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Application of Ultrasonic Methods for Evaluation the Anisotropy of Materials

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Abstract: The reason for anisotropy in material properties is the thermo mechanical effect in the process of plastic deformation, which creates a texture along the direction of deformation. One of the established nondestructive methods for evaluating the elastic constants in anisotropic materials is by measuring the velocities of ultrasonic waves propagating in different directions in the material. For studying the elastic anisotropy of textured media, the established measurement methods are hardly applicable because the materials are inaccessible for volumetric measurements. Moreover, the differences in the velocities of the ultrasonic waves are very small and the changes are localized in the surface and subsurface layers. The purpose of the study is to test a methodology and carry out the experimental studies to determine the anisotropy parameters of metallic materials based on the data from changes in the velocity of ultrasonic waves.

Keywords: Anisotropy, Low carbon steel sheet metal, Ultrasonic waves, Ultrasonic surface rayleigh wave, Ultrasonic subsurface wave

Introduction

The reason for the anisotropy in the properties of structural materials with crystalline structure is the thermomechanical effect in the plastic deformation process, which creates deformation texture (William, 2018). Deformation depends on the chemical composition, structure, grain structure, shape and distribution of carbides in steels, the condition of the sheet surface, the strain hardening coefficient as well as on the normal anisotropy coefficient of the sheet material (Miklyaev et al., 1986). The dependence of mechanical properties on texture direction can be useful in practice, but is usually an undesirable phenomenon. In the production of sheet materials with better mechanical and technological properties, it is necessary to perform quality control and evaluate the anisotropy of the metal sheets.

A standardized method is used to determine the anisotropy of sheet materials, which is carried out by conducting standard tensile tests according to EN ISO 6892-1:2009. The methodology requires cutting samples into at least three of the main directions 0°, 45° and 90° relative to the direction of rolling. Despite the reliability of the method, it also has its drawbacks. One of them is that a universal testing machine is needed to meet the requirements of the standard. In addition, sample preparation and testing also take time and costs.

Another method for determining the anisotropy of sheet materials is by measuring Vickers hardness. Before testing the specimens in one-dimensional tension, ten consecutive impressions with a Vickers Hardness Tester are applied to the specimens in a step of 0.50 mm, on which the diagonals are measured. After applying the 20% strain, the new diagonals of the Vickers indenter impressions on the specimens have to be measured. The determination of the anisotropy is evaluated by the anisotropy coefficient, which represents the ratio of the logarithmic ˆstrains in two mutually perpendicular directions of the examined sample bodies. The method and experimental results in the study of X5CrNi18-10 steel sheets are presented in detail in Yankov et al. (2014).

One of the well-established non-destructive methods for estimating the elastic constants of anisotropic materials is by measuring the velocities of ultrasonic waves propagating in different directions in the material (Sayers,1985; Tang et al, 2006). For investigating the elastic anisotropy of textured media, established methods are often inapplicable because the machine parts and products have limited dimensions. Furthermore, velocity differences are often very small and variations are localized in the surface and near-surface layers. The objective of the current study is to develop and test a methodology for determining an anisotropy parameter based on measurements of surface and subsurface wave velocities in several directions.

Statement of the Problem

The propagation of ultrasonic waves in an arbitrary direction in anisotropic materials is characterized by phase and group velocity differences (Viktorov, 1995). We consider dependences of ultrasonic surface wave parameters on elastic constants in the case of an orthotropic material (Barkhatov, 1999). Anisotropy of this kind arises in sheet rolling. The orthotropic material has three mutually orthogonal axes of symmetry of second order (Sedov, 1970). The orthotropy is a consequence of the technology – the randomly oriented crystals deform in a certain way (Adamescu et al.,1985). Figure 1 presented the coordinate system of an orthotropic material. In the sheets, the axis of symmetry is located along the rolling direction X_1, the axis X_2 is perpendicular to X_1, the axis X_3 is along the normal of the sheet plane (Barkhatov, 1999).

The first problem is to determine the wave propagation velocity along given medium densities, elastic physical moduli and wave propagation directions. The inverse problem is concerned with determining the components of the elasticity tensor under given density and wave propagation velocities. For these orthotropic media, the number of unknown components of the elasticity tensor is 9 (Royer et al., 1974; Landau et al., 2003; Sadd, 2009).

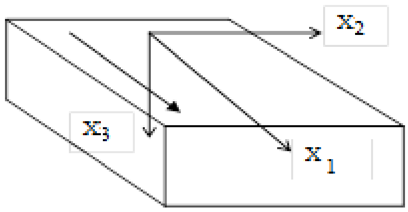


Figure 1. Coordinate system of an orthotropic material

$$C_{ij} = \left\| \begin{matrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{matrix} \right\|$$

Figure 2. Elasticity tensor of an orthotropic medium

An elastic wave propagating in a confined medium must satisfy the wave equation (1) (Barkhatov, 1999), (Krasilnikov, 1984) and the boundary condition for the absence of normal stresses on the material surface equation (2) at x_3=0 (Barkhatov, 1999).

$$\rho \frac{\partial^2 U_i}{\partial t^2} = C_{ijkl} \frac{\partial^2 U_k}{\partial x_j \partial x_l} \tag{1}$$

$$C_{ijkl} \frac{\partial U_k}{\partial x_l} = 0 \tag{2}$$

Among the solutions that satisfy this boundary condition, a solution in the form of a wave propagating along X_1, whose amplitude decreases in depth according to an exponential law, is searched (Royer et al., 1974) . The sought solution, inserted into the wave equation, leads to the Christoffel equation (Krasilnikov & Krylov, 1984; Barkhatov, 1999).

(3)

$$\rho V^2 U_i = C_{ijkl} N_j N_l U_k$$

According to Royer et al. (1974) and Barkhatov (1999) searching for the ultrasonic surface Rayleigh wave parameters, the problem reduces to find the eigenvalues and eigenvectors of the Christoffel equation.

$$\det\left[C_{ijkl} N_j N_l - \rho V^2 \delta_{ik}\right] = 0 \tag{4}$$

A 6th degree equation is obtained in which the ultrasonic surface Rayleigh wave velocity enters as a parameter. Each ultrasonic Rayleigh wave (URW) is a linear combination of three displacement components that propagate at the same velocity (Royer et al., 1974; Viktorov, 1995; Barkhatov, 1999).

$$U = \sum_{r=1}^{3} K^{(r)} U^{(r)} \tag{5}$$

The coefficients K and velocity are found by relation (5) in the free surface boundary conditions (2). According to (Barkhatov, 1999) after transforming the system of equations

$$\sum_{r=1}^{3} C_{i3kl} N_l^{(r)} U_k^{(u)} K^{(r)} = 0, i = 1,2,3 \tag{6}$$

we obtain a system of three equations concerning the displacement components of URW. Following Barkhatov (1999), after transformations, one can obtain a characteristic equation (7) that determines the URW velocity.

$$D.Z^2.(\delta - Z) = \left[(\delta - Z)D - Q^2\right]^2.(1 - Z) \tag{7}$$

Where

$$Z = \frac{\rho V}{C_{55}} = (\frac{V_x}{V_t})^2 ; D = \frac{C_{33}}{C_{55}} ; \; Q = \frac{C_{13}}{C_{55}} ; \delta = \frac{C_{11}}{C_{55}} = (\frac{V_l}{V_t})^2 = \frac{2(1-\nu)}{1-2\nu} ;$$

V_l and Vt are the velocities of longitudinal and transverse waves propagating along the X_1 axis direction and depend on four components of the elasticity tensor C_{11}, C_{33},C_{13},C_{55} ; ν is the Poisson's ratio and ρ is the density of the material.

$$\rho V_l^{\,2} = C_{11} , \; \rho V_t^{\,2} = C_{55}$$

By analogy with Adamescu (1985), the anisotropy coefficients A_1, A_5 have been introduced to account for the anisotropy in orthopropic materials. The coefficient A_1 represents the relative deviation of the tensile and compressive moduli along the X_1 and X_3 axes, and the coefficient A_5 characterizes the deviation of the shear moduli in the X_1 and X_2 planes from those of the isotropic material (Barkhatov, 1999).

$$A_1 = \frac{C_{11}}{C_{33}} \tag{8}$$

Where C_{11}, C_{33}, represent the in-plane tensile and compressive moduli of the X_1 and X_3 axes, respectively, and

$$A_5 = \frac{2C_{55}}{C_{11} - C_{13}} \tag{9}$$

Where C_{55} is the in-plane shear modulus of the X_1 and X_3 axes. The modulus C_{13} is a combination modulus of elasticity that characterizes the occurrence of transverse forces along the X_3 axes in tension or compression along the X_1 (Barkhatov, 1999). Then,

$$D = \frac{C_{33}}{C_{55}} = \frac{\delta}{A_1} \tag{9}$$

$$Q = \frac{C_{13}}{C_{55}} = \delta - \frac{2}{A_5} \tag{10}$$

With set anisotropy coefficients A_1, A_5 and the delta value (δ), the equation (7) is converted to (11). After transformations, equation (11) is presented in the form (12)

$$\frac{2(1-\nu)}{1-2\nu}(Z)^2\left(\frac{2(1-\nu)}{1-2\nu}-Z\right)=\left[\left(\frac{2(1-\nu)}{1-2\nu}-Z\right)\frac{2(1-\nu)}{A_1(1-2\nu)}-\left(\frac{2(1-\nu)}{1-2\nu}-\frac{2}{A_5}\right)^2\right]^2(1-Z) \tag{11}$$

$$\left(\frac{V_R}{V_t}\right)^3 AA(\nu)+B(\nu)\left(\frac{V_R}{V_t}\right)^2+CC(\nu)\left(\frac{V_R}{V_t}\right)+DD(\nu)=0 \tag{12}$$

Where V_R is the URW velocity and $Z = V_R / V_t$

$$Z^3 AA(\nu)+B(\nu)Z^2+CC(\nu)Z+DD(\nu)=0 \tag{13}$$

Where

$$AA(\nu) = D(\nu) - D(\nu)^2 \tag{14}$$

$$B(\nu)=2\delta(\nu)D(\nu)^2+D(\nu)^2-2D(\nu)Q(\nu)^2+Q(\nu)^4-D(\nu)\delta(\nu) \tag{15}$$

$$CC(\nu)=-\delta(\nu)D(\nu)^2-\delta(\nu)^2D(\nu)+2D(\nu)Q(\nu)^2\delta(\nu)-Q(\nu)^4\delta(\nu)-\delta(\nu)D(\nu)^2-Q(\nu)^4+2Q(\nu)D(\nu)^2 \tag{16}$$

$$DD(\nu)=\delta(\nu)^2D(\nu)^2-2D(\nu)Q(\nu)^2\delta(\nu)+Q(\nu)^4\delta(\nu) \tag{17}$$

The roots of the equation *Z* are determined in the Mathcad environment. In an isotropic material (A_1=1, A_5=1), the ultrasonic Rayleigh wave velocity depends on the Poisson's ratio ν and the transverse wave velocity. In the interval of change of Poisson's ratio ν= 0,1 to 0,265, three positive and three negative real roots are obtained.

The root Z_R, which is between 0 and 1, corresponds to a ultrasonic Rayleigh wave. When Poisson's ratio changes, the phase velocity varies in the range from 0,87.V_t to 0.97 V_t. The approximate expression for the velocity of the Rayleigh wave by (Viktorov, 1995) is presented in Figure 3 and shows a good approximation of the obtained solutions.

$$Z(\nu) = \left(\frac{0.87+1.12\nu}{1+\nu}\right)^2 \tag{18}$$

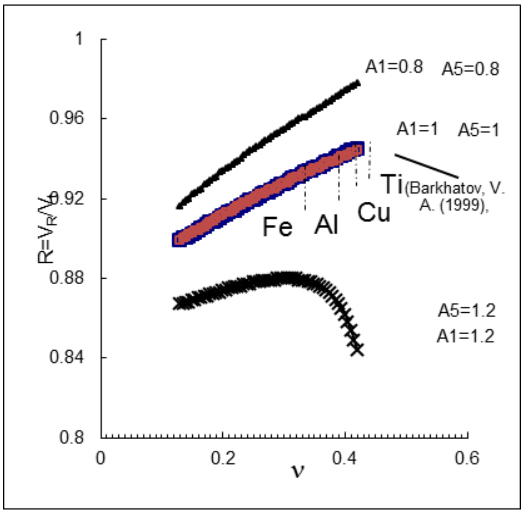


Figure 3. Dependence of the ultrasonic surface wave parameter R on the Poisson's ratio and the anisotropy parameters

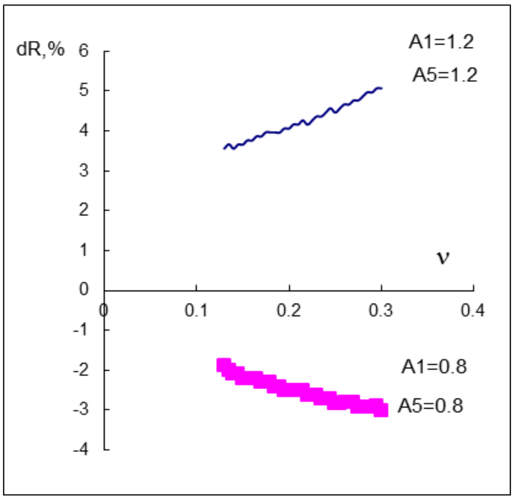


Figure 4. Relative variation of ultrasonic surface wave parameter R, %

The influence of anisotropy on the ultrasonic surface wave parameter $R = \sqrt{Z_R}$ is also given in Figure 3. When the ratios A_1 and A_5 are varied from 0.8 to 1.2, the *R* curve is shifted, but it is in the range from 0,85 to 0,98. The influence of anisotropy is weak. Figure 4 shows the relative variation $dR(v) = (R_o - R_i)/R_o$, where R_o are for an isotropic body, are R_i the values with the anisotropy accounted for. For iron with Poisson's ratio equals to 0.28 with anisotropy coefficients A_1 and A_5 equal to 1,2, the relative change in the velocities of Rayleigh waves is calculated as 4%.

In a ultrasonic Rayleigh wave, velocity dispersion is absent. The motions of the particles in this wave is along ellipses, with their major semi-axis perpendicular to the surface. The thickness of the wave localization layer is about 1.5λ, (Viktorov, 1995). Figure 5 presents the moduli of the components of the particle displacement vector in isotropic iron (Viktorov, 1995), where U3 denotes the relative amplitude of the oscillations of an ultrasonic surface wave along X_1 (along the surface) and U1 indicates the change in the relative amplitude of the oscillations along X_3 (perpendicular to the surface).

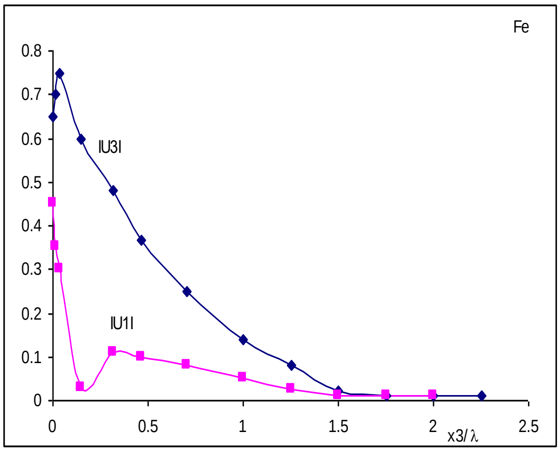


Figure 5. Moduli of the components of the Rayleigh wave displacement vector in an isotropic body

Basically the deformation in URW is a shear deformation and its velocity is close to the transverse wave velocity. The measured velocity along the X_1 direction is used to determine the shear C_{55} modulus, and along the X_2 direction the C_{44} modulus (Barkhatov, 1999).

$$C_{55} = \rho\left(\frac{V_R}{R}\right)^2 \text{ along the axis } X_1 \quad (19)$$

$$C_{44} = \rho\left(\frac{V_R}{R}\right)^2 \text{ along axis } X_2 \quad (20)$$

For Poisson's ratios greater than 0.265, equation (7) has complex-constrained roots that correspond to subsurface-longitudinal waves. According to Juozoniene, (1980) and Barkhatov (1999) the velocity of subsurface wave is close to the longitudinal wave speed. The ratio of subsurface-longitudinal wave (V_{pp}) velocity to longitudinal wave (V_l) velocity is expressed by the root of equation (7) as

$$G = \frac{\sqrt{\delta}\,\mathrm{Re}(\sqrt{Z})}{|Z|} = \frac{V_{pp}}{V_l} \tag{21}$$

where Z is the complex root, V_{pp} is the subsurface ultrasonic wave velocity. The calculations of the roots of the surface-longitudinal wave equation are shown in Figure 6.

The complex root indicates that the wave has parametric damping. The attenuation is determined by the imaginary part of the root. The attenuation ratio is the relative decrease in the amplitude of the wave over a distance of the order of the wavelength and is determined by (22)

$$K_\lambda = \frac{|U(x_1)|}{|U(x_1+\lambda)|} = \exp\left(2\pi\frac{\mathrm{Im(Z)}}{\mathrm{Re(Z)}}\right) \tag{22}$$

In isotropic materials, the subsurface wave parameters depend only on the Poisson's ratio. For values greater than 0.26 there exists a wave that is characterized by a complex root Z. In isotropic materials with Poisson's ratio smaller than 0 to 0.26, from the experimental point of view, no subsurface wave exists (Juozoniene,1980). Dependences of subsurface-to-longitudinal wave velocity ratio G on Poisson's ratio and anisotropy parameters are given in Figure 6. At ν ratios greater than 0.26, an unstable subsurface wave is formed, which quickly decays. The anisotropy of the elastic properties induced by deformation texture changes the solutions of the subsurface wave (Figure 6 and Figure 7). The larger the ν ratio, the smaller the layer of subsurface wave localization and the stronger the transverse waves are emitted. The attenuation ratio by (22) increases sharply (Figure 7).

The subsurface wave velocity value is close to the longitudinal wave velocity value and can be used to determine the tensile-stress modulus of the material.

$$C_{11} = \rho \left(\frac{Vpp}{G}\right)^2 \quad \text{along } X_1 \text{ direction} \tag{23}$$

$$C_{22} = \rho \left(\frac{Vpp}{G}\right)^2 \quad \text{along } X_2 \text{ direction.} \tag{24}$$

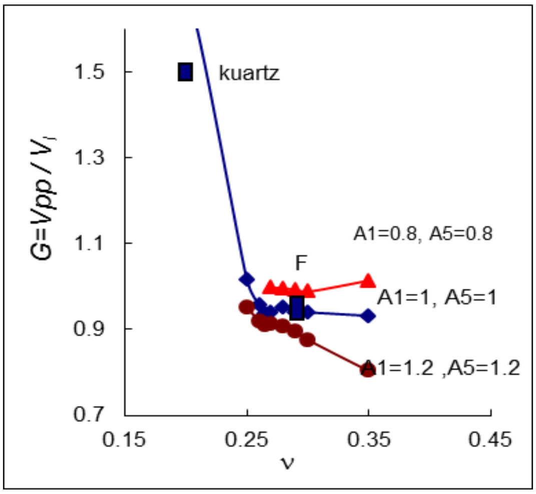


Figure 6. Subsurface-to-longitudinal wave velocity ratio and anisotropy parameters

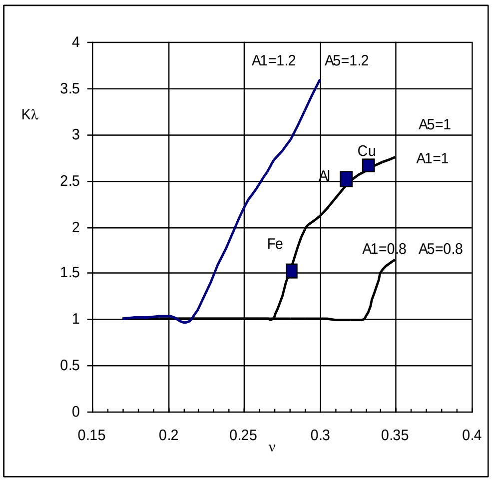


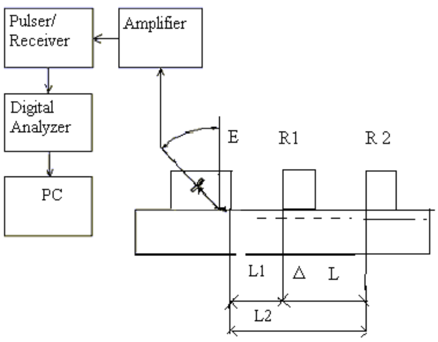
Figure 7. Subsurface wave attenuation ratio K_λ and the anisotropy parameters

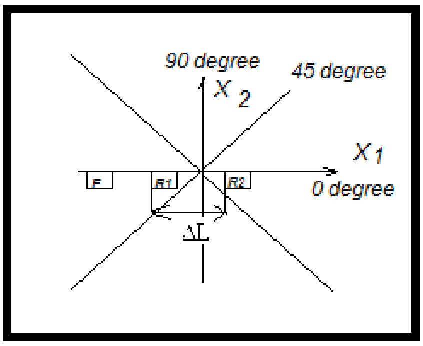
As a result of the calculations performed, the dependences that relate the surface Rayleigh and subsurface wave velocities to components of the elasticity tensor were obtained. The *R* and *G* ratios are not constant and depend on the anisotropy of the material. If the data for A_1, A_5 from X-ray texture analysis are used, the values of *R* and *G* can be refined and errors in the determination of elastic moduli can be reduced.

Based on the above, it is possible to determine four of the nine independent components of orthotropic materials such as rolled sheet and plate. The measurement of the velocities of the ultrasonic surface Rayleigh and subsurface waves in the plastic deformation direction X_1 allows to determine components of the elasticity tensor C_{11} and C55. The determination of the velocities in the perpendicular direction X_2 enables the possibility to determine the components C_{22} and C_{44}.

Results and Discussion

Ultrasonic investigations with surface and subsurface waves with a working frequency of 4MHz were carried out on a low carbon metal plates (300 mm x 300 mm) with a thiknesses of 6 and 10 mm. An experimental set-up is shown in Figure 8a. A computerized ultrasonic instrument consists of a generator, a receiver of ultrasonic waves and an ultrasonic card US - expert. The ultrasonic device allows measuring the time of ultrasonic impulse with accuracy up to 1 ns and 12 bits resolution at sampling rate of 160 MHz. In order to attain a higher accuracy of investigations precautions for maintaining constant conditions for the acoustic signals generation are undertaken. The surface waves are excited by a variable angle angle transducer, at a refraction angle close to the second critical angle for the plexiglass-steel. The wavelength is on the order of 0.75 mm. The subsurface waves are excited at a refraction angle close to the first critical angle for the plexiglass-steel. Using a through transmission technique, we register and record in digital form signals emitted by transducer E and received by transducer R as shown in Figure 8a. The receiving transducer moves along the specimen covering distance ΔL.





a b

Figure 8. Ultrasonic investigation of the anisotropy:
a) Experimental set-up for ultrasonic studies
b) Scheme of ultrasonic measurement of the anisotropy

The velocity of the surface waves (V_R) and subsurface waves (V_{pp}) is calculated by the formula:

$$V_{R,pp} = \frac{L_2 - L_1}{(\tau_2 - \tau_1)} = \frac{\Delta L}{\Delta \tau} \qquad (25)$$

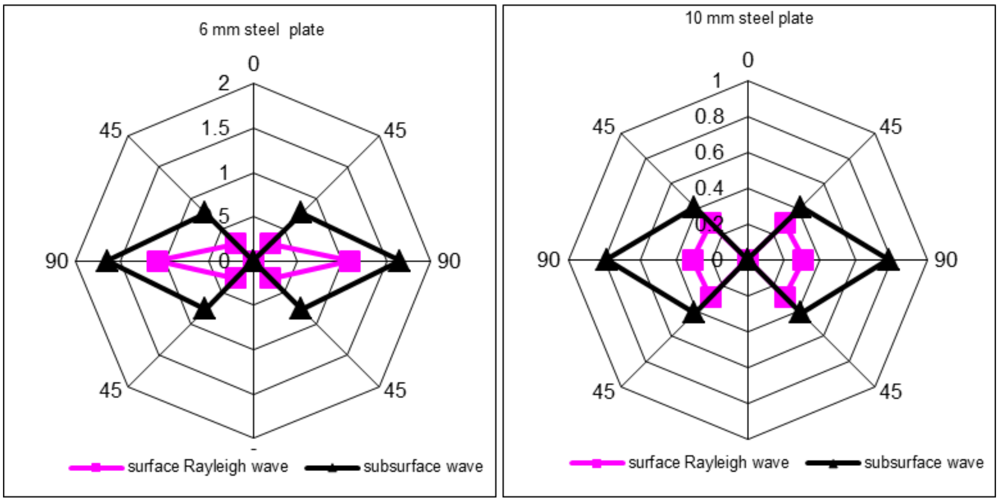
where ΔL is the distance between two positions of the receiver R, τ_1 and τ_2 are transit times of the wave obtained at distances L_1 and L_2. The transit time is registered from the beginning of the ultrasonic impulse.

The time of the recorded pulses is reported by the maximum envelope value of the signal and is measured to the nearest 1 ns. The $V_{R,pp}$ determination error is determined by $\Delta V_{R,pp}/V_{R,pp}=\Delta L/L+\Delta\tau/\tau$. For the distance ΔL=0.1 mm, L of order 50 mm and $\Delta\tau$=0,001μs, τ=10 μs the error in velocity determination is $\Delta V/V$=0,02%.The velocities of the surface and subsurface waves in the steel sheets were measured in three directions 0 ^{o}, 45^o and 90° to the X_1-axis, as shown in Figure 8 b. The step of movement of the sensors is 20 mm, which is the width of the receiving transducer. For each position of the transducers, the travelling times of the ultrasonic waves at three distances 0, 50 mm and 100 mm were determined. Table 1 gives average values of surface and subsurface wave velocities in the directions 0, 45 and 90 degrees of the steel plates.

Table 1. Velocities of ultrasonic surface Rayleigh (V_R) and subsurface (V_{PP}) waves

Variables		0 degree	45 degree	90 degree
6 mm steel plate	V_R, m/s	2928	2936	2977
	V_{PP}, m/s	6001	6047	6100
10 mm steel plate	V_R, m/s	2998	2980	2989
	V_{PP}, m/s	5982	6015	6037

Anisotropy is estimated as a relative change in wave velocities. The relative variation of the Rayleigh wave velocities $dV_R =(V_{R(X1)}- V_{R(X2)})/ V_{R(X1)}$ along the X_1 and X_2 axes is about 1% for the thinner 6 mm steel plate. For the same sample, the relative change of the subsurface wave $dV_{pp} =(V_{pp(X1)}- V_{pp(X2)})/ V_{pp(X1)}$ was measured to be 1.7%, as shown in Figure 9 a. Figure 9 b shows the relative variations of the Rayleigh and subsurface waves obtained for the 10 mm thick steel plate. Less pronounced anisotropy can be observed, less than 0.5% for surface waves and about 1% for subsurface waves.



a b

Figure 9. The relative variations of the velocities of ultrasonic Rayleigh and subsurface waves on different directions: a) 6 mm steel plate; b) 10 mm steel plate

Conclusion

Based on Barkhatov (1999), this work presents a methodology for determining the anisotropy of steel sheets using ultrasonic surface waves as a result of the performed calculations, the dependences were obtained that connect the velocities of surface Rayleigh and subsurface waves with the components of the elasticity tensor of orthotropic media.

The measuring the velocities of surface and subsurface waves of rolled steel sheets in the direction of plastic deformation and in the perpendicular direction allows four of the nine independent components of orthotropic materials to be determined.

Experimental studies performed using ultrasonic methods show weak anisotropy. The anisotropy is more pronounced with the thinner steel plate. The relative variation of surface wave velocity in both directions was found to be 1%. The change in wave speed below the surface is almost approximately 2% for the 6 mm thick plate.

Recommendations

The presented research can provide new knowledge about the anisotropy of steel sheets to students and engineers to put into practice the ultrasonic methods by surface and subsurface waves for evaluation the anisotropy of metal products. Further research will be aimed at comparing the results from destructive and non-destructive methods for anisotropy assessment in orthotropic media.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Acknowledgements or Notes

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