanomaterials, nanofluids etc.

Interferometer or continuous wave method and pulse technique are the general electrical method for the measurement of ultrasonic velocity. In CW method, the wavelength of wave in the test material is measured, which in turn provides the ultrasonic velocity with relation $V = \nu \lambda$. While in the Pulse technique, transit time (t: the time needed for a signal to travel between the front and back surface of the specimen or concerned medium) is measured with the help of echo pattern. If x is thickness of the material then ultrasonic velocity becomes equal to 2x/t.

For precise measurement, the Pulse technique has been improved in the form of following techniques (Papadakis, 1976, Raj, 2004).

a. Sing around
b. Pulse superposition method
c. Pulse echo overlap method
d. Cross-correlation method and
e. Phase slop method
f. Pulse transmission method

The pulse echo-overlap, pulse transmission and pulse superposition techniques are widely used techniques due to their absolute accuracy and precision respectively. Now a day, computer controlled devices of pulse echo overlap and pulse superposition techniques are being used. Resonance ultrasound spectroscopy and Laser interferometry are the recent techniques for the measurement of ultrasonic velocity in thin film, crystal, textured alloy etc.

5.1 C Application of ultrasonic velocity

Ultrasonic velocity has a wide range of application in the field of material characterization. Yet it is useful for the characterization or study of all the three phase of matter but here we

concentrate only its application to solid materials. It is used in the study of following properties of materials.

1. Elastic constants: The elastic moduli of a material are important for the understanding of mechanical behaviour. If V_L and V_S are the measured ultrasonic velocities of longitudinal and shear wave then longitudinal modulus (L), Shear modulus (G), Bulk modulus (B), Poisson's ratio (σ),Young modulus (Y) and lame's modulus (λ and μ) can be obtained with the following expression.

$$\left.\begin{aligned} L &= V_L^2 d \\ \mu = G &= V_S^2 d \\ B &= L - (4/3)G \\ \sigma &= \frac{L - 2G}{2(L - G)} \\ Y &= (1+\sigma)2G \\ \lambda &= (V_L^2 - 2V_S^2)d \end{aligned}\right\} \tag{5}$$

We can also find the stiffness constants or second and forth order elastic constants with the velocity. Using Table (1)-(2), one can find the second order elastic constants along different crystallographic direction for cubic and hexagonal structured materials. If we have ultrasonic velocity under different physical condition like temperature, pressure, composition of materials etc. then we can predict the mechanical behaviour of material in different physical condition. The anisotropy of material can be explained with the knowledge of anisotropy factor $A=[2C_{44}/(C_{11}-C_{12})]$. Knowledge of pressure derivatives of the elastic constants of a structured material can be used for the evaluation of Grüneisen parameter (γ). The Grüneisen parameter is used to describe anharmonic properties of solids. The quasi harmonic model is usually the starting point for the evaluation of mode gammas γ_i which is defined as $\gamma_i = -[d(\ln\omega_i)/d(\ln V)]$, where ω_i is a normal mode frequency of crystal lattice and V is the volume of the crystal. The values of γ_i for low frequency acoustic modes in a given material can be obtained with the pressure derivates of elastic constants of that material. Finally the Grüneisen parameter is obtained with the average of γ_i as shown in the following expression.

$$\gamma = \left[\sum_{i=1}^{3N} C_i \gamma_i \Big/ \sum_{i=1}^{3N} C_i\right] \tag{6}$$

Different workers (Mason, 1965; Brugger, 1964; Anil, 2005; Yadav, 2007; Yadawa, 2009; Yadav AK,2008) have studied this property of the different structured materials like isotropic, cubic, rhombohedral and hexagonal structured materials.

2. Debye temperature and Debye average velocity: These parameters are essential for the understanding of lattice vibration and low temperature properties of the material. These parameters can be found directly with the velocity values using equation (4) for the cubic and hexagonal structured materials. A detail study of Debye temperature, velocity and related theories of different structured materials can be seen elsewhere (Alers, 1965).

3. Porosity: The porosity of the porous material can be examined with the knowledge of elastic moduli and Poisson's ratio as a function of pore volume fraction. These parameters can be evaluated with help of measured velocity and density. A simple expression of Young modulus and shear modulus for a porous material can be written as,

$$\left.\begin{aligned} Y &= Y_0 \exp(-ap-bp^2) \\ G &= G_0 \exp(-ap-bp^2) \end{aligned}\right\} \quad (7)$$

Here Y_0 and G_0 are the modulus of material without pore; a,b and c are the constants; p is pore volume fraction which is equal to $\{1-(d/d_0)\}$ and; d is the bulk density determined experimentally from mass and volume while d_0 is the theoretical density determined from XRD.

The elastic moduli and Poisson ratio measured ultrasonically are compared with the theoretical treatment for the characterization. The elastic moduli of porous material are not only the function of porosity but also the pore structure and its orientation. The pore structure depends on the fabrication parameters like compaction pressure, sintering temperature and time. If the pores are similar in shape and distributed in homogeneous pattern then a good justification of mechanical property can be obtained with this study.

5. Grain size: There is no unique relation of average grain size with the ultrasonic velocity. The following typical graph (Fig. 5) shows a functional relation among velocity (V), grain size (D) and wave number (k). This has three distinct regions viz. decreasing, increasing and oscillating regions. Both the I and II region are useful for the determination of grain size determination, whereas region III is not suitable.

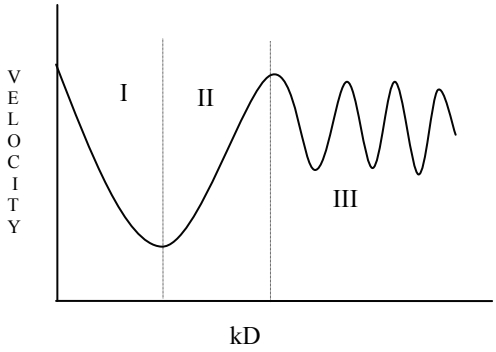


Fig. 5. Ultrasonic velocity as a function of kD

The obtained grain size with this study has good justification with grain size measured with metallography. The important advantage of using ultrasonic velocity measurements for the grain size determination is the accuracy in which ultrasonic transit time could be determined through electronic instrumentation. The different workers (Palanichamy, 1995) have studied this property for polycrystalline material with the study of ultrasonic velocity.

6. Anisotropic behaviour of compositional material: The intermetallic compound and alloys are formed by the mixing of two or more materials. These compounds have different mechanical properties depending on their composition. The different mechanical properties like tensile strength, yield strength, hardness (Fig.6) and fracture toughness at different

composition (Fig. 7), direction/orientation (Fig.8) and temperature can be determined by the measurement of ultrasonic velocity which is useful for quality control and assurance in material producing industries (Krautkramer, 1993; Raj, 2004; Yadav & Singh 2001; Singh & Pandey, 2009, Yadav AK, 2008).

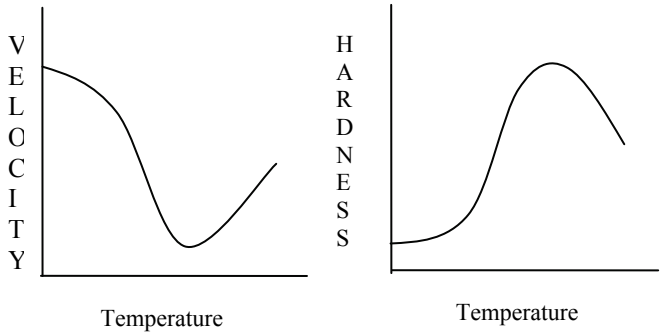


Fig. 6. Variation of velocity or hardness with temperature for some mixed materials

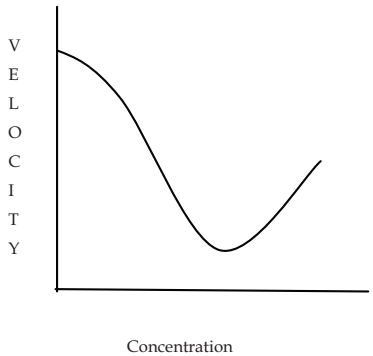


Fig. 7. Variation of velocity with concentration in some glasses

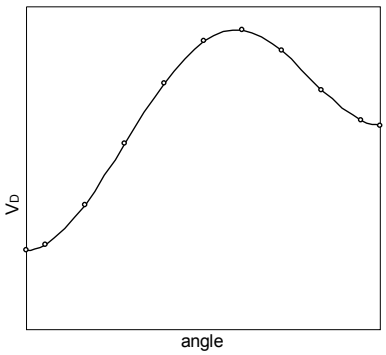


Fig. 8. Variation of V_D with the angle from the unique axis of hexagonal structured crystal

7. Recrystallisation: The three annealing process that amend the cold work microstructure are recovery, recrystallisation and grain growth. Among these processes, recrystallisation is the microstructural process by which new strain free grains form from the deformed microstructure. Depending on the material, recrystallisation is often accompanied by the other microstructural changes like decomposition of solid solution, precipitation of second phases, phase transformation etc. The hardness testing and optical metallography are the common techniques to the study the annealing behaviour of metals and alloys. A graph of longitudinal and shear wave velocity with annealing time (Fig.9) provides a more genuine understanding of recrystallisation process.

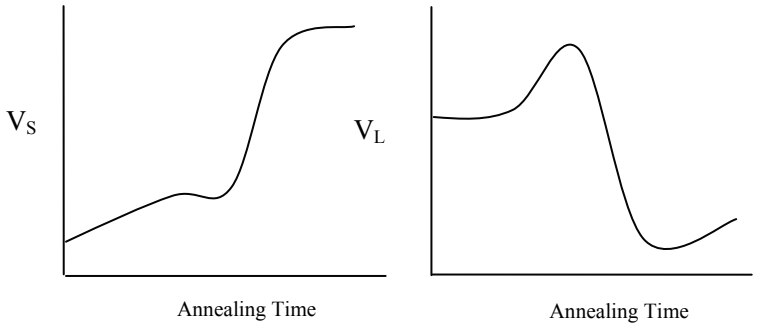


Fig. 9. Variation of V_L or V_S with annealing time

The variation of shear wave velocity represents a slight increase in recovery region followed by a rapid increase in the recrystallisation region and saturation in the completion of recrystallisation region. The slight increase in the velocity in the process of recovery is attributed to the reduction in distortion of lattice caused by the reduction in point defect due to their annihilation. The increase in velocity during recrystallisation is credited to the change in the intensity of lattice planes. The variation in longitudinal velocity have the just opposite trend to that of shear wave velocity which is credited to the change in texture and the dependence of velocity directions of polarisation and propagation of wave. The variation of velocity ratio (V_L/V_S) with annealing time shows a clear picture of recrystallisation regime (Fig. 10).

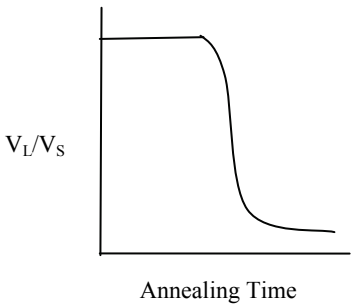


Fig. 10. Variation of V_L/V_S with annealing time

The selection of ratio avoids the specimen thickness measurement and enhances the accuracy. In short we can say that the velocity measurement provides the accurate prediction of on set and completion times of recrystallisation.

8. Precipitation: For the desired strength of material or component, the precipitation is a process like recrystallisation. It is a metallurgical process for the improvement of strength of material. The strength of improvement depends on spacing, size, shape and distribution of precipitated particles. A measurement of longitudinal ultrasonic wave velocity with ageing time provides precise value of Young modulus at different ageing temperature (Bhattacharya, 1994; Raj, 2004). With the knowledge Young modulus, the strength of material at different time of ageing can be predicted. Thus ultrasonic evaluation may be handy tool to study the precipitation reaction involving interstitial elements because this mechanism is associated with large change in the lattice strain.

9. Age of concrete: There are several attempts that have been made to find the elastic moduli, tensile strength, yield strength, hardness, fracture toughness and brittleness of different materials (Lynnworth, 1977; Krautkramer,1977). Similarly the age of concrete material can be determined with knowledge of crush strength that can be found with the ultrasonic velocity. A graph of pulse velocity of ultrasonic wave and crush with age of concrete is shown in Fig 11.

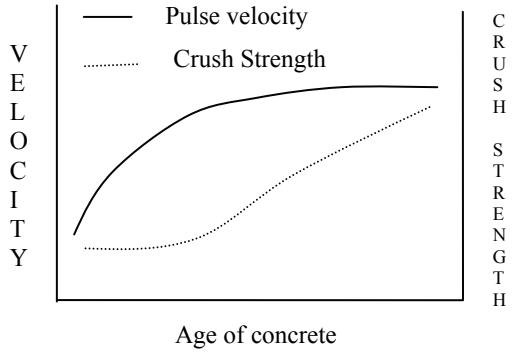


Fig. 11. Variation of velocity and crush strength with age of concrete

10. Cold work and texture: The texture of compounds can be understood with the knowledge of ultrasonic velocity. The expression of texture designates an elastic anisotropy due to the non-random distribution of crystalline directions of the single crystals in the polycrystalline aggregates. On the contrary, the isotropic, untextured solid is characterized by a totally random distribution of the grains. A study on texture gives insight into the materials plastic properties. Ultrasonic velocity measurements provide the state of texture in the bulk. For this purpose, ultrasonic velocity with cross correlation method {V_{IJ}; where I (direction of propagation) or J (direction of polarization) =1,2,3; 1:rolling, 2: transverse, 3:normal) }or Rayleigh wave velocity in transverse direction is measured as function of cold work (Raj,2004). Accordingly, three longitudinal (V_{11}, V_{22}, V_{33}) and six shears (V_{12}, V_{21}, V_{23}, V_{32}, V_{31} and V_{13}) wave velocities are measured. The velocities are found to be identical when the direction of propagation and direction of polarization are interchanged. Yet the measured velocities of longitudinal and shear wave propagating perpendicular to rolling

direction are important for estimation of cold work with good precision but V_{33} and V_{32} are found to be more suitable due to being easier in measurement. With the following relation, we can estimate the degree of cold work with help of velocity ratio (V_{33} /V_{32}).

$$V_{33} / V_{32} = 0.00527 \ \ (\% \text{ cold work}) - 1.83 \ ; \ \ \{ \text{Correlation coefficient} = 0.9941 \} \qquad (8)$$

The following graph (Fig. 12) represents the variation of velocity ratio with cold work.

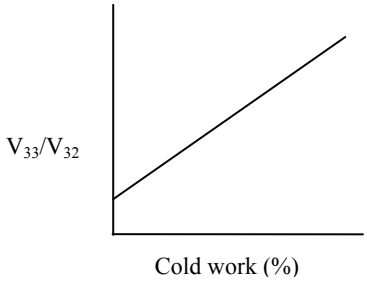


Fig. 12. Variation of velocity ratio with cold work

The Rayleigh wave velocity in transverse direction decreases with cold work and is linear in nature. A scatter in measurement is mainly attributed to the local variation in the degree of deformation, particularly close to surface caused by scattering. Both the methods are appropriate for the evaluation of cold work percentage in stainless steel. Thus measurement of bulk and surface Rayleigh wave velocities on cold rolled plates provide a tool to monitor the percentage of cold work during rolling operation.

5.2 Ultrasonic attenuation

The intensity of ultrasonic wave decreases with the distance from source during the propagation through the medium due to loss of energy. These losses are due to diffraction, scattering and absorption mechanisms, which take place in the medium. The change in the physical properties and microstructure of the medium is attributed to absorption while shape and macroscopic structure is concerned to the diffraction and scattering. The absorption of ultrasonic energy by the medium may be due to dislocation damping (loss due to imperfection), electron-phonon interaction, phonon-phonon interaction, magnon-phonon interaction, thermoelastic losses, and bardoni relaxation. Scattering loss of energy is countable in case of polycrystalline solids which have grain boundaries, cracks, precipitates, inclusions etc. The diffraction losses are concerned with the geometrical and coupling losses, that are little or not concerned with the material properties. Thus in single crystalline material, the phenomenon responsible to absorption of wave is mainly concerned with attenuation. An addition of scattering loss to the absorption is required for knowledge of attenuation in polycrystalline materials. So, the rate of ultrasonic energy decay by the medium is called as ultrasonic attenuation.

The ultrasonic intensity/energy/amplitude decreases exponentially with the source. If I_X is the intensity at particular distance x from source to the medium inside then:

$$I_X = I_0 e^{-\alpha X} \tag{9}$$

where α is attenuation or absorption coefficient. If I_{X_1} and I_{X_2} are the intensities of ultrasonic waves at x_1 and x_2 distance then from equation (9) one can write the following expressions.

$$I_{X_1} = I_0 e^{-\alpha X_1} \tag{10}$$

$$I_{X_2} = I_0 e^{-\alpha X_2} \tag{11}$$

On solving the equations (10) and (11), one can easily obtain the following expression of ultrasonic attenuation.

$$\alpha = \frac{1}{(x_2 - x_1)} \log_e \frac{I_{X_1}}{I_{X_2}} \tag{12}$$

The ultrasonic attenuation or absorption coefficient (α) at a particular temperature and frequency can be evaluated using equation (12). In pulse echo-technique the (X_2-X_1) is equal to twice of thickness of medium because in this technique wave have to travel twice distance caused by reflection, while is equal to medium thickness in case of pulse transmission technique. Attenuation coefficient is defined as attenuation per unit length or time. i.e. The α is measured in the unit of Np cm^{-1} or Np t^{-1}. The expression of α in terms of decibel (dB) unit are written in following form.

$$\alpha = \frac{1}{(x_2 - x_1)} 20 \log_{10} \frac{I_{X_1}}{I_{X_2}}; \text{ in unit of dB/cm} \tag{13a}$$

$$\alpha = \frac{V}{(x_2 - x_1)} 20 \log_{10} \frac{I_{X_1}}{I_{X_2}}; \text{ in unit of dB/}\mu\text{s} \tag{13b}$$

5.2 A Source of ultrasonic attenuation

The attenuation of ultrasonic wave in solids may be attributed to a number of different causes, each of which is characteristic of the physical properties of the medium concerned. Although the exact nature of the cause of the attenuation may not always be properly understood. However, an attempt is made here to classify the various possible causes of attenuation that are as.

a. Loss due to thermoelastic relaxation
b. Attenuation due to electron phonon interaction
c. Attenuation due to phonon phonon interaction
d. Attenuation due to magnon-phonon interaction
e. Losses due to lattice imperfections
f. Grain boundary losses
g. Loss due Bardoni relaxation and internal friction

A brief of these losses can be under stood by the following ways.

a. Loss due to thermoelastic relaxation

A polycrystalline solid may be isotropic because of the random orientation of the constituent grains although the individual grains may themselves be anisotropic. Thus, when a given stress is applied to this kind of solid there will be variation of strain from one grain to another. A compression stress causes a rise in temperature in each crystallite. But because of the inhomogeneity of the resultant strain, the temperature distribution is not uniform one. Thus, during the compression half of an acoustic cycle, heat will flow from a grain that has suffered the greater strain, which is consequently at high temperature, to one that has suffered a lesser strain, which as a result is at lower temperature. A reversal in the direction of heat flow takes place during the expansion half of a cycle. The process is clearly a relaxation process. Therefore, when an ultrasonic wave propagates in a crystal, there is a relaxing flow of thermal energy from compressed (hot region) towards the expanded (cool region) regions associated with the wave. This thermal conduction between two regions of the wave causes thermoelastic attenuation. The loss is prominent for which the thermal expansion coefficient and the thermal conductivity is high and it is not so important in case of insulating or semi-conducting crystals due to less free electrons. The thermoelastic loss $(\alpha)_{Th}$ for longitudinal wave can be evaluated by the Mason expression (Bhatia, 1967; Mason, 1950, 1965) .

$$\alpha_{Th.} = \frac{\omega^2 < \gamma_i^j >^2 KT}{2dV_L^5} \tag{14a}$$

$$(\alpha / f^2)_{Th.} = \frac{4\pi^2 < \gamma_i^j >^2 KT}{2dV_L^5} \tag{14b}$$

where ω and V_L are the angular frequency and longitudinal velocity of ultrasonic wave. d, K and T are the density, thermal conductivity and temperature of the material. γ_i^j is the Grüneisen number, which is the direct consequence of the higher order elastic constants (Mason, 1965; Yadawa 2009). In the case of shear wave propagation, no thermoelastic loss occurs because of no any compression & rarefaction and also for the shear wave, average of the Grüneisen number is zero.

b. Attenuation due to electron-phonon interaction

Debye theory of specific heat shows that energy exchanges occur in metals between free electrons and the vibrating lattice and also predicts that the lattice vibrations are quantized in the same way as electromagnetic vibrations, each quantum being termed as phonon.Ultrasonic absorption due to electron-phonon interaction occurs at low temperatures because at low temperatures mean free path of electron is as compared to wavelength of acoustic phonon. Thus a high probability of interaction occurs between free electrons and acoustic phonons. The fermi energy level is same along all directions for an electron gas in state of equilibrium, i.e. the fermi surface is spherical in shape. When the electron gas is compressed uniformly, the fermi surface remains spherical. The passage of longitudinal ultrasonic wave through the electron gas gives rise to a sudden compression (or rarefaction) in the direction of the wave and the electron velocity components in that direction react immediately, as a result fermi surface becomes ellipsoidal. To restore the spherical distribution, collision between electron and lattice occur. This is a relaxational phenomenon because the continuous varying phase of ultrasonic wave upsets this distribution.

In a new approach we may understood that the energy of the electrons in the normal state is carried to and from the lattice vibrations by means of viscous medium, i.e. by transfer of momenta. Thus the mechanism is also called as electron-viscosity mechanism. The ultrasonic attenuation caused by the energy loss due to shear and compressional viscosities of electron gas for longitudinal $(\alpha)_{Long}$ and shear waves $(\alpha)_{Shear}$ are given as (Bhatia, 1967; Mason, 1950, 1965,66):

$$(\alpha)_{Long} = \frac{\omega^2}{2dV_L^3}(\frac{4}{3}\eta_e + \chi) \tag{15a}$$

$$(\alpha)_{Shear} = \frac{\omega^2}{2dV_S^3}\eta_e \tag{15b}$$

where η_e and χ represent the electronic shear and compressional viscosities of electron gas.

c. Attenuation due to phonon–phonon interaction

The energy quanta of mechanical wave is called as phonon. With the passage of ultrasound waves (acoustic phonons), the equilibrium distribution of thermal phonons in solid is disturbed. The re-establishment of the equilibrium of thermal phonons are maintained by relaxation process. The process is entropy producing, which results absorption. The concept of modulated thermal phonons provides following expression for the absorption coefficient of ultrasonic wave due to phonon–phonon interaction in solids $(\alpha)_{Akh}$ (Bhatia, 1967; Mason, 1950, 1958, 1964, 1965; Yadav & Singh 2001; Yadawa, 2009) .

$$\alpha_{Akh} = \alpha_{PP} = \frac{\omega^2\tau\ \Delta C}{2dV^3(1+\omega^2\tau^2)} \tag{16a}$$

Where τ is the thermal relaxation time (the time required for the re-establishment of the thermal phonons) and V is longitudinal or shear wave velocity. ΔC is change in elastic modulli caused by stress (by passage of ultrasonic wave) and is given as:

$$\Delta C = 3E_0 < (\gamma_i^j)^2 > - < \gamma_i^j >^2 C_v T \tag{16b}$$

Here E_0 is the thermal energy density. ΔC is related with the acoustic coupling constant (D), which is the measure of acoustic energy converted to thermal energy due to relaxation process and is given by the following expression:

$$D = \frac{3\Delta C}{E_0} = 9 < (\gamma_i^j)^2 > 3 < \gamma_i^j >^2 \frac{C_v T}{E_0} \tag{16c}$$

Using equation (16c), the equation (16a) takes the following form under condition $\omega\tau << 1$.

$$\alpha_{Akh} = \alpha_{PP} = \frac{\omega^2\tau\ E_0 D}{6\ dV^3} \tag{16d}$$

d. Attenuation due to magnon-phonon interaction

Ferromagnetic and ferroelectric materials are composed of 'domains' which are elementary regions characterized by a unique magnetic or electric polarization. These domains are

aligned along a number of directions, but generally oriented along the polarization vector that is known as direction of easy magnetization (or electrification). These usually follow the direction of the principal crystallographic axis. Cubic crystal of a ferromagnetic material has six directions of easy magnetization lying in positive or negative pairs along the three perpendicular co-ordinate axes. Thus two neighbouring domains are aligned at 90^0 or 180^0. Because of the magnetostriction effect, assuming that the magnetostructive strain coefficient is positive (or negative), there is an increase (or decrease) in the length of domains in the direction of polarization. Which results an increase or decrease in elastic constants depending on sign of the magnetostructive coefficient. The magnitude of change depends on applied stress. The phenomenon is called as ΔE effect. Thus when a cyclic stress such as produced by ultrasonic wave, is applied to a ferromagnetic or ferroelectric material, the domain wall displaced as a result of ΔE effect that follows the hysterisis loop. Thus there is dissipation of ultrasonic energy. The loss per half cycle per unit volume is being given by area of hysterisis loop.

The another cause of the attenuation in ferromagnetic material is due to production of micro-eddy current produced in domain walls by the periodic variation of magnetic flux density. A simple consideration of the ultrasonic attenuation in ferromagnetic material is due to magnetoelastic coupling i.e attenuation is caused by interaction between magnetic energy in form of spin waves (magnon- energy quanta of spin waves) and ultrasonic energy (phonon). Thus it is called as ultrasonic attenuation due to magnon-phonon interaction.

e. Losses due to lattice imperfections

Any departure from regularity in the lattice structure for a crystalline solid is regarded as an imperfection, includes point defects such as lattice vacancies and presence of impurity atom and dislocation etc. Imperfections enhance the absorption of ultrasonic wave. Attenuation due to dislocation can occur in more than one way e.g. attenuation due to edge or screw dislocation, which is due to forced vibration in imperfect crystal i.e. due to interaction of ultrasonic energy (phonon) and vibrational energy of impurity atom or dislocation (phonon). Dislocation drag is a parameter for which the phonon-phonon interaction can produce an appreciable effect on the motion of linear imperfections in the lattice through drag phenomenon. The thermal loss due to such motion can be computed by multiplying the following drag coefficients by the square of the dislocation velocity (Yadav & Pandey, 2005).

$$B_{screw} = 0.071\varepsilon \tag{17a}$$

$$B_{edge} = \frac{0.053\varepsilon}{(1-\sigma^2)} + \frac{0.0079}{(1-\sigma^2)}\left(\frac{G}{B}\right)\chi \tag{17b}$$

Where $\chi = \varepsilon_L - (4\varepsilon_S / 3)$; $\varepsilon_L = E_0 D_L \tau_L / 3$, $\varepsilon_S = E_0 D_S \tau_S / 3$, $B = (C_{11} + 2C_{12}) / 3$, $G = (C_{11} - C_{12} + C_{44}) / 3$ and $\sigma = C_{12} / (C_{11} + C_{12})$. Here G, ε, σ, B and χ are the shear modulus, phonon viscosity, Poisson's ratio, bulk modulus and hydrostatic compressional viscosity respectively. ε_L & ε_S, D_L & D_S and τ_L & τ_S are phonon viscosity, acoustic coupling constant and thermal relaxation time for longitudinal and shear wave. C_{11}, C_{12} and C_{44} are the second order elastic constants for cubic metals.

f. Grain boundary losses

The grain boundary losses occur due to random orientation of the anisotropic grains in polycrystalline solid. At each grain boundary there is discontinuity of elastic modulus.

Therefore when ultrasonic wave of small wavelength compared to grain size propagates in such solid, regular reflections occur at grain boundaries, causes loss. The loss depends on the degree of the anisotropy of the crystallites, mean grain diameter and wavelength of wave. When the grain size is comparable to wavelength of wave then the ultrasonic attenuation caused by elastic hysterisis at grain boundary and scattering is frequency dependent and can be related as:

$$\alpha = B_1 f + B_2 f^4 \tag{18}$$

Where B_1 and B_2 are constants for the given material.

i. Loss due Bardoni relaxation and internal friction: The attenuation maximum at low temperature in some metarials like (Pb, Cu, Ag and Al) whose position on temperature scale is a function of the frequency of measurement is called as Bardoni peaks (Bhatia, 1967). These peaks are very small but when the crystal is strained by one or two percent, the peaks appear very prominantaly. These peaks are relaxational peaks. This relaxation is due to dislocation which are in the minimum energy position and are moved over the Peierls energy barrier by thermal agitation. A freshly strained material have its dislocations lying along minimum energy regions. A dislocation line between two pining points could be displaced by thermal agitation, and that the small stress would bias the potential wells and cause a change in the number of residing in the side wells, thus producing a relaxation effect. A typical graph showing Bardoni peaks under unstrained and strained condition is shown in Fig.13.

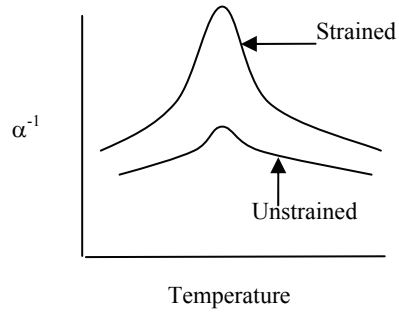


Fig. 13. Attenuation peaks at low temperature under unstrained and strained condition of materials

As the temperature increases there is an exponential increase in loss occuring at high temoperatures. It is observed for a number of polycrystalline material which is due to grain boundary relaxation effect. Such peaks are absent for the single crystals. There is also attenuation peaks on temperature scale for a number of material due to internal friction. This has been ascribed to the drag of dislocation as they are pulled through a concentration of vacancies. The internal friction peaks are caused due to damping effect of dragging the dislocations along vacancies or it can be assumed to be associated with the breakway of dislocations from their pinning points caused by thermal vibrations of the dislocation. This loss is independent of frequency and is greatly enhanced by the amount of cold work. The position of peaks appear to be independent of impurity content of the material. The loss due to internal friction can be related to frequency with following equation.

$$\alpha^{-1} = \frac{\Delta E}{E} \frac{(f / f_R)}{1 + (f / f_R)^2} \tag{19a}$$

Where $(\Delta E / E)$ is the relaxation strength, f and f_R are the frequency and relaxation frequency respectively. f_R is related to the activation energy (H).

$$f_R = f_0 \, e^{-H/RT} \tag{19b}$$

Here f_0 is the frequency with which the unit causing the relaxation attacks the energy and T is the temperature. For the frequencies f greater than f_R, the equation (19a) takes the following form.

$$\alpha^{-1} = \frac{\Delta E}{E} \frac{f_0}{f} e^{-H/RT} \tag{20}$$

On the basis of above theories of ultrasonic attenuation, it is clear that if hypothetical crystal under study is perfect, not ferromagnetic or ferroelectric then only three factors are predominantly responsible for ultrasonic attenuation that are attenuation due to thermoelastic relaxation, electron-phonon interaction and phonon-phonon interaction.

$$\alpha_{Total} = \alpha_{Th} + \alpha_{ep} + \alpha_{pp} \tag{21}$$

For nanosized metallic crystals the dislocation drag parameter gives informative results that can be used for the analysis of nanostructured materials. The electron-phonon interaction is prominant only at low temperatures while phonon-phonon interaction is effective at high temperatures. The total attenuation in magnetic material at high temperature is sharply affected with phonon-phonon and magnon-phonon interactions not only at bulk scale but also at nanoscale. When metal nano particles are dispersed in suitable polymer, then it is called as nanofluid. If the particles are of magnetic material then it is called as ferrofluid.
The total ultrasonic attenuation in ferrofluid on the temperature scale can be written as:

$$\alpha_{Total} = \alpha_V + \alpha_{MP} + \alpha_{pp} \tag{22}$$

where α_V:absorption due to viscous medium, α_{MP}: absorption due to interaction between acoustic phonon and magnon (energy quanta of spin wave associated with dis- persed particles) and α_{PP}: absorption due to interaction between acoustic phonon and dispersed crystal lattice phonon.

5.2 B Measurement techniques of ultrasonic attenuation

Similar to velocity measurement, the pulse technique and continuous wave method are being used for the measurement of ultrasonic attenuation now a day. On the basis of measurement procedure, the pulse technique is mainly classified in pulse transmission technique, pulse-echo-technique and pulse echo overlap technique. Following is a short view of pulse echo and pulse transmission techniques for the measurement of attenuation.
In the pulse-echo technique (PET) of ultrasonic testing, an ultrasound transducer generates an ultrasonic pulse and receives its echo. The ultrasonic transducer functions as both transmitter and receiver in one unit. The block diagram is shown in Fig 14. Most ultrasonic transducer units use an electronic pulse to generate a corresponding sound pulse, using the

piezoelectric effect. A short, high voltage electric pulse (less than 20 Ns in duration, 100-200 V in amplitude) excites a piezoelectric crystal, to generate an ultrasound pulse.

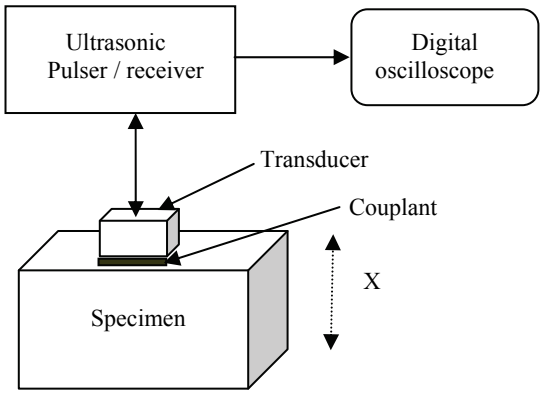


Fig. 14. Block diagram of PET

The transducer broadcasts the ultrasonic pulse at the surface of the specimen. The ultrasonic pulse travels through the specimen and reflects off the opposite face. The transducer receives the reflected echoes. The ultrasound pulse keeps bouncing off the opposite faces of the specimen, attenuating with time. The attenuation coefficient can be determined by measuring the amplitudes of the echoes from the time domain trace using the following equation.

$$\alpha = \frac{1}{2X} 20 \log_{10} \left[\frac{1}{(m-n)} \frac{I_n}{I_m} \right] \qquad \text{; in unit of dB/cm} \tag{23}$$

where I_m and I_n are the maximum amplitude (voltage) of the mth and nth pulse echoes respectively. X is the specimen thickness. Normally the first and second back wall echo are used that is m=2 and n=1. The accuracy of the transit time and attenuation in this technique depend on the selection of peak amplitude of echoes and its height respectively. The Overall accuracy in the transit time in this method is the order of nanosecond.

In the Pulse transmission technique (PTT), there is separate transducer and receiver for producing and receiving the signal, that are attached on the both side of specimen through suitable couplant via wave guides (Fig.15).

This technique can be used for the both velocity and attenuation measurement. For the velocity measurement, the transit times (t_1 and t_2) are determined in the in the absence and presence of the sample between waveguides. The difference of these transit times ($\Delta t = t_2 - t_1$) provides the actual transit time for sample. If sample thickness is X then ultrasonic velocity in the sample becomes equal to $X / \Delta t$. Similarly If $I_w(f)$ refers to the amplitude of the received signal with the waveguides only and $I_s(f)$ refers to the amplitude of the received signal when the sample is inserted between the wave guides then the attenuation of the ultrasonic waves in the sample is measured using the following relation.

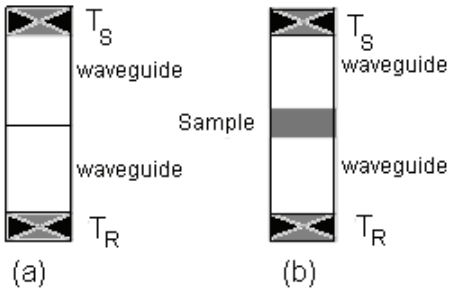


Fig. 15. Arrangement of transducer/receiver, waveguide and sample in PTT

$$\alpha = \frac{1}{X}\left[\ln T_C + \ln\frac{I_W(f)}{I_S(f)}\right] \tag{24a}$$

Here T_C is combined transmission coefficient at the sample and waveguide interface, that can be calculated with the following relation.

$$T_C = \frac{4\,Z_W Z_S}{(Z_W + Z_S)^2} \tag{24b}$$

Where Z_W and Z_S are the acoustic impedances of the waveguide and sample respectively. The exact value of attenuation in the material can not be measured from the direct measurements. It can be obtained only by the conventional attenuation method. The measured attenuation posses all loses introduced by couplant, diffraction, non-parallel specimen surfaces etc. The true value of attenuation can be obtained only when all these losses are accounted separately and subtracted from the experimental obtained value of attenuation.

5.2 C Properties characterized with ultrasonic attenuation

The ultrasonic attenuation coefficient is well correlated to several physical parameters and properties of the material. The following diagram (Fig.14) represents a view of their dependence.

Being a broad relation with material properties, the several properties of the material can be defined like grain size, yield strength, ductile to brittle transition temperature, Neel temperature, deviation number, behaviour of mechanical and magnetic properties with temperature and composition etc. The phenomenon responsible for attenuation can also be understood with the knowledge of ultrasonic attenuation. Yet there are several work have been made for the characterization of material on the basis of velocity and attenuation but here we will discuss the velocity attenuation in some structured materials like fcc, bcc, hcp, heaxagonal, NaCl / CsCl type structured materials etc.

6. Ultrasonic attenuation and velocity in different materials

Ultrasonic attenuation, velocity and their related parameters can be used to give insight into materials microstructures and associated physical properties. Behaviour of ultrasonic

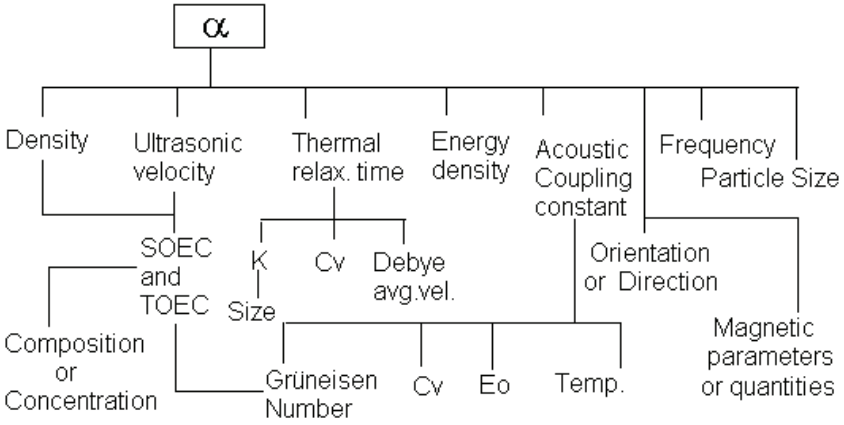


Fig. 14. Dependence of attenuation coefficient on several parameters of the material.

attenuation and velocity as a function of physical parameters related to different physical condition is used to characterize the material during the processing as well as after production. Ultrasonic can be used for the characterization of metal, rare-earth metal, semimetal, semiconductor, alloy, intermetallic, dielectric, glass, glass-ceramic, superconductor for the determination of their characteristic properties at different physical conditions like temperatures, pressure, field crystallographic direction, electric and magnetic field. Ultrasonic can also be used for the preparation and investigation of nanomaterials. Thus it is an efficient tool for the diagnosis of the material not only in bulk scale but also in nanoscale. Such interpretation is important for the quality control and assurance of the material for the industries. On the basis of structure, the materials can be divided into two classes mainly as crystalline (single crystal and polycrystalline) and amorphous. The crystalline material can have different structures like fcc, bcc, hcp, hexagonal, NaCl / CsCl type, trigonal, orthorhombic, tetragonal, monoclinic, triclinic etc. The ultrasonic study of some structured materials is written below.

Monochalcogenides of the rare-earth elements (ReX, with Re=rare-earth element Re=La, Ce, Pr, Nd, Sm, Eu, Tm and X=S, Se and Te) comprise a large class of materials that crystallize in simple NaCl-type structure. ReX exhibits interesting electrical, optical and magnetic properties. The thulium monochalcogenides TmX (X=S, Se and Te) have NaCl-type structure. Tm compounds exhibit Van Vleck paramgnetism at low temperatures owing to crystal-field singlet ground states. TmS, TmSe and TmTe are golden metal, red brown coloured intermediate valance system and silver blue semiconductor respectively. These materials are technologically important having many applications ranging from catalysis to microelectronics. Ultrasonic attenuation and other associated parameters like ultrasonic velocities, acoustic coupling constants etc. along <100>, <110> and <111> directions in the temperature range 100-300K have been studuied elswhere (Singh, Pandey & Yadawa, 2009). The order of thermal relaxation time for TmTe, TmS and TmSe are found of the order of 10^{-11}sec, 10^{-12}sec and 10^{-12}-10^{-13}sec respectively. This justifies that TmS, TmSe and TmTe have metallic, intermettallic and semiconducting behaviour. Total attenuation in these materials follows the expression $\alpha = \sum_{n=0}^{n=2} \alpha_n \, T^n$. The value of α_n depends on specific heat per unit

volume, energy density, thermal relaxation time, thermal conductivity, elastic constants and density.

The lowest attenuation is found in TmSe. This infers that this material has excellent purity and ductility in comparison to the TmS and TmTe. Thus on the basis of ultrasonic attenuation, the classification of materials can be made, i.e. it is either metallic, intermediate valence, semiconductor or dielectrics. Praseodymium and lanthanum monochalcogenides (PrS, PrSe, PrTe, LaS, LaSe, LaTe) are the materials which are used as a core material for carbon arcs in the motion picture industry for studio lighting projection. The ultrasonic study of these materials (Yadav & Singh, 2001, 2003) shows that the variation of ultrasonic attenuation with temperature in these are same as for thulium monochalcogenides. In the all monochalcogenides, the ultrasonic velocity increases with temperature due increases in the elastic constnats. The low temperature ultrasonic study of in intermetallic compound GdP, GdAs and GdSb (Yadav & Singh, 2001) shows that the temperature variation of the longitudinal ultrasonic attenuation is predominantly affected with the electrical resistivity and provides the information about the Neel temperature. The high temperature and directional ultrasonic study of SnTe, EuSe and CdO semi-conducting materials (Singh & Yadav, 2002) implies that the thermal conductivity is the governing parameter to the ultrasonic attenuation in SnTe, EuSe and CdO materials. The ultrasonic study of B1 structured CeS, CeSe, CeTe, NdS, NdSe and NdTe along different crystallographic directions at room temperature (Singh, 2009) implies NdS is more ductile and stable material in comparison to other chalcogenides systems (CeS, CeSe, CeTe, NdSe, NdTe, LaS, LaSe, LaTe, PrS, PrSe and PrTe) and rock salt-type LiF single crystal due to its lowest value of attenuation.

Aluminides are generally the most famous group of intermetallic compounds. Intermetallic compounds containing aluminium such as NiAl, offer new opportunities for developing low density, high strength structural alloys which might be used at temperatures higher than possible with conventional titanium and nickel-base alloys. Once developed, the intermetallic alloys and their composites will enable the design and production of higher performance, lighter (high thrust-to-weight ratio) engines for future military aircraft and supersonic commercial transport. Strong bonding between aluminium and nickel, which persists at high temperatures, can provide high strength at elevated temperatures such that the specific strength of intermetallics could be competitive with superalloys and ceramics. However, the high strength is usually associated with poor ductility. With respect to ductility, intermetallics fall between metals and ceramics. Intermetallics are not as brittle as ceramics because the bonding in intermetallics is predominantly metallic, compared to ionic or covalent bonding of ceramics. Nickel aluminide (NiAl) has been the subject of many development programs. The β-phase NiAl (50 at % Ni, 50 at % Al, with a CsCl, B_2 crystal structure), is very different from the γ'-phase Ni_3Al (75 at % Ni, 25 at % Al, $L1_2$ crystal structure) with respect to physical and mechanical properties. NiAl has four key advantage: its density of ≈5.95 g/cm^3 is approximately two thirds the density of state-of-the-art nickel-base superalloys; its thermal conductivity is four to eight times that of nickel-base superalloys (depending on composition and temperature); it has excellent oxidation resistance. In both the polycrystalline and single crystal forms, NiAl is brittle at room temperature in most cases and ductile at high temperatures.The elastic and ultrasonic study of β-phase NiAl at high temperature has been done elsewhere (Yadav & Pandey, 2006). A comparison of second order elastic constant Ni and Al pure metals at ≈300K with the values

of NiAl implies that the elastic anisotropy of NiAl is lower than the value of Ni and Al. A low value of anisotropy favors instability. Thus the intermetallic compound NiAl is unstable in comparison to pure metal Ni and Al. The anisotropy (A) of NiAl is found to increases with temperature. Thus intermetallic NiAl is stable at very high temperatures (300-1400K). The longitudinal ultrasonic attenuation in NiAl is found to decreases very fastly from 300 to 700K and slowly from 700K to 900K; then it recieves an increases gradually from ≈900 to 1400K. The ductile to brittle transition temperature (DBTT) is only 625 to 700K. Yield strength of NiAl decreases from ≈900K. This is predicted as the ultrasonic attenuation increases gradually from this temperature. Thus the structural stability, abrupt change in ductility at ≈DBTT, disordering at ≈DBTT could be predicted on the basis of temperature variation of the elastic constants and the ultrasonic attenuation in of NiAl.

Intermetallic compounds have received extensive attention in recent years because of technical promise as high temperature structural materials. The study of intermetallics has attracted the attention of the scientific world because of their anisotropic properties. It has also been found that fine application in advanced power engineering. Since many intermetallic compounds of different crystal structure have been found in alloy systems, the basic reason for their stability has drawn a great deal. The materials AgMg, CuZr, AuMg, AuTi, AuMn, AuZn and AuCd have a CsCl-type structure (B2 structure). The study of ultrasonic velocities, attenuation, Grüneisen parameters, non-linearity parameter (acoustic coupling constant), Debye temperature and thermal relaxation time at different crystallographic directions at room temperature can seen elsewhere (Singh & Pandey, 2009). The study of elastic constants shows that by introducing Mg, Zr, Ti, Mn, Zn, Cd in noble metals, the elastic behaviour slightly decreases due to loose interaction of impurity atoms with noble metal atoms. The Debye temperature (T_D) for Ag, Au, Cu, Cd, Zn and Mg are 226K, 289K, 224K, 214K, 272K and 400K respectively. The study also imples that the Debye temperature for mixed compounds with Ag or Cu lies between Debye temperatures of constituent materials while Debye temperature for mixed compounds with Au lies below than the constituent materials. The decrease or increase in Debye temperature indicates increase or decrease in acoustic contribution to the low temperature specific heat. The average sound velocities in these intermetallic compounds are not only larger than the noble metals but also with the Cs/Rb halides, which is due to low density of these compounds. Ultrasonic velocity in these materials decreases with their molecular weight. The velocity of these compounds is useful for determination of their anisotropic properties.The attenuation in these intermetallic compounds are mainly governed by phonon-phonon interaction and is greater than the Cs/Rb-halides and is less than the pure noble metals. The attenuation in these intermetallics are affected with combined effect of thermal conductivity, specific heat, average sound velocity and acoustic coupling constant. For CsCl-type structure, the deviation number Δ N exists from 1 to 3; Δ N denotes the difference of column number of noble metals and the secondary element in the helical periodic table. Δ N value for AgMg, CuZr, AuMg, AuTi, AuMn, AuZn and AuCd are 1, 3, 1, 3, 2, 1 and 1 respectively. The compounds AgMg, AuMg, AuZn and AuCd for which Δ N=1, have larger conductivity. The thermal conductivity are high for lower valued Δ N compounds. Since $(\alpha / f^2) \propto \tau \propto$ k thus one can write $(\alpha / f^2) \propto 1/\Delta N$. The ultrasonic attenuation in these intermetallics justify the above prediction. Thus, it may be concluded that in B2 structured intermetallic compounds the nature of ultrasonic attenuation can be determined by the deviation number.

Vanadium, Niobium and Tantalum are the transition elements of 5thB group in b.c.c. phase with high melting points and exhibit variable valency. Niobium and Tantalum are highly unreactive metals. Vanadium is seldom used on its own, but it is used in alloys of metals and acts like an important catalyst in oxidation reactions. Niobium is used in chromium nickel stainless steel, because it is unreactive and not rejected by human body. Tantalum is used for making metal plates, screws and wires for replacing badly fractured bones. The ultrasonic attenuation in these metal (Singh, Pandey, Yadawa & Yadav, 2009) decreases with the temperature and becomes negligible upto 40K, while in other normal metal this comes upto temperature 80K. This indicates that the electron-phonon interaction is possible upto 40K in these metals. Similar to other metals, the attenuation is dominated by the electrical resistance at low temperature in these metals.

The group III nitrides have unique properties such as wide direct band gap, high thermal conductivity, high thermal stability, high volume resistivity and high dielectric constant which make them the most serious candidates for high power and high frequency electronic and deep ultraviolet (UV) opto-electronic devices. The GaN, AlN and InN are hexagonal wurtzite structured Semiconducting materials. The temperature and orientation dependent ultrasonic study (Yadav & Pandey 2006; Pandey, Singh & Yadav 2007; Pandey & Yadav 2009) confirms that the AlN has minimum attenuation coefficient in comparison to GaN and InN. The temperature variation of attenuation coefficient for GaN has maximum at 400 K. The ultrasonic attenuation behaviour of AlN is just opposite to that found for GaN. Both studies indicate that the AlN is more stable and pure at high temperatures as it has low attenuation at each temperature than for GaN and the characteristic temperature for both is 400 K. It may also be predicted that at 400 K the material AlN has its purest and most ductile state as the ultrasonic attenuation in temperature range 300–800 K has a minimum at 400 K. The thermal conductivity/thermal relaxation and velocity/second order elastic constants are dominating factors to the ultrasonic attenuation before and after the temperature 400K respectively. The ultrasonic attenuation in GaN is affected by velocity and thermal energy density before 400K while after it the affecting factor is thermal relaxation time and acoustic coupling constant. In group III nitrides, the phonon-phonon interaction is the responsible mechanism for the total ultrasonic attenuation. The direction dependent ultrasonic study at room temperature of hexagonal structured rare-earth metals (Gd, Tb, Dy, Ho, Er and Tm), platinum group metal (Os and Ru), laves-phase compounds ($TiCr_2$, $ZrCr_2$ and $HfCr_2$) and fission products precipitated in nuclear fuel (Mo-Ru-Rh-Pd alloys) are reported in literature (Yadawa etal. 2009; Yadav AK etal. 2008; Pandey & Yadawa etal. 2007, 2009). The variation ultrasonic velocities with the angle from the unique axis of crystalline material are similar for all hexagonal structured material and are predominantly affected with the combined of second order elastic constants, while velocity magnitude differs due different elastic properties. Thermal relaxation times of these compounds are the order of 10^{-12}s which shows that the re-establishment of phonon distribution in equilibrium is obtained in 10^{-12}s after the passes of ultrasonic beam. The study shows that platinum group metals and rare-earth metals are durable and stable in their alloy form. The hexagonal structured materials have high elastic constant and low attenuation in comparison to fcc, bcc, NaCl/CsCl type structured material.

The ultrasonic study of fcc structured Pd and Pt, bcc structured Ta and hexagonal wurtize structured Zns at nanoscale indicates that the size dependent attenuation is dominated by

the thermal relaxation time/thermal conductivity (Yadav & Pandey, 2005; Pandey, Yadawa & Yadav 2007). The size variation of the thermal relaxation time for fcc/bcc follow the relation $\tau = \tau_0(1 - e^{-x/\lambda})$ while for hexagonal structure the expression is $\tau = \tau_0 e^{x/\lambda}$; here x: particle size, τ_0 and λ: constants. The attenuation and dislocation drag coefficient at nanoscale are larger than the normal scale.

When these nanoparticles are incorporated in suitable matrix (e.g. polymers) then nanofluids are formed. If the particles are of magnetic material then it is called as ferrofluid. The ultrasonic study of ferrofluid/nanofluid (Biwa, 2004; Singh DK etal 2009; Taketomi, 1986; Skumiel, 2000, 2003, 2004; Temkin, 1998; Gomez Alvarez, 2002) justifies the fact the velocity depends on the concentration of incorporated materials into the matrix and is independent of particle size in low frequency regime. At high frequency, both the particle size and concentration of nanoparticles are the affecting factor to the ultrasonic velocity. Ultrasonic attenuation in nanofluid is function of particle size, particle volume fraction and frequency. Commonly, the temperature dependence of ultrasonic velocity (V) for liquids is written as $V = V_0 + V_1 T$ (V_0 is ultrasonic velocity at initial temperature (273K), V_1 is absolute temperature coefficient of velocity and T is temperature difference between experimental and initial temperature). But the appropriate expression of velocity in nanofluid/Ferrofluid might be written as: $V = V_0 + V_1 T - V_2 T^2$. The third non linear term in velocity expression is caused by non-linear change in bulk modulus/density of solution/composite system with temperature. The ultrasonic study of Cr_2O_3 implies that the temperature variation of ultrasonic velocity in nano/ferrofluid mainly depends on the concentration of dispersed particles and the temperature variation of ultrasonic absorption provides direct information about Neel temperature of the ferrofluid. The Neel temperature of anti-ferromagnetic material increases at nanoscale. In the ferrofluid, absorption is mainly governed by viscous loss and magnon-phonon interaction below transition temperature while above it, the phonon-phonon interaction plays dominant role. The study of sound attenuation coefficient of magnetic fluid under an external magnetic fluid implies that the anisotropy in sound propagation is attributed to the two motions of the clusters of the ferrous colloidal particles in the fluid as rotational and translational (Taketomi 1986; Skumiel 2000, 2003, 2004).

The absorption study in glasses show a peak in attenuation at low temperature with change in temperature in simple glasses like silica, GeO_2, B_2O_3, As_2O_3 etc and in multicomponent glasses (Manghnami1,1974; Jackle, 1976). The change in velocity and attenuation in glasses are attributed to the structural change in glass network. The structural change are attributed to impurities or grain boundaries or anharmonicities of lattice. Several ultrasonic studies have been made to determine the elastic constants of the glasses such as alkali earth aluminosilicate, sodium borate, sodium borosilicate, and soda lime borosilicate glasses (Bhatti 1989; Rajendran, 2002). The transition temperature in high T_C superconductors can be obtained with the ultrasonic study (Bardeen, 1957). In this study the exponential decay of ultrasonic attenuation below T_C was used to obtain the energy gap in case of conventional mettalic superconductors, while change in ultrasonic velocity was used to explain transition temperatures for the type II superconductors.

The Grain size can be determined with the study of ultrasonic attenuation or relative attenuation (Papadakis, 1976). Normally the variation of ultrasonic attenuation or relative attenuation with average grain size or frequency follow the Fig. 15.

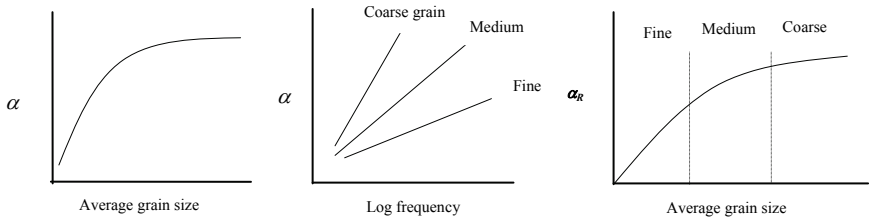


Fig. 15. variation of ultrasonic attenuation (α) or relative attenuation (α_R)with average grain size or frequency.

In this we can say the ultrasonics provide a big tool in the field of material characterization.

7. Summary

The present chapter deals the basics of ultrasonic wave generation and its detection. After that the theoretical and experimental techniques for the determination of ultrasonic properties have been discussed. The formulation of direction dependent ultrasonic velocity and its experimental measurement techniques are detailed for the understanding of mechanical properties in solids. The Different mechanisms responsible for the ultrasonic attenuation in solid material are explained to recognize the several properties of materials. Later on, the study of ultrasonic parameters in different structured materials like fcc, bcc, hcp, hexagonal, glasses, superconductors, nano-materials etc. and in nanofluids/ferrofluid is carried out. The whole study provides a short view of ultrasonic wave and its application to material characterization.

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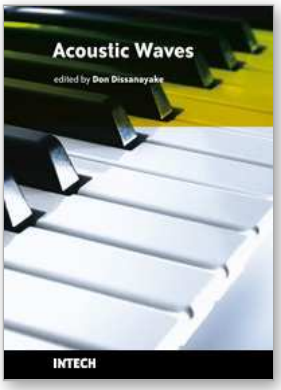

Acoustic Waves

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SAW devices are widely used in multitude of device concepts mainly in MEMS and communication electronics. As such, SAW based micro sensors, actuators and communication electronic devices are well known applications of SAW technology. For example, SAW based passive micro sensors are capable of measuring physical properties such as temperature, pressure, variation in chemical properties, and SAW based communication devices perform a range of signal processing functions, such as delay lines, filters, resonators, pulse compressors, and convolvers. In recent decades, SAW based low-powered actuators and microfluidic devices have significantly added a new dimension to SAW technology. This book consists of 20 exciting chapters composed by researchers and engineers active in the field of SAW technology, biomedical and other related engineering disciplines. The topics range from basic SAW theory, materials and phenomena to advanced applications such as sensors actuators, and communication systems. As such, in addition to theoretical analysis and numerical modelling such as Finite Element Modelling (FEM) and Finite Difference Methods (FDM) of SAW devices, SAW based actuators and micro motors, and SAW based micro sensors are some of the exciting applications presented in this book. This collection of up-to-date information and research outcomes on SAW technology will be of great interest, not only to all those working in SAW based technology, but also to many more who stand to benefit from an insight into the rich opportunities that this technology has to offer, especially to develop advanced, low-powered biomedical implants and passive communication devices.

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