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REVIEW OF ULTRASONIC VELOCITY METHODS OF DETERMINING
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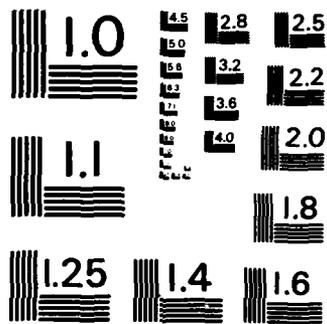
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Structures Technical Memorandum 416

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OF DETERMINING RESIDUAL STRESS**

by

S.J. RUMBLE and J.G. SPARROW

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SUMMARY

This paper summarizes the techniques used to determine residual stresses. It notes that whilst velocity methods have not been refined to the stage of practical use, they show considerable promise. The theoretical basis, and the experimental techniques of the ultrasonic methods are reviewed with emphasis on the separation of the competing effects of texture and stress on ultrasonic velocity. *Keyword: Australia*



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1. INTRODUCTION

Residual stress is the stress remaining in a body when all external forces have been removed. Residual stresses can occur as a result of fabrication, assembly, load history, heat treatment or welding. They may be compressive or tensile, and often contribute to the occurrence of component failure. The contribution of these stresses to premature structural failure has long been recognised. However their measurement has usually been difficult and in many cases not possible. Recognition of the benefits of knowing the value of residual stresses has led to recent efforts to improve the capability of known methods of measuring them and to the development of new techniques.

The residual stresses in a body can be divided into two classes depending on the extent of the stress. In typical engineering materials, residual microstresses extend over a few grains, whereas residual macrostresses occur on a scale of millimetres or greater. It is the residual macrostresses which are most amenable to the practical measurement methods discussed in this paper.

2. METHODS OF MEASURING RESIDUAL STRESS

The earliest method of determining residual stress was based on the hole drilling technique wherein measurements are made of the relaxation strains resulting from the drilling of a small hole in the centre of a strain gauge rosette¹. While this method is semi-destructive, it is both simple and inexpensive to apply and can be used both in the laboratory and as a field measurement². The method is presently limited to stress fields uniform with depth, having a stress less than approximately one third of the yield strength of the material. While the equipment needed is relatively inexpensive, the method requires skilled technicians to ensure that the hole location and diameter are within close tolerances³.

The most widely used non-destructive method of measuring residual stress is that of X-ray diffraction⁴ (XRD). This technique is based on the determination of the interatomic spacing of lattice planes in the specimen surface layer (25 μ). The procedure has been well developed

over the past twenty years and remains the only practical method in many situations⁵. Its most significant limitation may be the fact that the technique is only surface sensitive, while in the presence of strong texture and large grain size, for example in some aluminium alloys, the XRD results may be difficult to interpret. Energy dispersive X-ray spectrometry (EDXRS) using a range of high energy X-rays capable of penetrating considerable depths into steel offers the prospect of overcoming the surface limitation of XRD. The EDXRS method still requires considerable development before its full potential is reached⁶.

Ultrasound methods have not yet been refined to a stage where they may be put to practical use for the measurement of residual stress. However they offer such promise, particularly for three-dimensional stress fields, that intense research effort continues to be devoted to their development⁷.

Other potential methods of measuring residual stress have been suggested (Barkhausen^{8,9}; nuclear hyperfine¹⁰; neutron diffraction¹¹) but only neutron diffraction appears to offer potential for other than very limited application. A number of recent reviews of non-destructive methods of residual stress measurement have been published^{7,10,12-14}.

3. ULTRASONIC METHODS

The anharmonicity (higher order strain terms in the strain energy expression) of a material provides the physical basis for the measurement of stress/strain by ultrasound¹⁵. Most frequently, use is made of the approximately linear change in ultrasound velocity with absolute stress, and it is the application of this principle which will be discussed subsequently. Based on Murnaghan's¹⁶ theory of finite deformations, Hughes and Kelly¹⁷ formulated the following expressions for the velocities of elastic waves in an isotropic material under uniaxial stress:

$$\rho_0 v_L^2 = \lambda + 2\mu - \frac{T}{3K_0} \left[21 + \lambda + \frac{(\lambda + \mu)}{\mu} (4\mu + 4\lambda + 10\mu) \right] \quad (1)$$

$$\rho_0 V_T^2 = \mu - \frac{T}{3K_0} \left[m + \frac{\lambda n}{4\mu} + 4\lambda + 4\mu \right] \quad (2)$$

For propagation perpendicular to the direction of stress

$$\rho_0 V_L^2 = \lambda + 2\mu - \frac{T}{3K_0} \left[2l - \frac{2\lambda}{\mu} (m + \lambda + 2\mu) \right] \quad (3)$$

$$\rho_0 V_{T1}^2 = \mu - \frac{T}{3K_0} \left[m + \frac{\lambda n}{4\mu} + \lambda + 2\mu \right] \quad (4)$$

$$\rho_0 V_{T2}^2 = \mu - \frac{T}{3K_0} \left[m - \frac{(\lambda + \mu)n}{2\mu} - 2\lambda \right] \quad (5)$$

where ρ_0 is the material density at zero strain, T is the applied stress, positive being compressive and the L and T refer to longitudinal and transverse waves. The subscripts $T1$ and $T2$ refer to shear wave polarisation parallel and perpendicular to the direction of stress respectively. λ and μ are Lamé constants, while l , m , and n are Murnaghan constants. $K_0 = \lambda + \frac{2}{3}\mu$ is the bulk modulus for the isotropic material in the unstrained state.

From the above equations, in the first approximation, linear relationships can be shown between both shear and longitudinal wave velocities and uniaxial stress. In addition for shear waves

$$\frac{V_{T2} - V_{T1}}{V_{T0}} = \frac{T}{8\mu^2} (4\mu + n) \quad (6)$$

where $V_{T0} = \left(\frac{\mu}{\rho_0} \right)^{1/2}$ is the transverse wave velocity in the unstressed isotropic material.

Equation (6) is the basis for the advantage of the acoustic birefringence technique compared to the method based on measurement of longitudinal wave velocity. Whereas the latter requires very precise measurement of absolute velocities taking account of changes in length and temperature, acoustic birefringence is largely self-calibrating since only a differential velocity need be measured.

The above equations indicate that if the ultrasonic velocities in a uniaxially stressed, but otherwise isotropic material, could be determined, then a map of the relative stresses (residual and applied stresses) in the material could be obtained. If the velocity at zero stress was known or could be determined then the absolute stresses could be calculated, which in the absence of any applied stresses would be the residual stresses. However most metals, as a consequence of their thermal history and mechanical working during fabrication, contain some degree of "texture". The effect of texture on ultrasonic velocities is often the same as, or an order of magnitude larger than, that contributed by stress (40). This variation of velocity with texture or the presence of any residual stress does not affect the determinations of applied stresses, as the texture or residual stress altered velocity is still linearly related to any applied stress. This has enabled measurements of applied stress, using either longitudinal or shear waves, to become a practical and relatively straightforward procedure. However, to determine the residual stress at a given location, it is necessary to separate the contributions of texture and stress to the ultrasonic velocity.

4. TEXTURE

At the present time there are only three approaches which offer some prospect for this separation. In 1966 Mahadevan⁴¹ reported that for a steel specimen there is a linear relationship between the shear wave birefringence due to texture and frequency (between 2-5 MHz), and that the effect of stress is the same at each frequency. This offers the possibility of separating the two components of the observed birefringence. In 1968 Reynolds⁴² showed that, while each of the two shear wave and the longitudinal wave velocities is strongly affected by material texture, the sum of the squares of the three velocities is constant, independent of orientation of the crystallite axis and grain alignment. Furthermore from equations (3), (4) and (5) it can be shown that⁴⁰

$$\rho_0 \sum_{n=1}^3 v_n^2 = (\lambda + 4\mu) - \frac{PT}{3k_0} \quad (7)$$

where

$$P = 2l + 2m + 2\mu - 5\lambda - \frac{1}{4\mu} (\lambda n + 8\lambda m + 8\lambda^2 + 2\mu n) \quad (8)$$

indicating that the velocity combination is linearly dependent on stress. Other texture independent formulae have been derived⁴³ although none of them is as straightforward as equation (7).

An alternative approach to the determination of stress from the velocity of ultrasonic waves has been developed by Salama^{38,44} and by Chern et al³⁹. They have reported that the relative change in the temperature dependence of longitudinal velocity is a linear function of applied stress, the slope of this relationship being the same for all specimens of the same material tested. In addition they reported that the same relationship applies for a number of different aluminium alloys indicating that it is insensitive to both composition and texture.

5. TECHNIQUES OF MEASUREMENT OF ULTRASONIC VELOCITIES

The most commonly used methods of measuring ultrasonic transit times are based on the sing-around, pulse-echo overlap and superposition techniques. The sing-around method involves the successive retriggering of the emitting transducer by selected echoes received by a further receiving transducer on the opposite side of the specimen; or by the reflected echo returning to the emitting transducer. The frequency of retriggering is a measure of the transit time of the ultrasonic wave across a single or double path through the specimen. This repetition frequency can be measured to a precision of a few parts in 10^7 ¹⁸, probably in excess of that required in view of other sources of uncertainty (eg. $\pm .001^\circ\text{C}$ results in ± 2 in 10^7 for $\Delta V/V$ for most materials¹⁹).

In the pulse superposition method, the transducer is triggered by an oscillator whose frequency is manually adjusted until its reciprocal coincides with the round-trip transit time (or a multiple) of the ultrasonic wave in the specimen. Adjustment of the oscillator frequency is carried out to achieve overlap of an echo with a later echo in the same pulse train. Summation of coincident pulses occurs at the transducer and is observed on a CRO screen²⁰ or more recently as calculated by a computer²¹; in this latter system, a detection sensitivity of 1 part in 10^8 is claimed. In both the sing-around and pulse superposition techniques, a number of pulse trains are in the material at any one time. This occurs because the emitting transducer is retriggered before the ultrasonic pulse from the previous triggering has completely decayed.

The pulse echo overlap method is generically related to the superposition method except that the transducer excitation rate is low enough that all echoes decay before the transducer is retriggered. The echo overlap is achieved by adjusting the sweep frequency of a CRO to be equal to the reciprocal of the travel time in the specimen, and enhancing the CRO intensity during passage of the pair of echoes under examination. In this case overlap occurs optically in the CRO rather than in the transducer as with the superposition method. The transducer triggering frequency is obtained by division of the reciprocal of the echo travel time by a factor of 100 - 1000; reduction of this factor to 1 would make this technique equivalent to the superposition method. The pulse echo overlap technique has been developed and extensively used by Papadakis²². A comparison of a number of methods of measuring ultrasonic velocity is given in a review paper by that author¹⁹.

Adaptation of the above methods have included the use of an ultrasonic delay line to achieve overlap between successive pulses²³; the interference between echoes from passage of an ultrasonic pulse through two specimens, one under stress²⁴; and the use of separate transducers each side of the specimen to generate two principal shear waves with a variable electrical delay between them adjusted to achieve echo cancellation²⁵.

The use of shear rather than longitudinal ultrasonic waves introduces the possibility of another method of velocity measurement. In a stressed

or slightly anisotropic material, a shear wave will in general split into two polarised components with different velocities. Rotation of the shear wave transducer into an alignment with respect to the principal stress directions (for an isotropic material) or to the rolling direction for a textured specimen enables examination of a single polarised component; the above methods of velocity measurement can then be applied. For any other transducer orientation, the presence of the two polarised components generally requires another technique of measurement unless the differential velocity is large enough to provide temporal separation of the components²⁶.

Individual measurement of the velocities of the two perpendicular components appears to be the most popular approach to the use of shear wave birefringence²⁷⁻³². However some authors have exploited pulse spectroscopy whereby the two shear waves are allowed to interfere at the transducer and the echo of minimum amplitude determined³³⁻³⁶. Whereas in the past some form of frequency measurement has usually been adopted to achieve the necessary transit time precision, the advent of high frequency A/D converters has led to the use of Fourier transform computer methods of calculating phase^{26,37}.

6. EXPERIMENTAL DIFFICULTIES

Difficulties associated with the determination of residual stress using ultrasound are exacerbated by the relatively small stress induced velocity changes, of the order of 10^{-5} /MPa. Timing of the precision required (say ± 1 nsec) can now be readily achieved. However for longitudinal waves there is also a need for accurate path length (even an error of 1 part in 10^4 in the length results in a stress uncertainty of 10 MPa) and temperature measurements; changes in temperature must also be minimised to reduce its effect on path length (since the coefficient of linear expansion of aluminium is approximately $2 \times 10^{-5}/^{\circ}\text{C}$) and more directly because of the high temperature coefficient of sound velocity ($\sim 1.5 \times 10^{-4}/^{\circ}\text{C}$). One of the advantages of measuring acoustic birefringence is that the above problems are largely eliminated since the differential measure $\Delta V_s/V_s$ incorporates self-cancellation of the effects of changes of length and temperature.

On the other hand longitudinal waves may be launched into a metallic specimen through a simple fluid coupling, water⁴⁵ or ethylene glycol⁴⁶ being commonly used. Shear wave coupling requires the medium of a viscoelastic fluid although cementing the transducer to the surface would be preferred. Some authors have successfully employed dry coupling using interface pressure to achieve a reasonable level of shear energy transmission²⁸. The problem of shear wave coupling is accentuated for techniques which require measurements of the polarised components at two perpendicular orientations of the transducer. The difficulties of maintaining constant bond conditions while rotating a narrow bandwidth transducer have been highlighted by a number of workers^{31,34}, although others have either reported no problems or perhaps failed to verify their absence. Rudd¹² considers the area of transducer/specimen coupling to be one of the four major problem areas limiting the practical application of ultrasonic shear wave measurements of residual stress. Since the bond properties may also be frequency dependent, additional complications are introduced when measurements are carried out at a number of frequencies either with separate transducers or with a single broadband transducer. Some workers have overcome the variability of bond properties by keeping the transducer fixed during measurements, while others have overcome the bonding problem by changing from piezoelectric transducers to electromagnetic acoustic transducers (EMAT's)^{32,47-49}. The pulse spectroscopy approach does not require rotation of the transducer, nor does the method introduced by Arora and James. However in this latter experiment, the high degree of specimen texture and therefore birefringence was advantageous as the well separated polarised components were amenable to Fourier transform processing²⁶.

Simple application of both the ring-around and the pulse superposition methods tend to measure an ill-defined group velocity in a dispersive or attenuative medium. Since the group velocity relates to the required phase velocity by the expression

$$C_g = C_p - \lambda \frac{dC_p}{d\lambda} \quad (9)$$

this would result in an error in the calculated stress values unless a correction is made. The pulse echo overlap method is capable of measuring group velocity, while the choice of the proper cyclic overlap permits accurate measurement of phase velocity⁵⁰. A theoretical study of the potential errors in phase velocity measurements by pulse methods in dispersive media has been made by Edwards⁵¹, while Papadakis⁵², and Sachse and Pao⁵³ have discussed procedures aimed at ensuring that these sources of uncertainty are minimised. A practical algorithm for the correction of spurious 2π errors arising in a Fourier transform technique for determining phase using short duration pulses has been outlined by Allen and Cooper³⁷.

The effect of diffraction in increasing the measured wave velocity compared to the plane wave value has long been recognised⁵⁴. Theoretical analyses confirmed by experimental measurements indicate that diffraction errors may be reduced by increasing the effective path length over which the waves are transmitted^{50,55,56}. The Harwell group⁴⁷ have given a clear illustration of the asymptotic nature of the time delay between successive pulses indicating the need to concentrate on the interval between higher order pulses if accurate results are to be obtained. Unfortunately this benefit may well be offset by the larger error which may then be expected as a consequence of the interference from mode converted pulses.

7. DISCUSSION

The early development of the theoretical basis of acoustoelasticity is credited to Hughes and Kelly¹⁷. The derived equations relating the velocity of elastic waves in terms of finite strains and the second and third order elastic constants, from which they found the stress dependent relationships by assuming the simple stress-strain formulae. The need to resolve the dependency of ultrasonic velocity on stress and on strain has been highlighted by McDonald⁵⁷ whose mathematical model suggested a dependence on both parameters. In the use of acoustoelasticity for the measurement of residual stress resulting from plastic deformation, the assumption has generally been made that the velocity is a function only of

assumption has generally been made that the velocity is a function only of stress. For a non-work-hardening material, this is equivalent to specifying that the ultrasonic velocity is constant during yielding and that the change in velocity during unloading follows the same relationship as during loading⁵⁸. This assumption has been tested by Okada³⁵ who concluded that for his 1100 aluminium specimen the ultrasonic birefringence was directly related to stress and not to strain. Johnson⁴⁶, using longitudinal waves, reached a similar conclusion for the alloy 2024-T351, but for two other aluminium alloys an additional strain dependence was also apparent. Further work, both theoretical⁵⁹ and experimental, on the effect of elastic-plastic deformation on ultrasonic wave velocity is clearly desirable.

Much of the work already discussed has been based on one dimensional velocity measurements on uniaxial stress fields. However the ultimate aim of ultrasonic stress measurements must be the development of 3D methods. The Stanford group has already shown their capability of using longitudinal velocity measurements to map the 2D stress fields in a number of situations^{45,60-63}; and by using a focussed acoustic beam and a differential phase contrast technique they have achieved stress field measurements in three dimensions⁶⁴. Extension of their work to mapping with shear waves is proceeding. A number of other groups have also been active in these areas³¹ or in exploring ultrasonic tomography as a tool for 3D stress measurements⁶⁵⁻⁶⁷. The complementary nature of longitudinal and shear waves for 2D mapping is noted.³¹ The former give information about the sum of the principal stresses for the plane stress state, while shear waves can provide detail of the differences in the principal stresses.

The ultrasonic measurement of applied stress is currently both feasible and practical. Extension of the technique to include residual stress measurement still must await a convincing algorithm for separating the competing effects of texture and stress. Although its implementation is still many years away, the prospect of 3D stress measurement by ultrasonic means continues to stimulate considerable research effort.

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