Acoustical characterization of nickel aluminide (Ni$_3$Al) at low temperatures

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Abstract. Present research work deals with the acoustical characterization of Nickel Aluminide (Ni$_3$Al) at low temperature region from 10K to 50K. Particularly, the Ultrasonic waves have been used as a Non-destructive testing (NDT) tool to characterize this Ni$_3$Al. For this purpose, in our technique, the two parameters such as the nearest-neighbour distance and the hardness parameter is taken as two input parameters. Ultrasonic attenuation due to the cause of e-p (electron-phonon) interaction has been evaluated from 10K to 50K, for longitudinal as well as shear waves along <100> crystallographic direction and the elastic constants (second order) for this intermetallic alloy of nickel and aluminium is also evaluated in low temperature region and the obtained results have been discussed.

1. Introduction
Ni$_3$Al is an alloy consisting of Nickel and Aluminium both and it has the properties similar to ceramic and metal both. The different properties of Ni$_3$Al (L$_{12}$ phase) such as structural, mechanical and elastic properties have been investigated and discussed in recent years. In the literature study several data related with the mechanical properties are available for this alloy, but especially the data related with the ultrasonic characterization at low temperature region is not available. Therefore the present investigation is much required in which for characterizing this alloy acoustically, we have used the ultrasonic waves and the ultrasonic attenuation studies have been done in low temperature region i.e. due to the electron-phonon interaction.

There are several uses of different alloys which are Nickel based such as they are used as in aircraft engines, in turbine disks. The overview of different applications of Ni$_3$Al based intermetallic alloys is discussed in detail by Jozwik et al [1]. Also in the ultrasonic attenuation studies in intermetallics is done [2].
2. Theory

A review of these [3] studies shows that the ultrasonic attenuation varies from substance to substance in crystallographic directions and also according to the temperature regions studied. By taking the two input parameters such as the nearest-neighbour distance and hardness parameter, for the Ni$_3$Al Alloy having FCC structure (As per the already available data of X-ray diffraction analysis, Ni$_3$Al retains FCC structure) and by using the detailed concept of electrostatic and short-range repulsive potentials, the different elastic constants (Second Order) at 0K viz. $C_{ij}^{0}$ have been obtained by following the Brugger’s definition [4]. By using the above concepts of potentials and taking interactions up to next nearest neighbours, the expressions for Second and third order elastic constants at any temperature, T are given as:

$$C_{ij}(T) = C_{ij}^{0} + C_{ij}^{vib.}$$  \hspace{1cm} (1)

$$C_{ijk}(T) = C_{ijk}^{0} + C_{ijk}^{vib.}$$  \hspace{1cm} (2)

The expressions for $C_{ij}$’s and $C_{ijk}$’s have already been discussed [5, 6]. As per the basic concepts it is already well known that at low temperature in metals, the mean free path of a conduction electron becomes comparable to the wavelength of an acoustical phonon. The coupling of the conduction electron with a propagating ultrasonic wave causes dissipation of the energy of the wave, and thus a viscous loss occurs. The attenuation caused by the energy loss due to the compressional and shear viscosities of the lattice [7], at low temperatures are

$$\left( \frac{\alpha}{f^2} \right)_{\text{Longitudinal}} = \frac{2\pi^2}{dv_f} \left( \frac{4}{3} \eta_c + \chi_c \right)$$ \hspace{1cm} (3)

and

$$\left( \frac{\alpha}{f^2} \right)_{\text{Shear}} = \frac{2\pi^2}{dv_f} \eta_s$$ \hspace{1cm} (4)

In the above expressions, “$d$” is the density of the crystal, “$f$” is the ultrasonic frequency, $\eta_c$ is the transverse viscosity, $\chi_c$ is the compressional viscosity and this $\chi_c$ is zero as explained by Bommel [8].

The detailed behaviour of acoustical Phonons in Metals in low temperature region is investigated by S K Kor et al [9,10]. Also at any temperature, the resulting elastic constant is obtained by an addition of the vibrational energy contribution to the second order elastic constants SOEC at absolute zero and by using the anharmonic theory for lattice dynamics [11-13].

The expression for $v_l$ and $v_s$ (longitudinal and shear wave velocities) are as follows:

$$v_l = \sqrt{\frac{C_{11}}{d}}$$ \hspace{1cm} (5)

and

$$v_s = \sqrt{\frac{C_{44}}{d}}$$ \hspace{1cm} (6)

The viscosity of an electron gas is given by

$$\eta_e = \frac{Nme\bar{v}}{3}$$ \hspace{1cm} (7)

Where $N$ is the electron density, $m$ is its mass, $\bar{l}$ and $\bar{v}$ are mean free path and mean velocity of electron.

Where from the theory of electron gas [14], by substituting the values of $\bar{l}$ and $\bar{v}$ in equation 7, $\eta_e$ becomes:

$$\eta_e = \frac{9\times10^{11}h^2}{5e^2R} \left(3\pi^2N\right)^{2/3}$$ \hspace{1cm} (8)

Where $R$ is electrical resistivity and $N$ is free electron density.
3. Results and Discussion

The obtained results of the elastic constants (second order) for Ni$_3$Al alloy in the low temperature region i.e. from 10K to 50K is presented in table 1. According to which our evaluated value at 10K is $C_{11} = 27.94227 \times 10^{11}$ dynes/cm$^2$. Since no specific results are available for such an alloy in the said temperature region, So we have compared our result with the available results for other intermetallic alloys [2] and we have found that the orders of the results are the same. The “ultrasonic attenuation coefficient” due to e-p interaction for both the modes of propagation i.e. the “longitudinal as well as shear” from 10K to 50K i.e. $\frac{\alpha}{f}$ is evaluated by the help of the equations (3) to (8) and the same is as presented in figure 1. From this figure we can see that as usual this ultrasonic coefficient decrease with temperature but in the case of such a specific alloy Ni$_3$Al, this rate of decrease is very much small as compared to the other intermetallic alloys [2]. This nature of decrease in attenuation coefficient can be attributed to the inherent nature of this alloy [1]. The temperature variation of ultrasonic wave velocities (longitudinal and shear waves) is as presented in figure 2. This result of wave velocity is as expected [9]. So, we can conclude that the approach which is used in this research paper is correct and most easy and helpful to the different researchers.

Table 1. Second Order elastic constants ($10^{11}$dynes/cm$^2$) for Ni$_3$Al from 10K to 50K.

| Temp (K) | $C_{11}$ | $C_{12}$ | $C_{44}$ |
|---------|---------|---------|---------|
| 10      | 27.94227| 4.709194| 4.736072|
| 15      | 27.94226| 4.709173| 4.736073|
| 20      | 27.94222| 4.708981| 4.736074|
| 25      | 27.94219| 4.708376| 4.736078|
| 30      | 27.94236| 4.707228| 4.736088|
| 35      | 27.94292| 4.705556| 4.736105|
| 40      | 27.94402| 4.703449| 4.736129|
| 45      | 27.94547| 4.701007| 4.736160|
| 50      | 27.94797| 4.698315| 4.736197|

Figure 1. Temperature variation of $(\alpha/f^2)$ due to e-p interaction in Nickel Aluminide crystal for longitudinal and shear waves along <100> direction.
Figure 2. Temperature variation of Ultrasonic wave velocities (Longitudinal and Shear waves), $v_l$ and $v_s$ due to e-p interaction in Nickel Aluminide along <100> direction.

4. Conclusion
As per the detailed results and discussions as shown above, we can conclude that, in this present research paper, we have efficiently applied the concepts of two types of potentials such as “Born-Mayer and repulsive” and we have used very simple method for the present characterization technique by taking the two input parameters only. The detailed behaviour of Ni$_3$Al (L1$_2$ phase) such as its response to the ultrasonic wave when it passes through this material at low temperature as discussed above will definitely be very useful for different researchers who are working in the area of NDT Materials characterization for the materials having FCC structures and the observed results will definitely be very useful for many applications in industry.

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