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Material hardness and ageing measurement using guided ultrasonic waves

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ABSTRACT

Elastic properties of materials can be easily determined from the ultrasonic wave velocity measurement. However, material hardness cannot be obtained from the ultrasonic wave speed. Heat treatment and ageing affect the microstructure of many materials changing their hardness and strength. It has been already established that ultrasonic attenuation and dispersion are also affected by the material microstructure. It is investigated in this paper if the attenuation of ultrasonic guided waves can be correlated with the material ageing or duration of heat treatment and material hardness. To this aim six identical aluminum 2024 alloy plate specimens were subjected to different durations of heat treatment at 150 °C and were inspected nondestructively propagating Lamb waves through the specimens. Attenuation of the Lamb wave was found to be inversely related to the hardness. Rockwell hardness test was performed to corroborate the ultrasonic observations. In comparison to the Rockwell hardness test the ultrasonic inspection was found to be more sensitive to the heat treatment duration and material ageing. From these results it is concluded that guided wave inspection method is a reliable and probably more desirable alternative for characterizing the hardness and microstructure of heat treated materials. Earlier investigations correlated the bulk wave attenuation with the material ageing while this work is the first attempt to correlate the guided wave attenuation to the material hardness and ageing.

1. Introduction

Some material properties such as Young's modulus (E), Bulk Modulus (K), Shear modulus (μ), Poisson's ratio (v) and density (ρ) can be evaluated relatively easily by standard material testing techniques without damaging the specimen. It should be noted that for isotropic materials E, K, G and v are not four independent elastic constants; any two of these material constants can be treated as independent of each other and the remaining two can be derived from these two independent constants. However few other important material properties such as its strength and hardness cannot be determined from E, K, μ, v and ρ. These properties depend on the microstructure of the material such as grain size and grain orientation. The material hardness and its strength can be changed by heat treatment or natural ageing of the material by altering its microstructure. Since the material strength is not necessarily related to its stiffness and density and therefore cannot be expressed in terms of E, K, μ, v and ρ, the effect of the microstructure on the material strength is independent of its effect on stiffness and density. As a result, it is possible to have the material strength being affected strongly by the microstructure change while stiffness and density not being affected in the same manner. To measure the material strength the specimen needs to be loaded until failure. To obtain its hardness the Rockwell or Vickers hardness test can be carried out by indenting the test material by a hardened steel ball or diamond cone, thus a small surface area of the material is damaged. Therefore, neither strength nor hardness can be measured in a purely nondestructive manner when conventional material testing techniques are employed. In this paper it is investigated if any ultrasonic NDT/NDE (nondestructive testing/nondestructive evaluation) technique can measure material ageing or hardness. To this aim aluminum–copper alloy (AA2024) specimens were heat treated to 150 °C to alter their hardness and strength by changing their microstructure because at this temperature precipitation ($CuAl_3$) hardening occurs. Then the attenuation of the guided ultrasonic wave through those specimens was measured to see if any change is noticeable.

In early 20th century, Alfred Wilm made the accidental discovery of age hardening of aluminum alloy that later became known as Duralumin [1]. To satisfy the needs of aircraft industries in later years stronger Al–Cu–Mg alloys were developed such as 2024 (Al–4.3Cu–1.5Mg–0.6Mn) used for the DC-3 aircraft and in fuselage of most passenger aircrafts [2], 2014 (Al–4.4Cu–0.5Mg–0.9Si–0.8Mn) which in the artificially aged condition has a yield strength 50% higher than Duralumin, 2618 (Al–2.2Cu–1.5Mg–1.1F–1Ni–0.2Si) that was used for the skin and much of the structure of the

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Concorde aircraft. These alloys based on Al–Cu system have the advantage of superior creep strength at elevated temperatures [3]. Strength and hardness of alloys increase because fine precipitates of the foreign material or of the same material in a different phase provide barriers to the dislocation motion which is the cause of the plastic deformation and eventual failure of the material. Aluminum alloys (2024, 2618, etc.) are formed at high temperatures then, rapidly cooled to form supersaturated solutions of Cu and other elements in Al, and then precipitation hardened by heating at 150 °C. This causes $CuAl_3$ to precipitate out affecting the microstructure and thus altering the hardness and strength of the alloy. Stanke and Kino [4] showed the dependence of wave attenuation on microstructure – grain size and grain orientation. Since heat treatment of metal alloys alters its microstructure by affecting the size and distribution of precipitates, in principle the heat treatment duration or material ageing can be monitored by measuring the wave attenuation which is attempted here by propagating guided Lamb waves in plate specimens.

The energy decay, or ultrasonic attenuation, of elastic waves propagating in a solid or fluid medium can be divided into two types – attenuation due to geometrical effects such as spreading, and attenuation due to intrinsic material effects such as energy absorption. Geometrical effects include reflection and refraction at any interface, free surface, grain or phase boundary, and beam divergence, as well as waveguide effects due to multiple reflections at the boundary surfaces. Intrinsic effects include energy absorption or loss due to scattering of the ultrasonic wave at inhomogeneities, interaction with thermal phonons, dislocation damping, and conversion of acoustic energy to heat as a result of elastic deformation.

The theory behind guided waves is well established. The basic theory of guided waves and their applications to different NDT and NDE can be found in the works of many investigators [5–17]. However, none of those works address the problem of material ageing and hardness monitoring using guided waves. Rosen et al. [18] and Ringer et al. [19] investigated how ultrasonic bulk wave propagation characteristics are affected by the material hardness and ageing. The investigation reported in this paper is the first attempt to use guided waves for the ultrasonic characterization of heat treated materials and is therefore well suited for monitoring plate, pipe, beam and rod type structures.

2. Theory

Elastic waves that propagate through a waveguide are called guided waves. A waveguide is a structure with boundaries that help elastic waves to propagate from one point to another [17]. Waves are reflected by stress-free boundaries. Typical waveguides are plates, pipes, cylindrical rods and bars. The *Lamb Wave* is the guided wave that propagates in a solid plate. The Lamb wave is *dispersive* in nature, which means the speed of propagation of the Lamb wave is dependent on the frequency of the wave. At a single frequency different modes of Lamb wave propagate with different speeds.

Dispersion equations for Lamb wave propagation in a plate are given by [20],

$$\frac{\tanh(\eta h)}{\tanh(\beta h)} = \frac{(2k^2 - k_s^2)^2}{4k^2\eta\beta} \tag{1a}$$

$$\frac{\tanh(\eta h)}{\tanh(\beta h)} = \frac{4k^2\eta\beta}{(2k^2 - k_s^2)^2} \tag{1b}$$

Eqs. (1a) and (1b) correspond to symmetric and anti-symmetric Lamb modes, respectively. In the above equations,

$$\begin{aligned} k &= \frac{\omega}{c_L} \\ \eta &= \sqrt{k^2 - k_P^2} \\ \beta &= \sqrt{k^2 - k_S^2} \\ k_P &= \frac{\omega}{c_P} \\ k_S &= \frac{\omega}{c_S} \end{aligned} \tag{2}$$

where c_L is the Lamb wave speed (phase velocity), c_P is the P-wave speed, and c_S is the S-wave speed in the plate material. ω is the circular frequency (rad/s, $\omega = 2\pi f$) of the propagating wave. k_P, k_S and k are known as P-wave number, S-wave number and Lamb wave number, respectively.

Solution of Eq. (1) gives the Lamb wave speed as a function of frequency. It can give multiple wave speeds for multiple wave modes at the same frequency.

3. Experimental investigation

3.1. Experimental setup

The ultrasonic inspection was carried out on six plate specimens of aluminum 2024 alloy that had undergone controlled heat treatments. Plates were numbered as 1, 3, 5, 7, 9 and 11 with heat treatment time or ageing time of 6, 10, 14, 18, 22 and 26 h, respectively. The plate specimens have dimensions 6 in × 2 in × 0.16 in (=152.4 mm × 50.8 mm × 4.06 mm).

Ultrasonic experiments were carried out in an ultrasonic scanning Machine using two identical transducers placed in pitch-catch arrangement, one acting as the transmitter while the other one as the receiver, as shown in Fig. 1. Identical transducer pairs at two frequencies (1 and 3.5 MHz) were used for generating and receiving Lamb waves. Incident angles of the transducers required for generating Lamb modes were calculated from the dispersion curve (Fig. 2) as described below.

Dispersion curves for a 0.16 in (4.06 mm) thick plate used in our experiments are shown in Fig. 2. Phase velocities for different Lamb modes can be obtained from the dispersion curves at the desired frequency. For a plate immersed in a liquid (water in our case) with acoustic wave speed c_f (c_f = 1.49 km/s in water at room temperature) the angle of inclination (θ) of the ultrasonic transducer required for generating a specific Lamb mode having phase velocity (v_{PH}) = c_L can be obtained from Snell's law as shown below [20],

$$\theta = \sin^{-1}\left(\frac{c_f}{c_L}\right) \tag{3}$$

Since water is a good conductor of ultrasonic waves and is easily available, it is commonly used as the coupling fluid between the transducer and the specimen. Using the incident angle (obtained from Eq. (3)) for the ultrasonic transmitter one can generate the Lamb wave in the solid plate placed in the water tank of the ultrasonic scanning machine. Transducers were placed 50 mm above the specimen, then the distance between the transmitter and the receiver was increased as much as possible (more than 150 mm) so that Lamb wave propagates almost the full length of the specimen before being recorded by the receiver. Same transducer–receiver orientation relative to the specimen was used for all six specimens.

Experimental results (time histories for six different specimens) were recorded for two sets of paired or identical transducers of frequency 1 and 3.5 MHz for different inclination angles that were tuned to generate specific Lamb modes, shown in Fig. 2. For example at 1 MHz frequency there are four phase velocities (V_{PH} or c_L)