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Ultrasonic measurement of anisotropy and temperature dependence of elastic parameters by a dry coupling method applied to a 6061-T6 alloy

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Abstract

A pulse-echo ultrasonic method is presented to measure elastic parameter variations during thermal loading with high accuracy. Using a dry coupling configuration dedicated to high temperature investigation, this technique has been applied on 6061-T6 aluminium samples up to 220 °C. Experimental settings are described to assess the measurement reproducibility estimated at a value of 0.2%. Consequently, the anisotropy of this aluminium between the rolling direction and two orthogonal axes has been clearly detected and also measured versus temperature. As regards the temperature dependence of these elastic parameters, these results are compared with the estimations of the Young's modulus obtained during mechanical tests in conditions of low cycle fatigue (LCF). The same linear variation versus temperature is found but with a shift of 7 GPa. This difference has been classically attributed to systematic experimental error sources and to the distinction existing between dynamic and static elastic modulus.
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1. Introduction

6061-T6 alloy has superior mechanical properties such as high strength/weight ratio, good corrosion resistance and deformability. This material is mainly used for structural components in advanced applications as aircraft fittings, armour systems and high-speed machinery and so as structural material for internals of experimental nuclear reactors. For this reason, CEA (French Atomic Energy Commission) has engaged a wide program in order to obtain the mechanical properties of this alloy for a wide range of mechanical and thermal loading conditions. Indeed, this present work takes part in an attempt to establish European codes and standards for design and construction of pressure equipment for fast reactors [1]. For this reason, sets of material properties for base metals are required and the choice of materials has been enlarged to cover aluminium and zirconium alloys likely to be "transparent" to neutrons. For instance, fatigue rules require the modulus of elasticity associated with the fatigue curve of the material and also the same parameter from stress evaluation or equivalent data.

Classic mechanical tests are usually performed requiring tedious experimental procedures and specific devices such as thermal cabinet, strain gauge, etc. Secondly, their accuracies seem to be strongly dependent on the experimental settings and data analyse procedures (chordal, tangent/secant methods). For these reasons, ultrasonic methods are somewhat performed providing also a local

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and non-destructive investigation means. In basic pulse-echo configuration, a coupling fluid or a grease has to be used between the ultrasonic sensor and the material surface under test. Unfortunately, the acoustic propagation efficiency of this medium is generally reduced when temperature rises. For this reason, a so-called "dry coupling measurement" configuration is proposed. In this paper, the principle of this method will be first explained. Next, to illustrate its potentialities for research purpose, this technique will be applied to the measurement of the temperature dependence of Young's modulus and Poisson's ratio from 20 to 220 °C for 6061-T6 rectangular samples. Detection of anisotropy in this aluminium alloy will be also achieved along the three principal axes defined by the rolling direction. Experimental error sources and measurement reproducibility will be also discussed to assess the accuracy of this method. For comparison, low cycle fatigue tests will be performed on the same samples.

2. Dry coupling echography for high temperature elastic parameter evaluation

Physical constants can be obtained by various ultrasonic means from propagation velocity measurement. These techniques are usable on almost any material from liquids, solids or gazes and for a large range of size or geometry. Elastic parameters such as the Young's modulus "E" and Poisson's ratio "v" can be deduced from measurement of the longitudinal and transverse velocities using the following equations available for slightly anisotropic materials from the classic linear elastic theory [2]:

$$E = (\rho \cdot V_T^2)\frac{(3.V_L^2 - 4.V_T^2)}{(V_L^2 - V_T^2)} \quad \text{and} \quad v = \frac{(2.V_T^2 - V_L^2)}{(2.V_T^2 - 2.V_L^2)} \qquad (1)$$

with "V_L", "V_T", respectively, the longitudinal and transverse velocities of acoustic waves in the material under test. "ρ" corresponds to the specimen mass density.

The velocity of ultrasounds in materials is generally obtained from the flight time of ultrasonic waves through the known thickness of the sample [3]. For accurate delay time measurement, the specimen sides must have a sufficient parallelism level.

For high temperature measurement, ultrasonic sensors can be used up to the Curie limit temperature of their piezoelectric cells if their backing elements and soldered connections can also endure it. However, the coupling fluid generally used at the interface between the sensor and the specimen may become inefficient to ensure ultrasonic wave transmission beyond its boiling or transition temperature. These limitations can be overcome using specific sensors with long hard delay lines acting as thermal barriers and ensuring a correct contact by removing any gas void trapped between the actuator and the sample by compressing their polished surfaces together. In this so-called "dry coupling configuration", ultrasonic measurements have been done on various materials at least up to 1000 °C [4,5].

2.1. Principle of dry coupling ultrasonic device for high temperature

Ultrasonic sensors are generally composed by a thin plate of piezoelectric material glued on a rod made of glass or silica. This last part also called "delay line" enables the generation of a quasi plane wave at the sensor end surface if its length is superior to the Fresnel distance. In dry contact configuration, the transmission of ultrasonic wave will be only effective if any gas volume trapped within the interstitial voids between the sensor and the specimen is removed [6]. For instance, it has been experimentally demonstrated that a surface roughness inferior to one micron could completely prevent any ultrasound propagation in the range of 10–100 MHz [7,8]. Consequently, the sample and the sensor delay line surfaces have to be mirror polished. Moreover, to get a better mechanical matching at this interface for the ultrasound propagation, a compressive load of a few MPa has to be applied.

Fig. 1 presents our experimental set-up. A constant mechanical load is applied on the top of the acoustic sensor specially designed to endure this loading without any perturbation of its piezoelectric cell. For research purpose, a load cell of 500 N is used to monitor the applied stress while this parameter will be regulated during tests using a feed back control loop. The sample is heated between two heater elements laterally fixed on its sides.

As the temperature at the piezo-electric cell has to be inferior to its Curie limit during thermal tests, our sensor is air cooled down. A long silica rod acts as thermal barrier and acoustic delay line. Its length is around 5 cm.

A ball ring system is also used in order to apply a pure normal compressive stress to get a more efficient mechanical matching between the sensor and the material under test (cf. Fig. 1).

Conformably with Eq. (1), V_L and V_T have to be measured to get the elastic parameter values. Consequently, two specific transducers have to be used: one sensor to generate and detect longitudinal waves and an another one for transverse waves. In our case, the working frequency of the longitudinal sensor is around 50 MHz whereas the transverse one works at 7 MHz but velocity in metallic substrate is non-dispersive. Due to this low frequency evaluation for V_T, the 6061-T6 sample should not have one of its dimension inferior to roughly 4 mm. Indeed, the sample thickness must be superior to approximately ten wavelengths to prevent any time overlapping of the different round trip echoes for accurate and simple flight time measurement.

As regards acoustic data acquisition, the acoustic transducer receives an electrical burst with a repetition time of 1 ms. A digitising scope is triggered to this signal in order to display the same time window containing simultaneously the echo reflected at the sensor-sample interface and also the sample back end echo. Thus, the time mea-

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