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Characterization of material damage by ultrasonic immersion test

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Abstract

We present an innovative non-destructive experimental technique for a quantitative determination of the damage level in structural components. In particular, we study the propagation of ultrasonic waves in an isotropic material specimen before and after a mechanical fatigue incremental test. To this aim, we use an innovative goniometric device for ultrasonic immersion tests, designed and built for the mechanical characterization of anisotropic materials. In the first test, performed in absence of damage, we characterize the mechanical behavior of the isotropic material by the measure of time of flight (TOF) of ultrasonic waves, and then by determining the so-called natural velocities. In the next ultrasonic tests, performed after each fatigue test, we determine the response of the damaged material by measuring again the velocity of ultrasonic waves: the comparison between these velocities and the natural velocities allows for the evaluation of the level of damage in the material. Moreover, through the goniometric ultrasonic immersion device it is possible to relate the damage to the stress-induced anisotropy acquired by the specimen, which we characterize by identifying the acoustic axes and the dependence of the velocity of the ultrasonic waves on the direction of propagation.

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Keywords: Damage; Stress-induced anisotropy; Ultrasonic waves; Ultrasonic immersion test; NDT.

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1. Introduction

The characterization of the material damage by nondestructive techniques has recently gained a growing interest among researchers also thanks to the perspective of developing in-service tests of the integrity of components, crucial

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for the structural safety [1-4]. Among other non-destructive techniques, ultrasonic tests are particularly promising for these applications since they are capable of investigating what happens inside the material, and then are not limited to the detection of surface phenomena.

Usually, ultrasonic tests are employed as a qualitative method for the identification of defects in components, but from several decades the researchers are developing suitable experimental ultrasonic approaches, very effective for a range of quantitative evaluations.

In particular, ultrasonic methods have been developed for the study of the damage in solid materials: the evaluation of microstructural changes in plastically deformed solids, the characterization of the yield surface, the study of instabilities due to the microslip bands, etc.. These complex experimental techniques are based on the non-linear ultrasonic, i.e., on the analysis of the second and higher harmonics of the fundamental frequency of ultrasonic waves generated in a non-linear material. The amplitude of these harmonics allow for evaluating the damage in material by non-linearity parameters [5-11].

Moreover, acoustic methods based on the study of the so-called acoustoelastic effect are capable of determining applied or residual stress in the materials by measuring the variation of the velocity of ultrasonic waves [12-13].

In particular, acoustoelastic techniques are often based on the experimental study of the apparent anisotropy induced by the initial stress [14], sharing common points to some ultrasonic approaches for the experimental characterization of the mechanical response of anisotropic materials. In the past, the main limitation of these approaches was related to the use of contact testing method; thus, a great improvement of the experimental capability arises from the introduction of immersion testing techniques [15-17].

In this work, we present a new approach for studying the fatigue damage of materials, based on the use of an innovative goniometric ultrasonic immersion technique. In particular, we show that the fatigue damage affects the acoustic response of the material by inducing a variation of the velocities of propagating ultrasonic waves. Moreover, the employ of a goniometric experimental set-up allows for relating the fatigue damage to the variation of the acoustic axes, i.e., to an acquired anisotropy of the material (damage induced anisotropy).

Here we report some preliminary results of a wider and in-depth experimental analysis currently being carried out.

2. Propagation of ultrasonic waves in elastic bodies

The propagation of the ultrasonic waves involved in ultrasonic non-destructive tests are usually studied as small perturbations of an initial state of a body [18-19]. In this vein, the analysis can be performed by assuming the hypothesis that the ultrasonic waves are small superimposed elastic deformations of the body, within the linear theory of the elastodynamics. Then, in absence of body forces the wave propagation is governed by the equation of motion

$$\mathrm{Div}\left(\mathbb{C}\left[\nabla\mathbf{u}\right]\right) = \rho\ddot{\mathbf{u}} \tag{1}$$

where $\rho = \rho(\mathbf{x})$ is the mass density, $\mathbb{C} = \mathbb{C}(\mathbf{x})$ is the incremental fourth order elasticity tensor referred to the initial state of the body, and $\mathbf{u}=\mathbf{u}(\mathbf{x}, t)$ is the (small) displacement field defined for any point $\mathbf{x}$ of the body at the time t.

In particular, the propagation of plane progressive elastic waves may be described by assuming a displacement field of the form

$$\mathbf{u}(\mathbf{x},t) = \mathbf{a}\ \varphi(\mathbf{x}\cdot\mathbf{n} - v\ t) \tag{2}$$

where $\mathbf{a}$ is the direction of motion, $\mathbf{n}$ is the direction of wave propagation, v is the velocity of propagation and φ is a real valued smooth function. The plane wave is longitudinal if $\mathbf{a}$ and $\mathbf{n}$ are linearly dependent, while is transverse if $\mathbf{a}$ and $\mathbf{n}$ are perpendicular.

The plane elastic wave (2) is a solution of (1) if and only if $\mathbf{a}$ satisfies the classical Fresnel-Hadamard propagation condition

$$\left[\mathbf{\Gamma}(\mathbf{n}) - \rho v^2\mathbf{I}\right]\mathbf{a} = \mathbf{o} \tag{3}$$

where $\mathbf{\Gamma}(\mathbf{n})$ is the second order Christoffel tensor for the direction **n**, defined by

$$\mathbf{\Gamma}(\mathbf{n}) = \mathbb{C}^{t}[\mathbf{n} \otimes \mathbf{n}] \tag{4}$$

Fixed a direction of propagation **n**, the Christoffel tensor $\mathbf{\Gamma}(\mathbf{n})$ is independent of the density, and is then associated only to the elastic properties of the body through the elasticity tensor $\mathbb{C}$. By (4), for a given direction of propagation **n** if $\mathbb{C}$ is symmetric, then the tensor $\mathbf{\Gamma}(\mathbf{n})$ is symmetric; moreover, if $\mathbb{C}$ is strongly elliptic, then $\mathbf{\Gamma}(\mathbf{n})$ is positive definite. Thus, under the mild and commonly adopted hypotheses of $\mathbb{C}$ symmetric and strongly elliptic, the spectral problem (3) admits at least three positive and real eigenvalues, and hence for every direction of propagation **n** there exist at the point **x** at least three orthogonal directions of motion **a** with real associated velocities of propagation v for traveling plane progressive waves.

Equations (3)-(4) clearly show that the material symmetries of the elastic response affect the properties of the propagating waves and, in particular, that the wave velocities v are related to the elastic moduli, i.e., the components of elastic tensor $\mathbb{C}$.

The Federov-Stippes theorem [18] further shows that if the elasticity tensor $\mathbb{C}$ is symmetric and strongly elliptic, then at a point **x** there exist longitudinal and transverse elastic progressive waves.

Now, assume that **e** is an axis of symmetry of the material response; if the direction of propagation **n** coincides with the direction **e**, then there exist a longitudinal elastic wave and two transverse elastic waves propagating in direction **n≡e**. These waves are called "pure" waves. As a consequence, in isotropic materials, for each possible direction of propagation **n** there exist "pure" longitudinal and "pure" transverse elastic waves.

If the direction of propagation **n** is different from an axis of material symmetry, then it became possible the propagation of "not pure" waves, i.e., neither longitudinal nor transverse waves. These waves, usually called "quasi" longitudinal waves or "quasi" transverse waves depending on the direction of motion **a**, are then typical of anisotropic materials. Since the acoustic properties above described, the axis of material symmetry are also called the principal acoustic axes. Inversely, by plotting the slowness surface of the material, i.e., the polar diagram of the slowness (the inverse of the velocity) in function of the direction of propagation it is possible to experimentally determining the principal acoustic axes of material, and consequently to identifying the degree of anisotropy of the material [20-21].

It is worth to note that an anisotropy of the acoustic response may also occur if the material is isotropic but the initial state of the body is characterized by an initial stress $\mathbf{T}_0$ (residual or applied), and/or if inelastic phenomena, like for example plastic deformations and damage, have occurred in the past history of the body [14].

3. Experimental setup

For ultrasonic experiments, we employ an innovative goniometric device specifically designed and built at our laboratory (Laboratorio "M. Salvati" – Politecnico di Bari) for ultrasonic immersion tests aimed at the mechanical characterization of anisotropic materials. This goniometric device, whose concept represents an evolution of the experimental set-up described in Balasubramaniam [22], allows for measuring the velocity of ultrasonic waves for any angle of incidence of an ultrasound beam on the sample surface. In this way, it is possible to determine the ultrasonic velocity of any kind of polarized waves ("pure" and "not pure" or "oblique" waves) propagating in the sample according to the Snell's law, for any direction of propagation. The experimental measure of those ultrasonic velocities allows for determining the elastic constants of the material by solving the so-called "inverse problem". In particular, this innovative ultrasonic device supports effectively experimental approaches to the two fundamental problems in the mechanical characterization of the materials [23-24]. The first is the "classification problem", that is the determination of the degree of anisotropy of the mechanical response and the identification of the axes of material symmetry (acoustic axes). To this aim, starting from the experimental measurement of the ultrasonic velocities for different directions of propagation in the sample, the slowness surface of the material has to be reconstructed. The second problem is the so-called "representation problem", that is the identification of the elastic moduli by ultrasonic velocity measurements, once known the axis of material symmetry.

The main components of our device are: an immersion water tank, a frame housing ultrasonic immersion transducers and/or a reflective surface in Plexiglas, and a rotating sample slot operated by a stepper motor (Fig. 1) capable of rotating the sample at very small angular steps (0,036°). During the test the stepper motor allows for varying the angle of incidence of the ultrasound beam on the sample surface. The device can be configured for two different experimental set-up: the first configuration employ two mutually opposite probes, one transmitter and one receiver; in this case, the test is performed by the through-transmission technique. In the second experimental configuration, used in this work, only one transducer (acting as transmitter and receiver) is employed, and in the opposite slot of the frame a reflective surface in Plexiglas is placed; in this case, the test is performed by the back-reflection technique.

Fig.1. Ultrasonic immersion device.

In particular, in the experiments below described the ultrasonic signals are generated and received by an unfocused ultrasonic probe with a central frequency of 5 MHz connected to an ultrasonic pulser/receiver Olympus 5072PR. Moreover, we used an oscilloscope Agilent DS06014A (100 MHz, 4 channels) for monitoring the signals. A suitable LabVIEW software, expressly designed for this test, manages each component of the ultrasonic set-up, reprocesses the acquired ultrasonic signals, and provides the experimental data required for the mechanical characterization of the material.

The ultrasonic velocities in the material are determined by measuring the time of flight (TOF) of ultrasonic waves for each rotation angle of the sample, i.e. for each possible direction of propagation of the ultrasound beam into the sample. To this aim, first an auto-correlation process with the signal acquired in water without the sample allows to determine the origin of the time scale (reference signal). Subsequently, after placed the sample in the rotating slot of the device, for each angle of sample rotation a large number of ultrasonic signals are acquired. The noise of these signals is minimized by a normalization process performed through the LabVIEW software. The time of flight of the ultrasonic waves into the sample, for each angle of incidence of the ultrasonic beam, is then evaluated by a cross-correlation between the auto-correlated reference signal and the average of the normalized signals acquired for the prescribed angle of incidence.

In this experimental work, since we perform a back-reflection ultrasonic immersion test, the phase velocity v_p of ultrasonic waves travelling into the sample is evaluated using the following relation:

$$v_p = \left[\left(\frac{\Delta t}{2d} \right)^2 - \frac{\Delta t / d}{v_w} \cos\theta + \left(\frac{1}{v_w} \right)^2 \right]^{-1/2} \tag{5}$$

where, for a given angle of incidence θ of the ultrasonic beam, Δt is the difference between the time of flight t_2 of ultrasonic waves in presence of the sample and the time of flight t_1 of ultrasonic waves in the water; d is the thickness of the sample; v_w is the ultrasonic velocity in the water (about 1.473 m/s).

At the end of the ultrasonic test, when the sample has performed the entire rotation angle initially prescribed, the LabVIEW software presents the experimental results in a graph having on the horizontal axis the angle of incidence of the ultrasonic beam θ (deg) and on the vertical axis the measured ultrasonic phase velocity v_p (m/s).

4. Experimental results

4.1. Fatigue damage of the specimens

Our experimental analysis concerned parallelepiped aluminum samples having cross sectional area A = 55,726 mm^2. First, by a tensile test we determined the yield stress f_y = 183,00 MPa and ultimate strength f_t = 209,78 MPa of the material. For the tensile test, an Instron 5860 electromechanical testing machine has been employed.

Then, we analyzed the influence of the fatigue damage on the ultrasonic properties of the material in order to correlate the acoustic parameters with the fatigue damage of the material. For this purpose, we performed ultrasonic goniometric immersion tests on another aluminum specimen subjected to different fatigue levels, achieved by imposing to the sample different numbers of stress cycles by a MTS uniaxial fatigue testing machine: 10^4 cycles, $1{,}1\cdot 10^5$ cycles and $3{,}6\cdot 10^5$ cycles. In particular, the sample was fatigued with a load frequency of 17 Hz, a maximum load of 7.800 N and a minimum load of 1.110 N. These load values correspond to a maximum stress of 140 MPa (about 77 % of the yield stress f_y), a minimum stress of 20 MPa, a mean stress of 80 MPa and a stress amplitude of 60 MPa.

4.2. Mechanical characterization of undamaged aluminum samples by ultrasonic immersion test

We show the experimental results obtained in the ultrasonic immersion test on an aluminum sample before the mechanical damage. We performed the experiments by arranging the sample in the goniometric device with the axis of rotation parallel to the longitudinal axis x_3 of the specimen (see Fig. 2), coincident with the direction of the load which will be applied in the subsequent fatigue damage tests.

The sample was subjected to an overall rotation sufficiently large (about 30°) to obtain the mode conversions needed, according the Snell's law, for generating each kind of ultrasonic polarized waves whose velocites has to be measured.

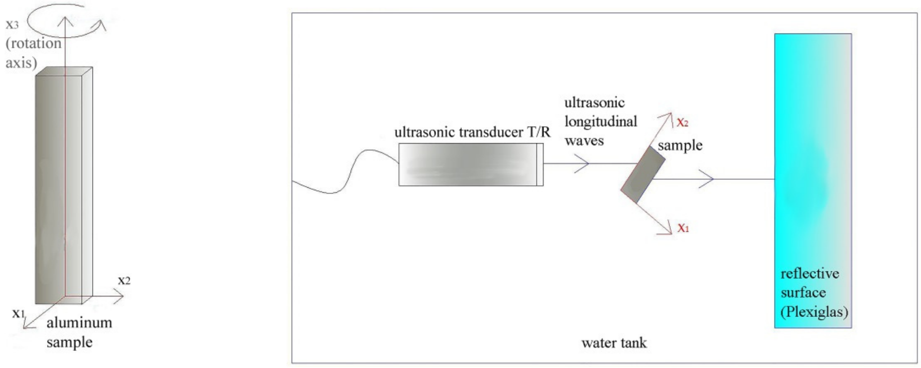

Fig. 2. Experimental configuration of ultrasonic immersion tests: ultrasonic wave propagation in plane x_1x_2, rotation axis x_3

Figure 3 shows the graph phase velocity – incident angle obtained as the result of the test. According to the Snell's law, the ultrasonic waves propagating into the sample are longitudinal until the first critical angle (approximately 15.2°) is reached. Notice that the velocity of longitudinal waves depends on the angle of incidence θ, ranging from 6360 m/s at θ=0° to 5247 m/s at θ=15.2°. The variation of the longitudinal velocity with the angle of incidence of the ultrasound beam is a typical behavior of anisotropic materials: this leads us to suppose that there is an initial slight anisotropy of the sample, probably due to the manufacturing process. Thus, more properly the measured ultrasonic velocities pertain to “quasi” longitudinal waves.

After the first critical angle, transverse waves are observed; their velocities maintains almost constant with the angle θ. We observe that in correspondence of the first critical angle the smallness of the angular steps used in our goniometric device (0.036°) allows for experimentally measuring (few) experimental points between the longitudinal mode and the first transverse mode; most likely these point are to be understood as spurious measurements.

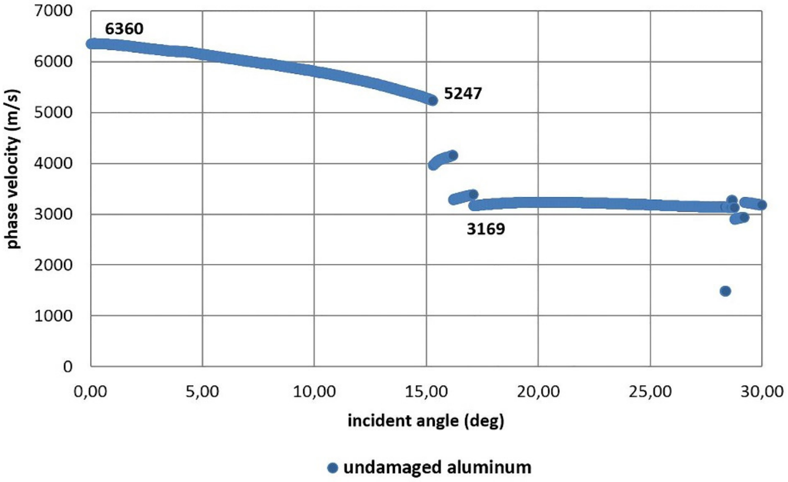

Fig. 3. Ultrasonic phase velocity vs. incidend angle in undamaged aluminum sample

Once determined the mass density of the material, which has found to be about 2.700 kg/m^3, the velocity data recorded in the test allow us to determine the two elastic constants of the isotropic aluminum sample by the inversion of the equations (4), and then to determine the engineering elastic constants. The values of the elastic moduli and the ultrasonic velocities of longitudinal waves (at 0°) and transverse waves have been collected in Table 1.

Table 1. Ultrasonic velocity and elastic modules of isotropic aluminum sample.

Longitudinal velocity (m/s)	6.360
Transverse velocity (m/s)	3.169
C_{1111} (GPa)	109
C_{1122} (GPa)	27
Young Modulus (MPa)	72.389
Shear Modulus (MPa)	27.115
Poisson’s ratio (-)	0,334

4.3. Mechanical characterization of fatigued aluminum samples by ultrasonic immersion test

Here, we show the experimental results obtained by the ultrasonic immersion goniometric technique on fatigued aluminum samples. For the sake of brevity, we report in Figure 4 only the results concerning the sample fatigued by the highest number of load cycles (i.e., $3.6 \cdot 10^5$ cycles); notice that for lower fatigue levels the observed alteration of the acoustic response is less pronounced. For these tests, the sample was placed in the goniometric device with the axis of rotation parallel to the direction of the applied fatigue load.

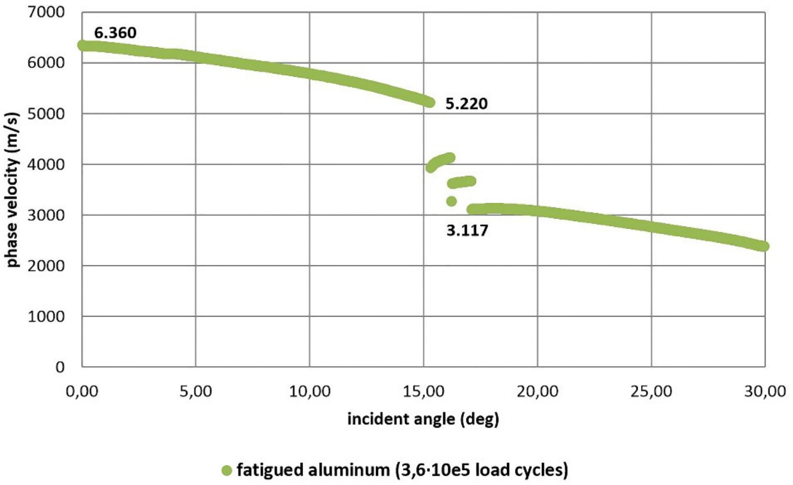

Fig. 4. Ultrasonic phase velocity vs. incidend angle in fatigued aluminum sample ($3.6 \cdot 10^5$ load cycles)

Overall, we observe – except for the value of the longitudinal velocity for 0° incident beam (unchanged) – a reduction of the velocity of propagating ultrasonic waves. As in the case of the ultrasonic tests performed on the undamaged aluminum sample, there is a clear dependence of the velocity of longitudinal waves on the incident angle θ, ranging from 6360 m/s at $\theta=0°$ to 5220 m/s at $\theta=15.3°$. But now, differently from what occurs for the undamaged sample, also the velocity of transverse waves depend on the incident angle: this means that after the first critical angle quasi transverse waves propagate in the material, and thus the degree of anisotropy of the material is increased. In particular, the transverse velocity ranges from 3117 m/s at $\theta=0°$ to 2387 m/s at $\theta=30°$ (maximum rotation angle).

Apparently, the ultrasonic tests clearly reveal the effect of the damage generated by the fatigue load cycles as an alteration of the acoustic response of the material. In particular, this change consists in an acquired anisotropy (fatigue induced anisotropy), eventually superposed to the initial anisotropy (texture induced anisotropy) due, for example, to the manufacturing process. This behavior is much more marked as the number of fatigue load cycles increases.

In order to characterize the fatigue induced anisotropy, by identifying the acquired acoustic preferential directions (classification problem) and the related elastic moduli (representation problem), it would be necessary to analyze the propagation of ultrasonic waves also in the plane x_1x_3. From the experimental point of view, this require the rotation of the sample about x_2 axis, but the geometry of the examined samples does not allow us to perform this kind of test.

We are currently conducting further tests on samples having a suitable geometry that allows for overcoming the above described limitations.

5. Conclusions

By adopting an innovative ultrasonic goniometric immersion device, we have shown that the fatigue damage induced in an aluminum specimen is related to the change of the acoustic properties of the material. The experimental results clearly show that the propagation velocity of the damage material depends on the direction of propagation, similarly to what occurs in anisotropic materials; this leads to conclude that the fatigue involves the emergence of an acquired damage induced anisotropy of the material. Thus, the fatigue level could be quantitatively related to the variation of the ultrasonic velocities and of the acoustic axes.

The experimental approach here proposed could prove to be very effective for studying the damage within the entire thickness of components. This encourage to further developing the experimental studies we are currently carrying out in our laboratory.

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