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INVESTIGATION OF INTERMETALLIC GdFeAl TERNARY COMPOUND BY ELASTIC, THERMOPHYSICAL AND ULTRASONIC ANALYSIS

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Higher order elastic constants were calculated of the intermetallic GdFeAl ternary compound using Lennard Jones potential approach. With the using of second order elastic constants (SOECs), other elastic moduli; shear modulus, bulk modulus, Young's modulus, Pugh's ratio, constants of elastic stiffness and Poisson's ratio are estimated for mechanical and elastic characterization at room temperature. Born stability and Pugh's criteria are used to examine the nature and strength of the intermetallic ternary compound and found that it is mechanically stable compound. For the investigation of anisotropic behaviour and thermophysical properties, ultrasonic velocities and thermal relaxation time have been also calculated along with different orientations from the unique axis of the crystal. The temperature variation of ultrasonic velocities, Debye average velocity and thermal relaxation time along the z axis is evaluated using SOECs. The ultrasonic properties correlated with elastic, thermal and mechanical properties which is temperature dependent is also discussed. Ultrasonic attenuation was calculated at different temperatures due to phonon – phonon (p – p) interactions. The responsible reason of attenuation is p-p interactions; it was got that the thermal conductivity is a core contributor to the characteristic of ultrasonic attenuation as a role of temperature. GdFeAl ternary compound behave as its purest form at lower temperature and are more ductile demonstrated by the minimum attenuation.

Keywords: intermetallic ternary compound, elastic properties, mechanical properties, thermal conductivity, ultrasonic properties

Introduction

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RTX types of intermetallic ternary compounds, including rare earth R, transition metal T and p element X, have performed an extremely classy variation of the crystallographic structures for magnetic characterization. These ternary compounds have different crystallographic structures [1]. The GdFeAl ternary compound was seen crystallize into $MgZn_2$- type hexagonal crystal structure, wherever rare-earth atoms involve the 4f site while Fe and Al are positioned at sites 2a and 6h [2, 3]. The GdFeAl had been observed an $MgCu_2$-type structure, when cooling gradually after annealing [4]. TbFeAl and GdFeAl ternary compounds had been observed as a ferrimagnet's nature with transition temperatures 195 K and 260 K respectively, with decreased the magnetic moment of rare-earth atoms due to disordered contribution detected by the neutron experiments. A second order magnetic phase transition has confirmed at 265K [5, 6]. Magnetocaloric effect (MCE) was attracted considerable attention predominantly because of likely application in magnetic cooling or the gas liquefaction. These ternary compounds have excellent magnetocaloric properties, namely high entropy change and large temperature change [7,8]. In the last few years compounds with magnetic transition had been commonly connected with structural transition due to his huge entropy change [9, 10]. In last decay, it may be used in magnetic refrigeration cycle.

It is probable that magnetic cooling would be obtainable to buyer in several years as a more effective environmentally safe for the traditional type of refrigerator [11, 12]. The properties of GdPdX (X = Al, Si, Ga, Ge, In, Si) compounds were expansively examined their characterization [13]. Ultrasonic attenuation (UA) is the exact main physical parameter to describe a material, whichever appreciates the specific relationship between the anisotropic behaviour of the proximal hematinic planes and affinity of structural motion, some physical measures like thermal energy density, specific heat and thermal conductivity, is well associated with higher-order elastic constants [14].

In this work, we were worked diligently to make the relationship between thermo physical and microstructural properties for intermetallic ternary compound. Intermetallic GdFeAl ternary compound will help in understanding the mechanical behaviour of intermetallic ternary compounds and it will performance and significant role in the illustration of manufacturing apparatus with useful physical properties under moderate working conditions. For that, we have considered temperature dependent ultrasonic attenuation coefficient, elastic stiffness constant, acoustic coupling constants, thermal relaxation time and the ultrasonic velocity for ternary compounds. Bulk modulus (B), Young's modulus (Y), shear modulus (G), Pugh's ratio (B / G) and Poisson’s ratio were also calculated and then discussed for this ternary compounds. The findings should serve as a theoretical foundation for future research of intermetallic ternary compound. The theoretical technique and calculation methods of this analysis will be presented in this paper, which will be accompanied by theoretical results, discussion and conclusions.

1. Computational theory

There exists numerous approaches to analyses high-order (SOECs, TOECs) elastic factors of hexagonal materials. According present our effort, the Lenard Jones interaction potential approaches was using for the evaluation for SOECs and TOECs. Higher order elastic constants of hexagonally based materials are a consequence to lattice parameters, according to the potential methodology to evaluation. A general description of elastic coefficient of n^{th} order is the fractional derivatives of the medium constrained to determinate deformation as well as mathematically conveyed by subsequent expression as [14, 15]:

$$C_{ijklmn\ldots} = \frac{\partial^n F}{\partial\eta_{ij}\partial\eta_{kl}\partial\eta_{mn\cdots}} \tag{1}$$

Whenever, F (free energy density) may be extended in relations of strain η_{ij} (Lagrangian strain component tensor) Taylor series expansion as:

$$F = \sum_{n=0}^{\infty} F_n = \sum_{n=0}^{\infty} \frac{1}{n!}\left(\frac{\partial^n F}{\partial\eta_{ij}\partial\eta_{kl}\partial\eta_{mn\cdots}}\right)\eta_{ij}\eta_{kl}\eta_{mn}\cdot\cdot\cdot \tag{2}$$

Thereby, the free energy density is written such as:

$$F_2 + F_3 = \frac{1}{2!}C_{ijkl}\eta_{ij}\eta_{kl} + \frac{1}{3!}C_{ijklmn}\eta_{ij}\eta_{kl}\eta_{\mathrm{mn}} \tag{3}$$

In order that HCP compounds the basis vectors are $a_1 = a\left(\frac{\sqrt{3}}{2}, \frac{1}{2}, 0\right)$, $a_2 = a(0,1,0)$ and $a_3 = a(0,0,c)$. Where a and c are the lattice parameters. For hexagonal compound, unit cell contains 6- atoms in basal plane and 3-3 atoms upper and lower the basal plane. The consequently, both first and second neighborhood contains of 6 atoms. Here $r_1 = a(0,0,0)$and $r_2 = \left(\frac{a}{2\sqrt{3}}, \frac{a}{2}, \frac{c}{2}\right)$ represent position vectors.

The form of potential energy is written as following:

$$U_2 + U_3 = \sum_{I=1}^{6} U(r_I) + \sum_{J=1}^{6} U(r_J) \tag{4}$$

Wherever, I represent the above basal plane and J denote below the basal plane. Interatomic vectors in non-deformed state (r) and deformable state (r') are associated as:

$$(r')^2 - (r)^2 = 2\varepsilon_i\varepsilon_j\eta_{ij} = 2\Theta \tag{5}$$

Whenever, ε_i and $\varepsilon_j$are the component of cartesian vector r. U (energy density) may be describing based onΘas [17-18]:

$$U_n = (2V_c)^{-1}\Sigma\frac{1}{n!}\Theta^n D^n \varphi(r) \tag{6}$$

Equations (4) and (6) give the U including cubic terms as:

$$U_2 + U_3 = (2V_c)^{-1}\left[\sum_{I=1}^{6}\frac{1}{2!}{\Theta_I}^2 D^2\varphi(r_I) + \sum_{J=1}^{6}\frac{1}{2!}{\Theta_J}^2 D^2\varphi(r_J)\right]$$

$$+(2V_c)^{-1}\left[\sum_{I=1}^{6}\frac{1}{3!}{\Theta_I}^3 D^3\varphi(r_I) + \sum_{J=1}^{6}\frac{1}{3!}{\Theta_J}^3 D^3\varphi(r_J)\right] \tag{7}$$

Wherever, $D=R^{-1}d/dR$ and $\varphi(r)$ represents the interaction potential, The value of $V_c = [3^{1/2}/2]\ a^2\ c$ signifying the per unit volume. The energy density is examined in terms of Lennard Jones potential and specified as:

$$\varphi(r) = -\frac{a_0}{r^m} + \frac{b_0}{r^n} \tag{8}$$

Wherever, a_0 and b_0 are constants. Establish the Lenard Jones potential approach leads to computed 6 SOECs and 10 TOECs of the hexagonal compound and formulations of elastic constants were taken by our previous papers [14, 15].

Bulk modulus and shear modulus were calculated using Voigt and Reuss' methodologies [16, 17]. The calculations of unvarying stress and unvarying strain were used in the Voigt and Reuss' methodologies, correspondingly. Furthermore, the average values of the both methodologies were used toward compute ensuing values of B and G using Hill's methods, [17, 18]. Using the values of Bulk modulus (B), Shear modulus (G), Poisson's ratio (σ) and Young's modulus (Y) are evaluated [19, 20]. The following expressions were used for the evaluation of Y, B, G and σ.

$$\left.\begin{aligned} & M = C_{11} + C_{12} + 2C_{33} - 4C_{13}, \mathrm{C}^2 = (C_{11} + C_{12})C_{33} - 4C_{13} + {C^2}_{13}; \\ & B_R = \frac{C^2}{M}; \mathrm{B}_V = \frac{2(C_{11}+C_{12})+4C_{13}+C_{33}}{9}; \\ & G_V = \frac{M+12(C_{44}+C_{66})}{30}; \mathrm{G}_R = \frac{5C^2C_{44}C_{66}}{2[3B_VC_{44}C_{66}+C^2(C_{44}+C_{66})]}; \\ & Y = \frac{9GB}{G+3B}; \quad \mathrm{B} = \frac{B_V+B_R}{2}; \quad \mathrm{G} = \frac{G_V+G_R}{2}; \sigma = \frac{\mathrm{3B\text{-}2G}}{2(\mathrm{3B}+G)} \end{aligned}\right\} \tag{9}$$

Ultrasonic velocities in hexagonal compound are one longitudinal V_L and two shear (V_{S1}, V_{S2}) waves velocities, where, V_L is the longitudinal and V_{S1} and V_{S2} are shear and quasi-shear and shear wave velocities [21]. The Debye average velocity is specified by the equation as [22]:

$$V_D = \left[\frac{1}{3}\left(\frac{1}{V_L^3} + \frac{1}{V_{S1}^3} + \frac{1}{V_{S2}^3}\right)\right]^{-1/3} \tag{10}$$

At the low temperature regime, the mean free path of electron is alike as the mean free path of acoustical phonons. Accordingly, a high probability coupling arises between acoustic phonons and free electrons [14]. The mathematical formulation of UA for longitudinal $(\alpha)_{Long}$ and shear waves $(\alpha)_{\mathrm{Shear}}$ is given by:

$$\alpha_{long} = \frac{2\pi^2 f^2}{\rho V_l^3}\left(\frac{4}{3}\eta_e + \chi\right) \tag{11}$$

$$\alpha_{shear} = \frac{2\pi^2 f^2}{\rho V_S^3}\eta_e, \tag{12}$$

where 'ρ' is the density and 'f' is the frequency of the ultrasonic wave of hexagonal compound, 'η_e' represent the electron viscosity and 'χ' is the compressional viscosity, V_L and V_S are given as:

$$V_L = \sqrt{\frac{C_{33}}{\rho}} \; and \; V_S = \sqrt{\frac{C_{44}}{\rho}} \, . \tag{13}$$

The viscosity of the electron gas (η_e) [21, 22] is given by

$$\eta_e = \frac{9\times10^{11}\hbar^2(3\pi^2 N)^{2/3}}{5e^2 R} \; , \tag{14}$$

where 'R' is the resistivity and 'N' represents the number of molecules per unit volume.

At high temperature, p-p interaction (Akhieser's type of losses) and thermoelastic losses are the two prevailing methods, whichever are considerable for ultrasonic attenuation. The Akhieser's type of loss is specified by the subsequent equation:

$$(\alpha/f^2)_{Akh} = \frac{4\pi^2\tau E_0(D/3)}{2\rho V^3}. \tag{15}$$

Here E_0represent thermal energy density. Also, the acoustical coupling constants (D) is given by:

$$D = 3(3E_0 < (\gamma_i^j)^2 > - < \gamma_i^j >^2 C_V T)/E_0 \tag{16}$$

Here C_V is the specific heat per unit volume and γ_i^j is the Grüneisen numberof the material. The thermal relaxation time, signified by 'τ' is given by:

$$\tau = \tau_S = \tau_L/2 = \frac{3k}{C_V V_D^2} \tag{17}$$

Here τ_L and τ_S are the thermal relaxation time for the longitudinal wave and shear wave respectively, the thermal conductivity represents as 'k'. The thermoelastic loss $(\alpha/f^2)_{Th}$ is evaluated by the subsequent equation [21, 22]:

$$(\alpha/f^2)_{Th} = 4\pi^2 < \gamma_i^j >^2 \frac{kT}{2\rho V_L^5} \, . \tag{18}$$

The total ultrasonic attenuation is specified by the subsequent equation as:

$$(\alpha/f^2)_{Total} = (\alpha/f^2)_{Th} + (\alpha/f^2)_L + (\alpha/f^2)_S \, . \tag{19}$$

Wherever $(\alpha/f^2)_{Th}$is the thermoelastic loss, $(\alpha/f^2)_L$and $(\alpha/f^2)_S$ are the ultrasonic attenuation coefficient for the longitudinal wave and shear wave correspondingly.

2. Results and discussion

2.1 Higher order elastic constants

We have used interaction potential approach to calculate the elastic constants (six of SOECs, ten of TOECs) in this investigation. The lattice parameters 'a' (basal plane parameter) and 'p' (axial ratio) for intermetallic GdFeAl ternary compound is 5.442 Å and 1.622 respectively [23]. The chosen values of m and n for intermetallic GdFeAl ternary compounds are 6 and 7. Values of b_0 are 1.13x10^{-62} erg cm^7 for GdFeAl compound. SOECs and TOECs were calculated for the intermetallic GdFeAl ternary compound at room temperature is offered now Table 1.

Table1. Second and third order elastic constants (SOEC and TOEC) in (GPa) at room temperature.

Ternary compound	C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	C_{66}	B
GdFeAl	64.5	15.83	13.56	64.28	16.27	25.27	32.5

Ternary compound	C_{111}	C_{112}	C_{113}	C_{123}	C_{133}	C_{344}	C_{144}	C_{155}	C_{222}	C_{333}
GdFeAl	-1050	-1666	-347	-442	-2171	-2035	-515	-343	-8315	-8042

Intermetallic GdFeAl ternary compound had the highest elastic constant values, which are important for the material, as these are associated with the stiffness parameter. SOECs are used to determine the UA and associated parameters. Highest elastic constant values found for this intermetallic ternary compound are indicative of their better mechanical properties over another intermetallic ternary compound.

Evidently, for steady of the hexagonal compound, they would satisfy the renowned Born- Huang's stability norms [19, 20], i.e. C11− |C12| > 0, C11> 0, C44 > 0 and (C11+C12) C33− 2C213> 0 (Table-1). It is evident that the values of above elastic constant are positive too satisfies Born-Huang's mechanical stability criteria and therefore totally this intermetallic GdFeAl ternary compound are mechanically stable. The bulk modulus for intermetallic GdFeAl ternary compound can be calculated and presented in Table 1. Comparing our results with the Debye temperature of GdFeAl ternary compound. The current value of Debye temperature is 170.6 K, evaluated using SOECs, while the Debye temperature experimentally determined by Kastil et al. [24] is 170 K. Thus, there is good agreement between the present value and reported value by Kastil et al.

Thus, there is respectable agreement between the presented and the informed values, which is correlated with second order elastic constants. Therefore, our theoretical methodology is well justified for the evaluation of SOECs of hexagonal ternary compound. We present the calculated values of TOECs in table 1. The negative sign of TOECs designate a negative strain in the solid. Negative TOECs appear in the previous paper on hexagonal structure ternary compound. Therefore, this applied theory for valuation of higher order elastic constants is justified [25, 26]. Also, this theory is applicable for other hexagonally binary and quaternary compounds [27, 28].

The values of B, G, Y, B/G and 'σ' for intermetallic GdFeAl ternary compound at room temperature are calculated using Equation (9) and existing in Table 2.

Table 2. Voigt–Reus' constants (M and C^2), B (x 10^{10}Nm^{-2}), G (x 10^{10}Nm^{-2}), Y (x 10^{10}Nm^{-2}), σ, B/G for intermetallic GdFeAl ternary compound.

Ternary compound	M	C^2	B_r	B_v	G_r	G_v	Y	B/G	G/B	σ
GdFeAl	155	5290	34	31	21	22	53	1.51	0.66	0.228

The intermetallic GdFeAl ternary compound has little Stiffness and bonding. B/G and 'σ' are the measure of brittleness and ductility of solid. If σ = 0.228 ≤ 0.26 and B/G = 1.51≤1.75, the solid is generally brittle, otherwise it is ductile in nature [28, 29]. Our finding of lower values of B/G and σ compared to their critical values indicates that chosen ternary compound are brittle in nature at room temperature. It is well known that for stable and elastic material the value of σ should be less than 0.5. The value of 'σ' evaluated for GdFeAl is smaller than its critical value. The compressibility, hardness, ductility, toughness, brittleness and bonding nature of the material are also well connected with the SOECs.

2.2 Ultrasonic Velocity and allied parameters

In present analysis, we have correlated the mechanical and isotropic behavior of the hexagonal compound with ultrasonic velocity. We have calculated all three velocities $V_{L,}$ V_S, V_D and thermal relaxation time (τ) for intermetallic GdFeAl ternary compound. The thermal conductivity of intermetallic GdFeAl ternary compound has been evaluated from electrical resistivity using Wiedemann- Franz law [23] and presented in Table. 3 The values of temperature dependent thermal energy density (E_0) and specific heat per unit volume (C_V) are calculated using the tables of physical constant are presented in Table. 3. The values of temperature dependent acoustic coupling constant (D_L and D_S) are shown in Table. 3

Table. 3. Density (ρ:x 10^3 kg m^{-3}), specific heat per unit volume (C_V: x $10^5 Jm^{-3}K^{-1}$), thermal energy density (E_0: x $10^8 Jm^{-3}$), thermal conductivity (k: x 10^4 $Wm^{-1}K^{-1}$) and acoustic coupling constant ($D_{L,}$ D_S) of GdFeAl ternary compound.

Temp	ρ	C_V	E_0	k	D_L	D_S
50	6.18	3.84	7.57	0.76	53.65	1.12
100	6.16	5.58	3.22	1.45	54.81	1.12
150	6.14	6.01	6.11	2.19	55.18	1.12
200	6.12	6.15	9.15	2.84	55.37	1.12
250	6.10	6.21	12.19	3.42	55.47	1.12
300	6.08	6.23	15.22	4.04	57.14	1.12

It is clear form Table3 that for all temperature, the values of D_L are larger than those of D_S for GdFeAl ternary compound. It indicates that for the shear ultrasonic wave the transformation of ultrasonic energy into thermal energy is less than for longitudinal ultrasonic wave.

The angular dependence ultrasonic velocities are shown in Figs. 1-4. The angles are measured form the z-axis of the crystal. Form figs. 1 and 2, velocities V_L and V_{S1} of GdFeAl ternary compound has minima and maxima at 45^0 at all temperatures. In Figure 3, we find that V_{S2} increases with temperatures along the z- axis. The irregular behavior of orientation dependent velocity is due to combined effect of second order elastic constants and density of the material. The nature of the orientation dependent velocity curves in this work is similar to nature of orientation dependent velocity curve found for other hexagonal type's material [25, 26]. Thus, the angle dependence of the velocities in intermetallic GdFeAl ternary compound is justified.

Figure 4 shows the variation of Debye average velocity (V_D) with the angle made with the z- axis of the crystal. It is clear that V_D increases with the angle and reaches maximum at 55^0 for intermetallic GdFeAl ternary compound. As the calculation of V_D involves the velocities V_L, V_{S1} and V_{S2} [26, 28]. It is understandable that the variation of debye average velocity is affected by the fundamental acoustics velocities. The maximum value of V_D at 55° is due to a significant increase in pure shear and longitudinal wave velocities and a decrease in quasi-shear wave velocity. It may be determined that average sound wave velocity is a maximum when a sound wave travels at 55^0 angles with the z- axis of this crystal.

Figures 5 shows a plot of the calculated thermal relaxation time 'τ' with the orientation dependent. Angle dependent 'τ' curves track the reciprocal nature of V_D as$\tau \propto 3K/C_V V_D^2$.

It is clear that thermal relaxation time for intermetallic GdFeAl ternary material is mostly affected by 'k'. Thermal relaxation time 'τ' for hexagonally type structured compounds is of order at picoseconds [29, 30, 31]. Therefore, the calculated 'τ' explains the hexagonal structure of intermetallic GdFeAl ternary compound. Along θ = 55^0, the lowest value of 'τ' for wave propagation denotes that the re-establishment time for equilibrium distribution of thermal phonons will be minimum for propagation of wave along this direction. Ultrasonic attenuation due to p-p interaction and thermal relaxation occurrences.

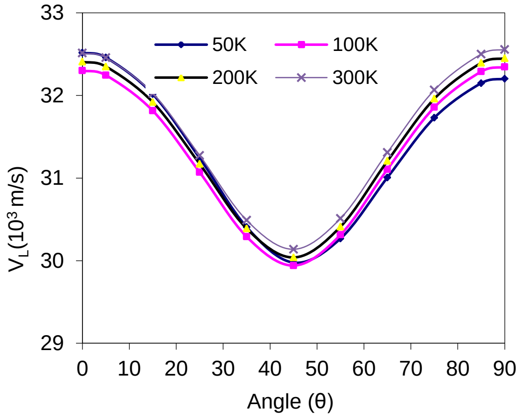

Fig1. V_L vs angle with z- axis of crystal.

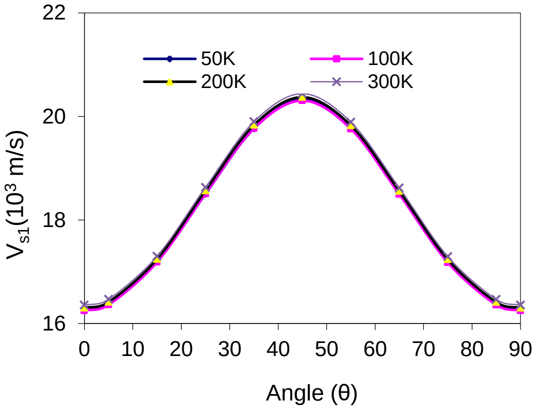

Fig 2. Vs_1 vs angle with z- axis of crystal.

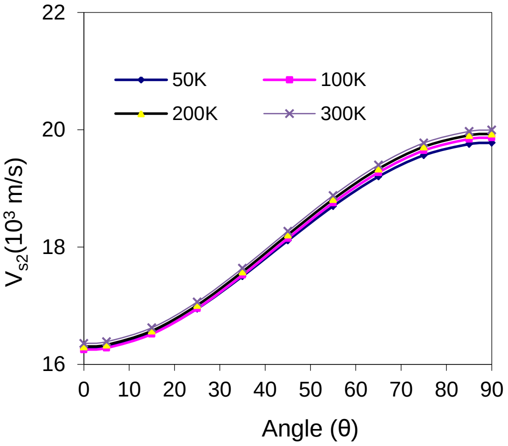

Fig 3. Vs_2 vs angle with z- axis of crystal.

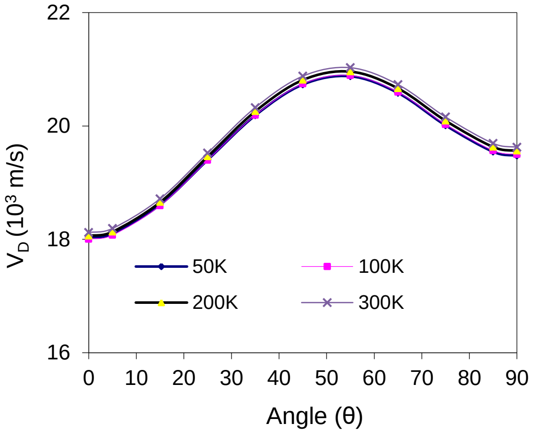

Fig.4. V_D vs angle with z- axis of crystal.

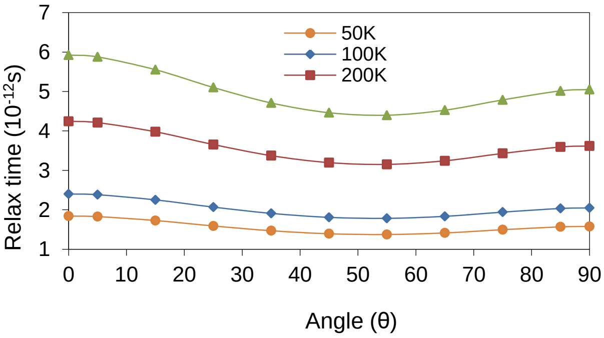

Fig.5. Relaxation time vs angle with z- axis of crystal

2.3 Ultrasonic attenuation due to phonon-phonon interaction and thermal relaxation phenomena

While evaluating the UA, the attenuation coefficient divided by frequency squared $(\alpha/f^2)_{Akh}$ is calculated for the longitudinal wave $(\alpha/f^2)_L$and for the shear wave $(\alpha/f^2)_S$using Eqns. 11 and 12 under the condition ωτ<<1 at different temperature along the z- axis of intermetallic GdFeAl ternary compound. Eqn. 18 has been used to calculate the thermo-elastic loss divided by frequency squared $(\alpha/f^2)_{Th}$. Figures 6-7 present values of the temperature dependent longitudinal, shear and total attenuation of intermetallic GdFeAl ternary compound.

In this work, the acoustic wave is assumed to propagate along the z- axis of the crystal from Fig. 6-7. It is evident that the Akh. type of energy losses $(\alpha/f^2)_{Akh}$ proportional to D, E_0, τ and V^{-3} (Eqns. 15 and 18). Table 3 shows that' E_0' and 'V' are increasing with temperature. Hence Akhieser losses in GdFeAl ternary compound are overwhelmingly affected by E_0 and the 'k'. Consequently, the increase in UA is due to the increase in thermal conductivity. Therefore, it is the p-p interaction which predominantly governs the ultrasonic attenuation; outstanding to deficiency of theoretical/experimental facts in the literature a comparison of UA could not be made.

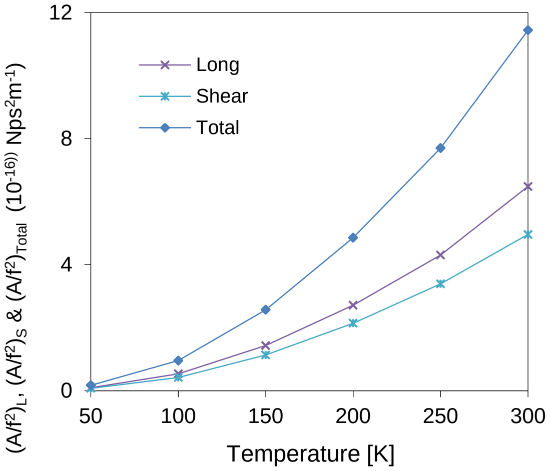

Fig.6. Long.& Shear and Total attenuation vs temperature of GdFeAl compound.

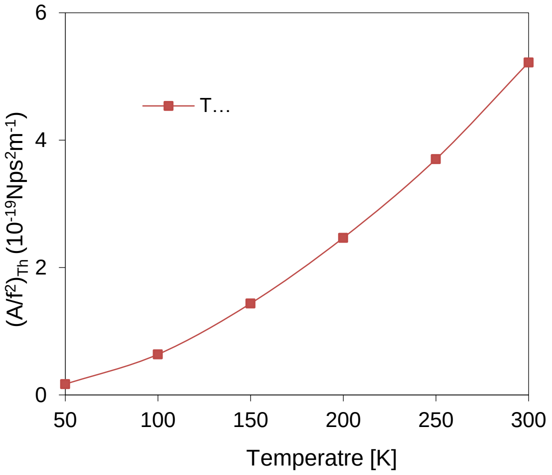

Fig.7. Th. attenuation vs temperature of GdFeAl compound.

In Figures 6-7, it is clear that the thermo-elastic loss is much lower in comparison to Akhieser loss for intermetallic GdFeAl ternary compound, and also the total attenuation using Eqn. 19. UA due to p–p interaction for longitudinal wave and shear wave is leading factor. The thermal conductivity and thermal energy density are main factor that affects the total attenuation. Thus, it may be predicted that the GdFeAl ternary compound behave as his purest form at low temperature (50K) and are further ductile demonstrated by the minimum attenuation although at high temperature (room temperature) of intermetallic GdFeAl ternary compound are least ductile.

Therefore, at lower temperature there will be least impurity in intermetallic GdFeAl ternary compound. Since the velocities is largest for intermetallic GdFeAl ternary compound at this temperature and the ternary compound would be most ductile. Minimum values of UA for intermetallic GdFeAl ternary compound at lower temperature defends its quite stable hexagonal type structure state.

Conclusions

Based on the above conversation is valuable to state that:

– The principle established on simple interaction potential approach remains valid for calculating higher-order elastic coefficients for hexagonally structured intermetallic ternary compound.

– The elastic constants should satisfy the renowned Born's stability criteria for stable nature of intermetallic ternary compound. The Pugh's ratio confirms the ductile nature of ternary compound.

– Intermetallic GdFeAl ternary compound. 'τ' is found to be of the picoseconds order, which defends their hexagonal structure. As 'τ' has smallest value along $\theta = 55^{0,}$ at all temperatures, the time for re-establishment of symmetry spreading of phonons, will be minimum, for the wave propagation in this direction.

– Over total attenuation**,** UA caused by p-p interaction mechanism is dominant and is a leading factor of thermal conductivity and energy density.

– GdFeAl ternary compound behave as its purest form at lower temperature and are more ductile demonstrated by the minimum UA while at higher temperature this compound is least ductile.

The research could help with ternary intermetallic compounds processing and non-destructive characterization. These studies will form a basis for further research into the essential thermophysical features of various another ternary compounds.

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