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Original Research Article

Application of ultrasonic method for quality evaluation of adhesive layers

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ABSTRACT

A discernible increase in importance of the methods used to evaluate and to control industrial processes has been observed over recent years. More and more frequently, companies utilize advanced methods of non-destructive testing to be competitive on the market and to provide high quality products. Thus, constant qualities of each single product are guaranteed and company's reputation is strengthened.

This paper supplements various investigations and potential applications of ultrasonic testing to analyze imperfections in adhesive joints in practice. The findings should extend a relatively scarce knowledge on potential use of ultrasounds to determine the types and sizes of defects in adhesive joints.

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1. Introduction

Ultrasonic waves have been applied to investigations of material properties for over 150 years, however no earlier than from a dozen or so years they are used to test adhesive properties of bonding joints [1–5]. In recent years, the dynamic development in research of adhesive joints has been noted [6–8]. Particularly, advantageous results can be obtained using ultrasonic methods [8–11].

The European standard EN 923:2000, Adhesives, Terms and definitions, defines adhesive bonding as a joining technique using non-metallic substance – adhesive, by bonding surfaces (adhesion) of materials to be joined together, while maintaining appropriate internal strength of the joint (cohesion). At least three media exist in bonding process, their variable acoustic parameters and acoustic phenomena existing at their boundaries can be used to detect adhesive layer existence, adhesive force to substrate and possible inconsistencies existing in the joint.

A medium is distinguished by its acoustic impedance (Z), the value defined as a product of longitudinal wave speed (c_L)in the medium and its density (ρ):

$$Z = c_L \cdot \rho \quad (1)$$

While considering an ultrasonic beam propagating in two homogeneous media, having acoustic impedances Z_1 and Z_2, incident at right angle to the boundary surface (Fig. 1) an assumption can be made that a fraction of energy of the wave propagating in medium 1 will be reflected and the remaining part will be transmitted in medium 2.

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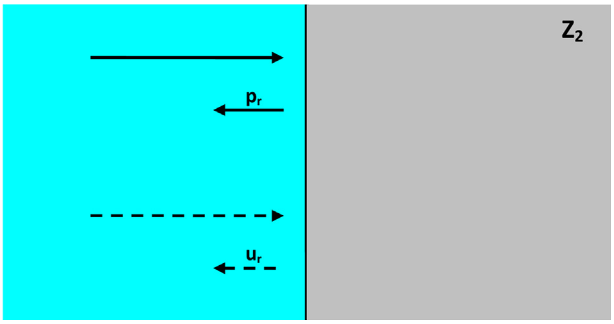

Fig. 1 – Schematic representation of boundary between media [12,13].

If, p_i, p_r and p_t mean acoustic pressures (or stresses) of incident, reflected and transmitted waves, respectively, and u_i, u_r and u_t represent speeds of particle propagation in the medium, then, neglecting the losses in media, the acoustic pressure and speed of particles can be expressed by the formulae:

$$p_i = A_1 \sin(\omega t - k_1 x) = u_i Z_1 \tag{2}$$

$$p_r = B_1 \sin(\omega t + k_1 x) = -u_r Z_1 \tag{3}$$

$$p_t = A_2 \sin(\omega t - k_2 x) = u_t Z_2 \tag{4}$$

where A_1, B_1, B_2 – pressure amplitudes of incident, reflected and transmitted waves, respectively, in media of acoustic impedances Z_1 and Z_2, k_1, k_2 – wave numbers.

It is assumed that the following conditions are met at the boundary surface between medium 1 and 2:

To maintain the continuity, the acoustic pressures must be the same on both sides of the boundary surface, i.e.:

$$p_t = p_i + p_r \tag{5}$$

To keep the particles of adjacent materials in direct contact, the speeds of particles perpendicular to the boundary surface must be equal on both sides, i.e.:

$$u_t = u_i + u_r \tag{6}$$

Taking x = 0 as boundary conditions at the boundary of media, the two above equations lead to:

$$A_2 = A_1 + B_1 \tag{7}$$

and

$$Z_1 A_2 = Z_2(A_1 - B_1) \tag{8}$$

Following transformations and respective substitutions, the ratio of acoustic pressures of transmitted to incident waves can be as follows:

$$d_a = \frac{p_t}{p_i} = \frac{A_2}{A_1} = \frac{2Z_2}{(Z_1 + Z_2)} \tag{9}$$

The ratio d_a is known as the pressure amplitude penetration coefficient. The ratio of acoustic pressures of reflected wave to incident wave:

$$\frac{p_r}{p_i} = \frac{B_1}{A_1} = \frac{(Z_2 - Z_1)}{(Z_1 + Z_2)} \tag{10}$$

denoted as r_a bears the name of pressure amplitude reflection coefficient. It results from above equations, that:

$$d_a - r_a = 1 \tag{11}$$

Two cases are noteworthy. The first one is when the wave is transmitted from a medium of greater acoustic impedance to a medium of smaller acoustic impedance (metal–adhesive interface). In this case, the pressure reflection coefficient is negative and is less than one. The negative sign of the pressure reflection coefficient means that, at the interface, the reflected wave is in opposite phase to the incident wave (Fig. 2a).

When the wave goes from lower impedance medium to that of higher acoustic impedance (adhesive–metal), the reflection coefficient is positive, which means that the reflected and incident wave have consistent phases. It is worth considering that the transmission coefficient, due to Eq. (11) is:

$$d_a = 1 + r_a \tag{12}$$

Hence, the amplitude of wave transmitted in higher impedance medium will be greater than that of the incident wave (Fig. 2a and b).

Typical adhesive joint, e.g. in automotive vehicles, is a system composed of at least three layers, wherein the ultrasonic wave is to go through a distance including: sheet metal, layer of adhesive, the other sheet metal.

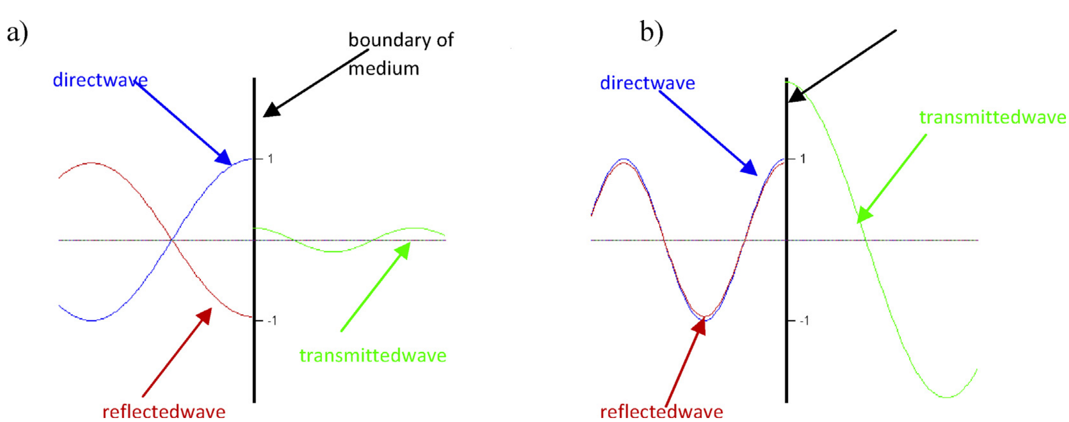

Fig. 2 – Transmission of acoustic wave at a boundary of media. Pressure amplitudes at the interface (a) steel–adhesive and (b) adhesive–steel [14].

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