DETERMINATION OF MATERIALS DAMAGE NON-DESTRUCTIVELY

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ABSTRACT

In the present work, an experimental technique, based on ultrasound is introduced for the determination of material damage. The pure aluminium specimens used were loaded in tension gradually *until* fracture occurred. The degree of damage was measured by the change in attenuation of ultrasonic longitudinal waves propagating througth the stressed specimens. The obtained results showed that, the damage of a material can be determined quickly by using a non-destructive ultrasonic testing method,for measuring only changes of attenuation.

INTRODUCTION

It is well known that materials subjected to a stress field below that required for macroscopic failure, produce internal defects. In recent years, there has been considerable effort to study this so-called material damage and its evaluation, and to correlate it with the ultimate failure of the material. Material damage is defined as the property whereby the material strength diminshes before failure occurs. It is mainly due to the creation and development of discontinuities in the solid, such as: cracks, micro-cracks or micro cavities, breakage of bonds, decohesion of grains and fibers etc. Considering the mechanism, there are various different types of damage, such as: brittle damage, ductile damage, creep damage and fatigue damage[1]. One particular experimental approach that has been used to study the development of these forms of damage is based on the use of ultrasonic waves.

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Martinson et al. [2] have applied an acoustic imaging method to study damage fields near crack tips in strained propellant sheets. They found that, the shapes of the damage zones resemble the kidney-shaped plastic zones, often found, near crack tips in strained ductile metals. Knollman and Yee [3] also used an ultrasonic imaging technique for portraying and evaluating interal damage in engineering materials. Stigh[4] studied the influence of damage on ultrasonic velocity and derived a relationship between them. He showed also that, measurements of ultrasonic velocity can be used to predict the remaining life of a material. From the damage behaviour, he showed that, rupture is preceded by a rapid increase in growth of damage.

The purpose of the present work is to derive a relationship between ultrasonic wave attenuation and material damage and to study the effect experimentally. The paper describes the evaluation of the damage which develops arround the middle of specimens of pure aluminium loaded in tension gradually until fracture occurs. The method used is that of ultrasonics [5] and the features measured during the loading cycle of each specimen are the echo heights on the cathod ray tube (CRT)-display screen of an ultrasonic flaw detector.

THEORETICAL APPROACH

Damage and attenuation measurements:

Damage can be defined as the effective surface density of micro-cracks and cavities in any plane of a representative volume element. The definition of damage in the continuum mechanics context as follows [6]:

If n is the normal which defines a surface of intersection dS of a volume element δV and if δS_0 is the effective surface of intersection of micro-cracks and micro-cavities with the plane of dS, then, the damage is defined by the expression:

$$D_n = \frac{\delta S_0}{\delta S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

thus, when $D_n = 0$, there is no damage in the direction n, while when $D_n \to 1$, the element breaks into two parts along the palne n. Cheng and Huang [7] proposed an equivalent form for the continuous damage parameter D.For a bar subjected to a tensile

load (when damage micro-cavities are created within the specimen as voids, micro-pores, micro-cracks ets.), let its apparent area of cross-section by A_α [see Fig (1)], the area occupied by micro-cavities be A_d and the effective cross-sectional area be A_ε. Then, the continuous damage parameter D may be defined as:

$$D_k = 1 - \frac{A_\varepsilon}{A_\alpha} \quad \dots\dots (2)$$

where , when $A_\alpha = A_\varepsilon$, $A_d = 0$, $D_k = 0$ there is no damage, while when $A_\alpha = A_d$, $A_\varepsilon = 0$, $D_k = 1$ there is damage.

Based on the definitions of damage expressed by the formulae (1) and (2), several measuring formulae for the damage parameter D can be derived. Among various methods mentioned in the literature, some of the more important are those presented by Lemaitre and Dufailly [1] and Cheng and Huang [7]. It will briefly present those which are based on ultrasonic wave propagations and on variations of electrical potential (potential drop).

Ultrasonic wave propagation:

Lemaitre and Dufailly [1] showed that , if the velocity of longitudinal ultrasonic waves in a non- damaged material is c_ℓ^0, and the corresponding velocity in damaged material is c_ℓ, then the value of damage D is given by

$$D = 1 - \frac{\rho c_\ell^2}{\rho^0 c_\ell^{0^2}} \quad \dots\dots (3)$$

where ρ^0 is the density of the initial non- damaged specimen and ρ is the density of the same specimen when damaged .

Variations of electrical potential :

Lemaitre and Dufailly [1] also defined so-called effective intensity of electrical current by the following formula :

$$i = \frac{i_O}{1 - D} \quad \dots\dots (4)$$

where i is the current intensity which effectively exists in the cohesive parts of a damged volume element and i_0 is the intensity in the non - damaged element.

The potential difference V_0 (From Ohm's Law) for a non - damaged element of length ℓ, area s and resistivity r_0 and the same quantities V, r for the same damaged element, are written as:

$$V_0 = r_0 \frac{\ell}{s} i_0 \;,\; V = r \frac{\ell}{s} i \quad \text{..........................} \quad (5)$$

The damage parameter D, from equations (4) and (5) then can be easily derived in the form:

$$D = 1 - \frac{V_o}{V} \quad \text{...} (6)$$

On the other hand , ultrasonic attenuation, is not influenced by the geometry of propagation, but is influenced by a material characteristics. The attenuation is a manifestation of the scattering and absorption of acoustic energy. The amount of attenuation is measured in decibels (dB), which is a logarithmic comparative unit defined as follows [5 and 8-10]:

$$\alpha = \frac{20}{2x} \log \frac{V_o}{V} \quad \text{............ ....} \quad (7)$$

where α is the attenuation coefficient and x the thickness of the material. Since the cathod ray tube (CRT) - display screen of the ultrasonic flaw detector apparatus indicates echo heights H_i, which are proportional to the echo impulse voltages V_i received, then,

$$\frac{H_o}{H} = \frac{V_o}{V} \quad \text{..} \quad (8)$$

where Ho and H are the echo heights on the CRT - display screen. Substituting from Eqn. (8) into Eqn. (7), yields;

$$\alpha = \frac{20}{2x} \log \frac{H_o}{H} \quad \text{...} \quad (9)$$

With the help of equation (9), the change in acoustic attenuation Δα of a material as a function of applied stress on a specimen is, represented as :

$$\Delta\alpha = \frac{20}{2x} \log \frac{H_o}{H} \quad \text{...} \quad (10)$$

where H_0 is now the echo height on the CRT -display screen at zero stress (σ= 0), and H is the height of the same echo on the screen at stress σ.

In determining the relationship between the damage parameter D of equation (6) and the received echo heights of damaged material on the CRT-display screen, it must be considered the following :

In the case of equation (5) the electric current which passes through an element has as a result, such that the creation of a pulse whose amplitude on the CRT - display screen is H. When the area of cross- section of this element decreases, due to the Poisson's ratio or the damage development during stress loading, then, the potential difference V increases. In this case, the screen pulse amplitude also increases according to the relation (8) where now V_0 and H_0 are corresponding to non-damaged material, while V and H to damaged material. In the case of ultrasonic materials examination, an electric current is transformed to an ultrasonic elastic wave which passes through the material. This elastic wave after its exit from the material is transformed again to another electric current. In this case, because of the appearance of damage, the attenuation (scattering and absorption) of the ultrasonic elastic wave increases and its energy consequently decreases. So, as this second electric current is produced from a weakened elastic wave of smaller energy than the initial wave, it will be of smaller energy than the initial electric current and, of course, of smaller intensity and smaller potential difference V corresponds to a smaller echo (or pulse) on the CRT- display screen, height H.

So, we have an element under increasing stress in which the effective cross- section S decreases on account of the damage development. In this case two different problems arise:

a) If this element is traversed by an electric current, the potential difference V will be increasing according to equation (5). It considers that, the change of the other quantities in relationships is negligible.

b) If this electric current is transformed to an elastic wave which passes through the element and, then transformed back again to an electric current, the ptential difference will be decreased.

In the first case, the damage in the element will affect the passing electric current, while in the second case the same damage will affect the passing elastic wave. The damage influences the elastic wave. So, as the damage increases, the effective cross-section of the element becomes smaller, the potential difference increases and the elastic wave becomes weaker. The result of this behaviour of an element being stressed is that, as its damage increases, the intensity of the passing ultrasonic elastic wave decreases and furthermore decreases the amplitude of the received echo on the CRT-display screen. So, the relation (8), in this case is reversed and takes the form:

$$\frac{V_o}{V} = \frac{H}{H_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Then, according to the above relation (11), the relation(6) will be :

$$D = 1 - \frac{H}{H_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

MATERIAL AND EXPERIMENTAL PROCEDURE

Material used in the present work was commercially pure aluminium (99.7% commercial purity) plate, 8 mm thick. For the experimental determination of the damage from the ultrasonic longitudinal elastic wave attenuation, tensile specimen tests of 8 mm thickness, 25 mm width and 80 mm gauge length (according to ASMT standard E8- 82 [11]), were cut from the plate. The longest axis of each specimen is parallel to the roll direction of raw plate. Tensile loads were performed statically using a 20 ton universal testing machine (fully computerized). All the tests were performed by setting the cross - head speed at 0.5 mm/min.

Experimental set-up used for attenuation measurement during loading is shown in the block diagram illustrated in Fig. (2) An ultrasonic pulse generator (Model USM2, Krautkramer Inc., Germany) was used. The apparatus is capable of producing high frequency pulses, and usually operates with the transducer (Probe) as transmitter and receiver at the same time. Applying the ultrasonic pulses to the specimen under investigation will result in a train of echoes on the face of cathod ray tube (display screen) as shown in Fig. (3). The examination of the damage was carried out by studying the change of the first echo amplitude on the display screen of the ultrasonic flaw detector using an ultrasonic pulse-echo

technique [5 and 8-10] at a nominal 2 MHz operating frequency. The surface condition of specimen and test temperature (room temperature) were kept almost constant during the ultrasonic measurements. The change of attenuation $\Delta\alpha$ was determined by using equation (10) and the corresponding damage D from equation (12). Five identical specimens were tested in tension until fracture occurred using this procedure. Also, two identical specimens were tested in simple tension, to determine the elastic properties of the material.

RESULTS AND DISCUSSION

The stress -strain (σ-ε) curve of the investigated material is shown in Fig. (4). Form this, the modulus of elasticity was found to be E = 7x 10^7 MPa, the fracture stress σ_u=112.6 MPa and the yield stress to be $\sigma_{y_{0.2}}$ = 86.4 MPa.

Figure (5), shows the mean value of the change of attenuation $\Delta\alpha$ versus the applied stress up until fracture. As shown , initially the increase of $\Delta\alpha$ is very small, but as the stress approaches the yield point it increases, and after this point there is a sudden increase.

Figure (6), shows the change in the mean value of the damage parameter D versus the applied stress σ. As shown , the damage behaves in the same way as the attenuation in Fig. (5). Also, from this figure, it can be seen that, for small values of applied stress, the change in damage remains insignificant. Indeed the slow increase in damage continues until the yield point, after which it increases suddenly towards the upper limit value of 1, when the specimen breaks.

Comparison the curves of these three diagrams, it can be seen that, the three quantities ε, $\Delta\alpha$ and D behave similarly during the loading cycle to fracture. This is a reasonable result. Since attenuation and strain are influenced in the same way by the damage in the material. Thus, as the damage is insignificant at small stresses, so also the values of attenuation and of the corresponding strain are insignificant. But near the yielding point of the material, where the material passes slowly from elastic to plastic deformation, many defects appear and the damage suddenly takes significant values, as do the other two quantities $\Delta\alpha$ and ε.

CONCLUSIONS

From this study, the following conclusions may be drawn :

1. The damage of a material can be determined quickly by using a non - destructive ultrasonic method, measuring only changes of attenuation.
2. Techniques based on the change of ultrasonic longitudinal wave velocity are less appropriate for the determination of damage, since the change of velocity is not so sensitive quantity as attenuation for studying material damage during loading.

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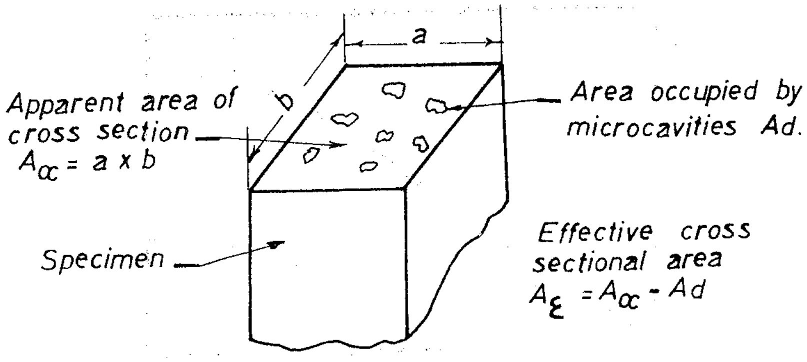

Fig.(1) A ***typical damaged cross.section.***

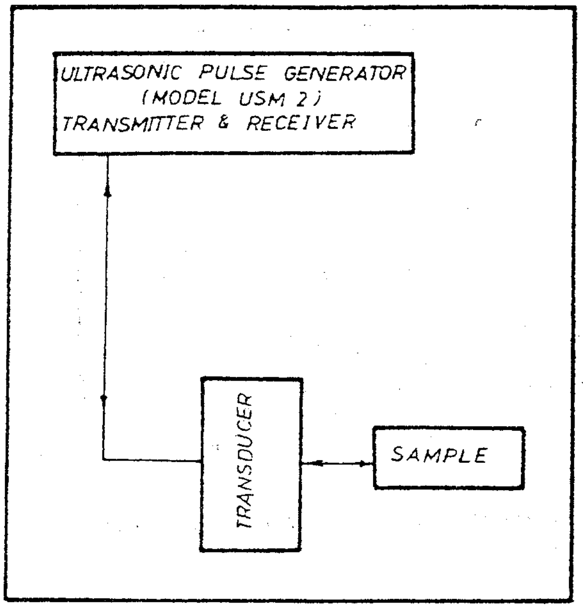

Fig.(2) The block diagram of attenuation measurement.

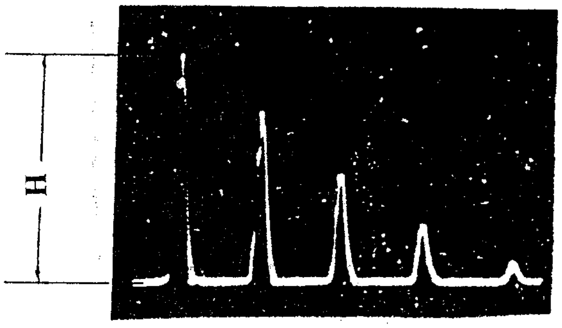

Fig.(3) Photographic picture of the exponentially decayed pattern used for ultrasonic attenuation coefficient measurements.

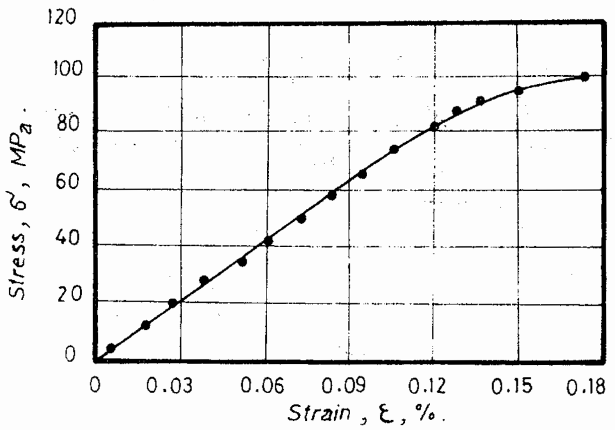

Fig.(4) Stress_strain curve of the material used.

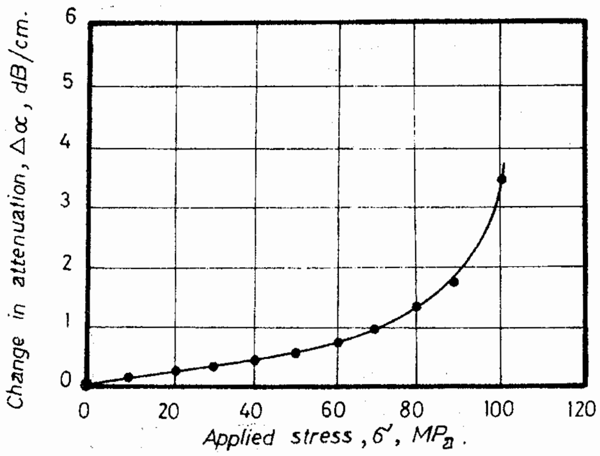

Fig.(5) Variation of $\Delta\alpha$ versus the applied stress σ.

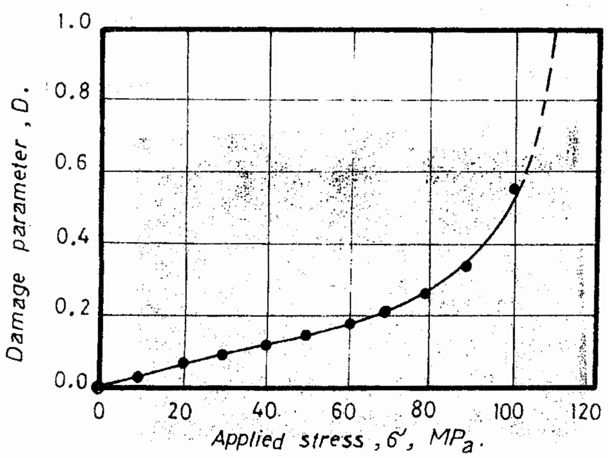

Fig.(6) Variation of damage D versus the applied stress σ.

" تعيين تصدع المواد لا إتلافياً "

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ملخص البحث :

يهدف هذا البحث إلى تقديم أسلوب معملى لا إتلافى (لاتدميرى) لإستخدام الموجات الفوق سمعية فى تعيين مقدار التصدع الذى يحدث فى المواد أثناء تحميلها. وتحقيقاً لهذا الهدف فقد تم إعداد عينات شد مسطحة بسمك ٨ ملليمتر من الألمنيوم النقى (درجة نقاوة ٧ ,٩٩ ٪). كذلك اشتمل البحث على دراسة نظرية لإيجاد العلاقة بين كل من معامل التصدع **Damage Parameter D** ، التغير فى معامل الإخماد للموجات الفوق سمعية Change in Attenuation Coefficient $\Delta\alpha$ وبين بعض بارامترات الموجات التى يمكن مشاهدتها على شاشة الجهاز Display Screen أثناء تحميل العينة .

كما تم إستخدام أسلوب صدى النبض Pulse- Echo Technique للموجات الفوق سمعية وعند تردد مقداره ٢ ميجا هرتز لتعين كل من معامل التصدع **D** وكذلك التغير فى معامل الإخماد $\Delta\alpha$ أثناء تحميل العينات السالفه الذكر بأحمال شديه . ولقد خلصت الدراسة إلى أنه يمكن إستخدام هذا الأسلوب السهل والسريع فى تعيين مقدار التصدع الذى يحدث فى المواد أثناء عملية التحميل.