ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

Behaviour of ultrasonic wave velocities in materials under elastic thermo mechanical effect

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Abstract

This study deals with the propagation of longitudinal and shear ultrasonic waves which are transmitted in isotropic thermo elastic materials supposed initially in a stress free state. Ultrasonic waves propagating in a material depend on some elastic properties of the propagation medium such as volume mass and induced deformation resulting from applied mechanical or thermal stresses. They also depend on the nature of propagated longitudinal or shear waves and in this last case they also depend on the polarization direction of the wave. For homogeneous and isotropic materials, no linear mechanics provides acoustoelastic expressions of velocities as function of second and third elastic constants and applied stresses. Submitting a sample to a small temperature change, we study the behaviour of ultrasonic waves in presence of thermomechanical stresses applied according to considered directions of propagation, polarization and loading. A numerical simulation of elastic thermo mechanical effect has been applied to two usual materials in C 33 steel and in AlMg3 aluminium alloy. This method allows simulating the behaviour of ultrasonic wave velocities under elastic thermo mechanical effects.

Key-words: Acoustoelasticity; material; thermo mechanical effect; temperature change; stresses.

1. INTRODUCTION

Nowadays, ultrasonic waves constitute an advantaged investigating tool for analysis of mechanical and structural properties of materials under mechanical, thermal and thermo mechanical stresses. To study the interaction of the ultrasonic wave with an isotropic medium under elastic mechanical or thermal stresses, we use the acoustoelasticity theory.

For homogeneous isotropic materials, Hughes and Kelly [1-2] used no linear mechanics to establish the dependence of velocities according to the second (λ,μ) and third (l,m,n) order elastic constants. From the Murnaghan model, Hughes and Kelly determined seven relations between propagation velocities and stresses [1]. These equations constitute the basis of all measurement methods of applied and residual stresses by Non-destructive Ultrasonic Evaluation. In acoustoelastic studies, the effect of temperature didn't make the object of an abundant works. This effect seems important for an extension of the applicability of the acoustoelasticity theory to measure thermal stresses. Effects of temperature and stress on the ultrasonic velocity have been studied by Salama [3]. In the Kobori's experimental study [4-5], limited to uniaxial stresses and small temperature changes, it has been confirmed that the velocity variation is proportional to the temperature variation that the factor of proportionality is linearly dependent of the applied stresses. Of this fact, the acoustoelastic constant varies directly with the temperature change. To note that stress and temperature effects on velocities have been studied experimentally in order to extend the acoustoelastic equation for thermoelastical materials. Thermo elastic behaviour of materials resides in an elongation, a volume dilation or a contraction under temperature variations effect. Commonly, materials undergo an elongation under the heat effect corresponding to dilation. In the case of the cold effect, they undergo a reduction corresponding to a contraction. The thermo elasticity effect is associated to the concept of reversibility: the reply of the material to the imposed thermal and /or mechanical solicitation is instantaneous and its cancellation carries out the material to return in its initial state without any permanent effect.

The present communication deals with a simulation applied to two usual materials made of C33 steel and AlMg3 aluminium alloy which theirs acoustic and physical properties are known. The objective resides in studying behaviour of ultrasonic wave velocities in materials under elastic mechanical stress (traction or compression), thermal stress (heating or cooling) and thermo mechanical stress (traction-heating, compression-cooling).

2. THEORY

Variations of temperatures induce some thermal effects in materials. These effects act on the normal deformations resulting from thermal stresses. The thermal stress depends on the linear coefficient of the thermal expansion α, the temperature variation $\Delta\theta$ and the Young's modulus E.

$$\sigma_{th} = \alpha E \Delta\theta \tag{1}$$

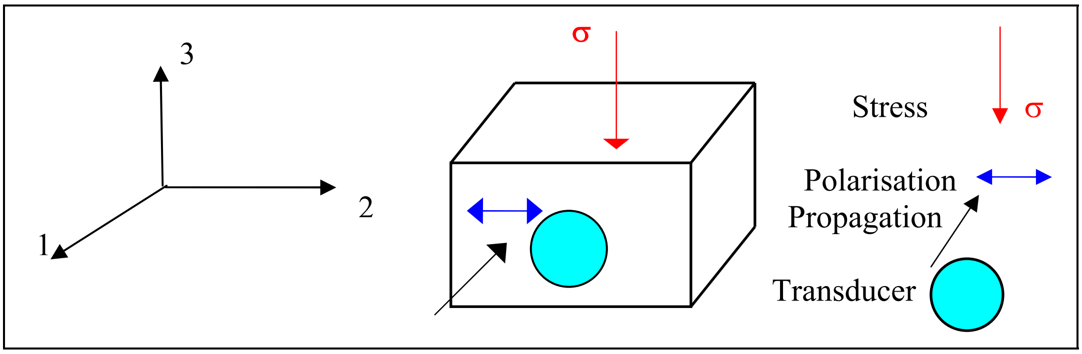

Figure 1. Loading mode and wave propagation with regard to the referential of the sample

Considering that the temperature field is uniform, then there is a coupling between the thermal problem and the mechanical problem. The acoustoelasticity theory allows determining expressions of longitudinal and transversal or shear waves according to some intrinsic characteristics of the material and applied stresses (interaction ultrasonic waves - applied stresses). Assuming an isotropic sample insonified by different propagation waves of which polarizations are parallel or perpendicular to the direction of the applied stress (see figure1). By convention, for the applied mechanical compression stress $\sigma_{me}<0$ and for the traction stress σ_{me}>0. To study the different cases of loading, we establish expressions of longitudinal and transversal wave propagation according to the applied stresses in the deformed configuration of the studied material [2].

2.1. Acoustoelastic equations in presence of thermo mechanical stresses

To study the influence of the variation temperature on the propagation velocity in presence of applied mechanical stresses, we consider that the total applied stress in acousto elastic equations will be composed by mechanical and thermal stresses: $\sigma_{tot} = \sigma_{me} + \sigma_{th}$ with: $\sigma_{th} = \alpha E \Delta\theta$. Therefore, equations can be presented as following:

2.1.1. Thermo mechanical stress applied according to the axis (1):

- Case of a longitudinal wave propagating according to the axis 1:

$$\rho^{\circ} V_{11(1)}^2 = 2\mu + \lambda + \frac{\alpha E \Delta\theta + \sigma_{me}}{3\mathrm{K}} \left[\frac{\lambda + \mu}{\mu} (4\lambda + 10\mu + 4m) + \lambda + 2l \right] \quad (2)$$

- Case of a transversal wave propagating according to the axis 1 and polarised according to the axis 2 :

$$\rho^{\circ} V_{12(1)}^2 = \rho^{\circ} V_{13(1)}^2 = \mu + \frac{\alpha E \Delta\theta + \sigma_{me}}{3\mathrm{K}} \left[4\lambda + 4\mu + m + \frac{n\lambda}{4\mu} \right] \quad (3)$$

2.1.2. Thermo mechanical stress applied according to the axis (2):

- Case of a longitudinal wave propagating according to the axis 1:

$$\rho^{\circ} V_{11(2)}^2 = \lambda + 2\mu + \frac{\alpha E \Delta\theta + \sigma_{me}}{3\mathrm{K}} \left[-\frac{2\lambda}{\mu} (\lambda + 2\mu + m) + 2l \right] \quad (4)$$

- Case of a transversal wave propagating according to the axis 1 and polarised according to the axis 3 :

$$\rho^{\circ} V_{13(2)}^2 = \mu + \frac{\alpha E \Delta\theta + \sigma_{me}}{3\mathrm{K}} \left[-2\lambda + m - \frac{\lambda + \mu}{2\mu} n \right] \quad (5)$$

- Case of a transversal wave propagating according to the axis 1 and polarised according to the axis 2 :

$$\rho^{\circ} V_{12(2)}^2 = \mu + \frac{\alpha E \Delta\theta + \sigma_{me}}{3\mathrm{K}} \left[\lambda + 2\mu + m + \frac{n\lambda}{4\mu} \right] \quad (6)$$

2.1.3. Thermo mechanical stress applied according to the axis (3):

- Case of a longitudinal wave propagating according to the axis 1:

$$\rho^{\circ}\ V_{11(3)}^{2}=\lambda+2\mu+\frac{\alpha E\Delta\theta+\sigma_{me}}{3\text{K}}\left[-\frac{2\lambda}{\mu}\left(\lambda+2\mu+m\right)+2l\right] \tag{7}$$

- Case of a transversal wave propagating according to the axis 1 and polarised according to the axis 2 :

$$\rho^{\circ}\ V_{12(3)}^{2}=\mu+\frac{\alpha E\Delta\theta+\sigma_{me}}{3\text{K}}\left[-2\lambda+m-\frac{\lambda+\mu}{2\mu}n\right] \tag{8}$$

- Case of a transversal wave propagating according to the axis 1 and polarised according to the axis 3 :

$$\rho^{\circ}\ V_{13(3)}^{2}=\mu+\frac{\alpha E\Delta\theta+\sigma_{me}}{3\text{K}}\left[\lambda+2\mu+m+\frac{n\lambda}{4\mu}\right] \tag{9}$$

3. THERMO-ACOUSTOELASTIC SIMULATION

For thermo-acousto-elastic simulation, we use data of two studied materials: a C33 steel and an AlMg3 aluminium alloy (see Table 2). Notice that the maximal temperature change is determined by using criteria of elastic limit for each material. These criteria are also used for coupling of thermal and mechanical stresses. We admit that stresses depend linearly on the temperature change from a known uniform state θ_0=20°C. The application of equations allows computing variations of longitudinal and transversal wave velocities according to temperature changes.

3.1. Wave velocities as function of temperature changes

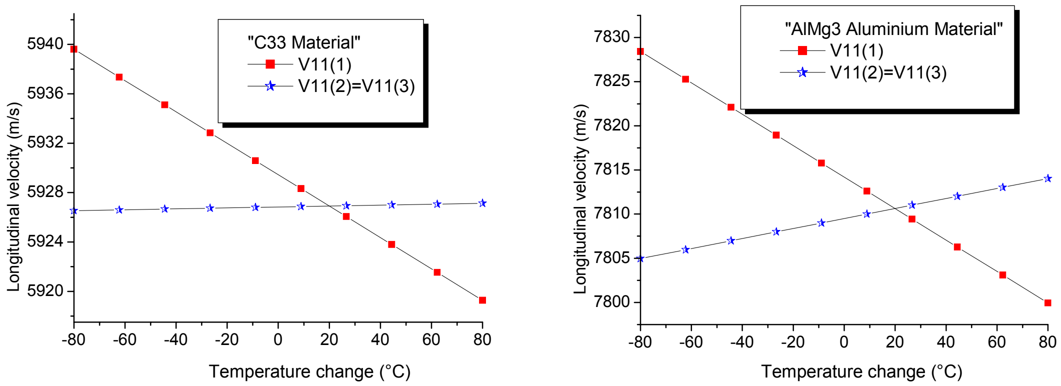

Figure 2. Longitudinal velocity as function of temperature variations for C33 and AlMg3 Materials.

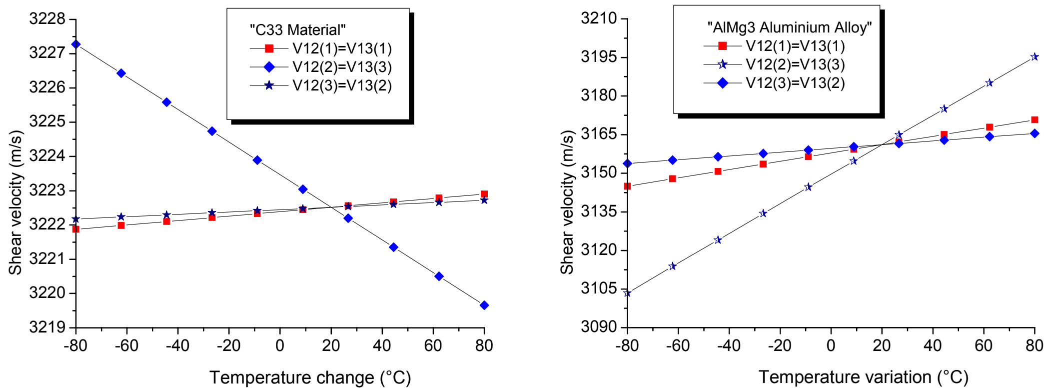

Figure 3. Shear velocity as function of temperature variations for C33 and AlMg3 Materials

3.2. Wave velocities as function of mechanical stresses under ambient temperatures

For two ambient temperature variations 40°C and -20°C, we determine longitudinal and shear wave velocities as function of mechanical compression and tensile stresses (see figures 4 and 5).

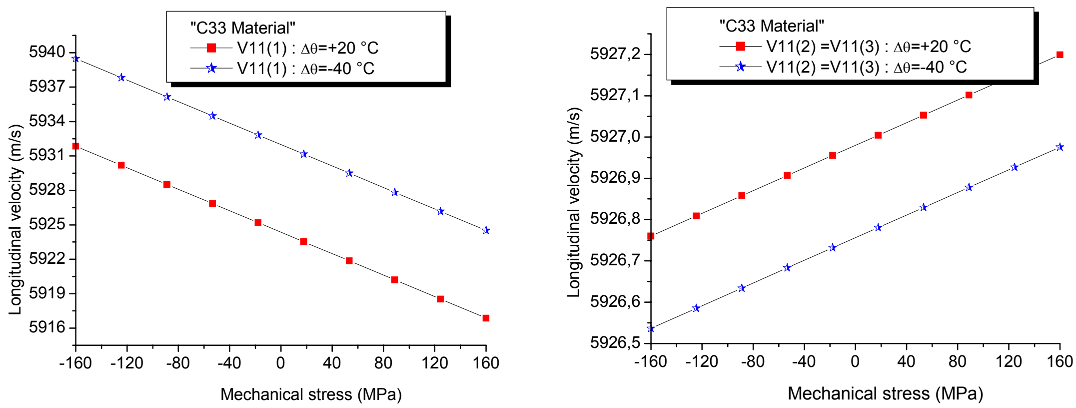

Figure 4. Longitudinal velocity as function of the applied mechanical traction and compression stresses under temperature variations Δθ =20°C and Δθ = -40°C.Case of C33 Material.

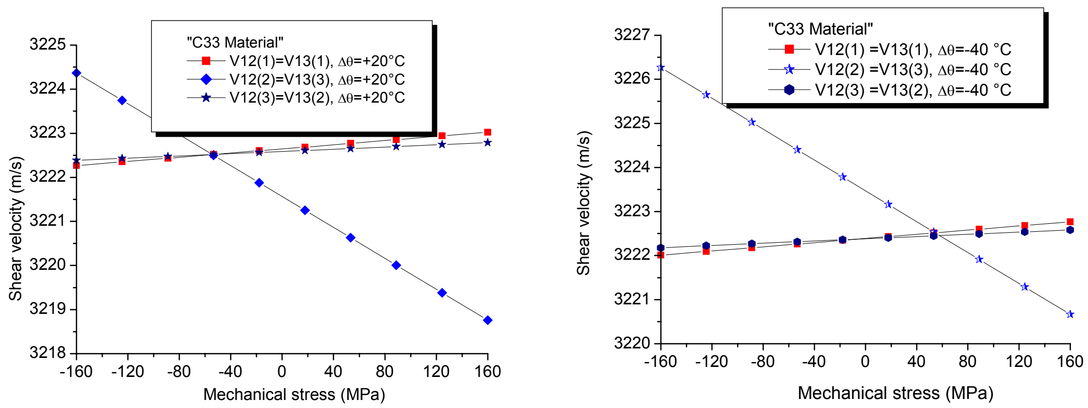

Figure 5. Shear velocity as function of the applied mechanical traction and compression stresses under temperature variations Δθ =20°C and Δθ = -40°C.Case of C33 Material.

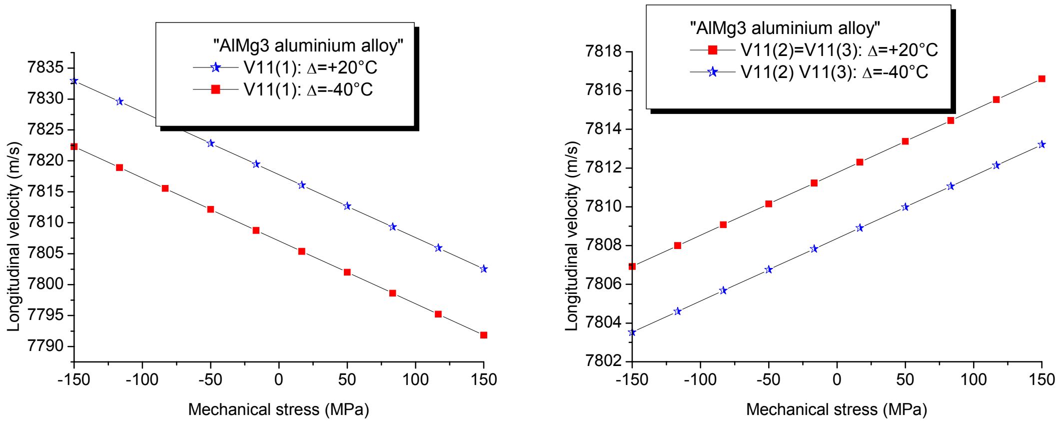

Figure 6. Longitudinal velocity as function of the applied mechanical traction and compression stresses under temperature variations Δθ =20°C and Δθ = -40°C.Case of AlMg3 Material.

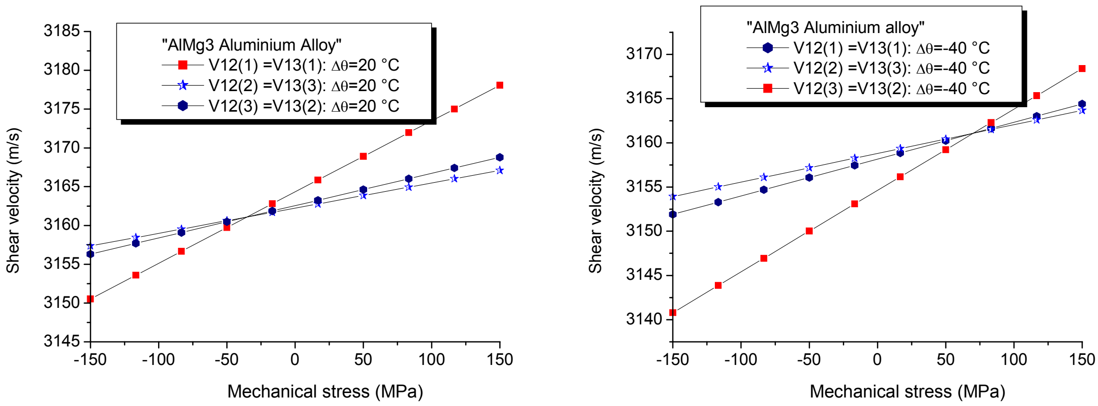

Figure 7. Shear velocity as function of the applied mechanical traction and compression stresses under temperature variations Δθ =20°C and Δθ = -40°C.Case of AlMg3 Material

4. ANALYSIS OF COMPUTED CURVES

- As shown in figure 2, the propagation velocity of the longitudinal wave decreases quickly for positive temperature variation (case of heating) that induces an elongation in direction parallel to the propagation; but it increases slightly when the temperature variation which induces a contraction in direction perpendicular to the propagation wave. This tendency becomes opposite in the case of the negative temperature variations (case of cooling).

- In the case of the transversal wave (see figure 3), the propagation velocity decreases quickly if the temperature variation (heating) leads to an elongation in parallel direction to the propagation and perpendicular to the polarization. This velocity increases when the elongation direction is perpendicular to the wave polarization. In the case of the contraction (cooling), the tendencies of evolution are opposite.

- According figure 4, we note that the longitudinal velocity decreases slightly in the case of thermo mechanical stress (traction- heating) acting parallel to the propagation.

But it increases when this stress is perpendicular to the propagation. These tendencies reverse in the case of the compression – cooling loading.

- In the case of the shear wave (see figure 5), the propagation velocity decreases quickly if the thermo mechanical effect (traction- heating) acting perpendicular to the propagation. But it increases a little when this stress is perpendicular to the propagation. In the case of the contraction (compression-cooling), the tendencies of evolution are opposite.

Table 1 recapitulates the different simulated cases for a C33 Steel.

Table 1. Recap of the different simulated cases of C33 Steel

Longitudinal wave												
	Mechanical stress				Temperature change				Thermo-mechanical coupling			
	$\sigma_{me}>0$		**$\sigma_{me}<0$**		**$\sigma_{th}>0$**		**$\sigma_{th}<0$**		**$\sigma_{me}+\sigma_{th}>0$**		**$\sigma_{me}+\sigma_{th}<0$**	
Propagation	//	⊥	//	⊥	//	⊥	//	⊥	//	⊥	//	⊥
Polarisation	//	⊥	//	⊥	//	⊥	//	⊥	//	⊥	//	⊥
Wave velocity	↘	↗	↗	↘	↘	↗	↗	↘	↘	↗	↗	↘

Transversal wave																		
	Mechanical stress						Temperature change						Thermo-mechanical coupling					
	$\sigma_{me}>0$			**$\sigma_{me}<0$**			**$\sigma_{th}>0$**			**$\sigma_{th}<0$**			**$\sigma_{me}+\sigma_{th}>0$**			**$\sigma_{me}+\sigma_{th}<0$**		
Propagation	//	⊥	⊥	//	⊥	⊥	//	⊥	⊥	//	⊥	⊥	//	⊥	⊥	//	⊥	⊥
Polarisation	⊥	//	⊥	⊥	//	⊥	⊥	//	⊥	⊥	//	⊥	⊥	//	⊥	⊥	//	⊥
Wave velocity	↗	↘	↗	↘	↗	↘	↗	↘	↗	↘	↗	↘	↗	↘	↗	↘	↗	↘

5. ONCLUSION

Using simulations of acoustoelastic equations that depend on some physical characteristics of the material, mechanical, thermal uniaxial and thermo mechanical stresses, it appears that longitudinal and transversal wave velocities vary linearly according to considered stress. The simulation shows that the case of the material dilation, the longitudinal wave velocity decreases if the applied stress is parallel to the propagation direction and increases if this stress is perpendicular to the propagation. For the transversal waves, the application of a stress according to a perpendicular direction to the polarization, we will have an increase of the propagation velocity and a decrease if it is parallel. This tendency reverses in the case of traction. The results denote that acoustoelastic effects are depending of propagation and polarisation directions, the considered wave and the nature of the applied stress (mechanical, thermal and thermo mechanical). The theoretical result analysis confirms the contribution of ultrasonic methods like a privileged investigating tool for the characterization of the mechanical behaviour of materials and metallic structure under mechanical, thermal and thermo mechanical stresses.

Table 2. Mechanical properties of studied materials

	Units	C33 [2]	AlMg3 [6]
V_L ($\sigma = 0$)	m/s	5926.9	7810.4
V_T ($\sigma = 0$)	m/s	3222.5	3161.1
ρ	kg/m^3	7800	2664
λ	GPa	112	109,27
μ	GPa	81	26,62
α	1/°C	13.10^{-6}	$23,5.10^{-6}$
L	GPa	-274	-102.40
M	GPa	-495	-249.69
N	GPa	-630	-288.51
E	GPa	209	74.64
σ_e	MPa	220	180
$\Delta\theta_{max}$	°C	81	102.6

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