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Making Screws as Axial Load and Temperature Probes Using Integrated Ultrasonic Transducer

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Abstract— Sol-gel sprayed piezoelectric composite films have been made at the head of a screw as integrated ultrasonic transducer to propagate longitudinal and shear waves simultaneously along the axial direction of the screw up to 150°C. A discontinuity step is also made near the screw end for accurate velocity measurement. Such screws may be used for axial load and temperature measurements.

Keywords- Longitudinal and shear waves; integrated ultrasonic transducer; axial load measurement; temperature measurement and mode conversion

I. INTRODUCTION

Structural parts which are held together by screws (bolts, rivets or fasteners) under tensile stress must be designed and assembled so that these screws are sufficiently loaded to prevent the parts from separating while the structure is in service. Therefore a reliable measurement of the axial load or preload in such screws is essential to secure structural safety and a precise control of the fastening force is required. Several ultrasonic methods have been studied. The most promising ones are measuring the time delays of both longitudinal (L) and shear (S) wave along the screw direction [1-3]. In the most recent report [3] the use of L and S waves allowed the elimination of time-of-flight measurement of both waves in the unstressed state. Thus the tightening tension can be evaluated without loosening the assemblies bolted. All the previous works using conventional UTs which need ultrasonic couplants and cannot be easily operated at elevated temperatures.

Temperature measurements are also of importance to structures such as engines and material processing involving molten metal. The thermocouple may not be rugged enough when high temperature flames or corrosive molten metal present. It has been reported that ultrasonic waveguide with discontinuities can be used as temperature sensor [4, 5]. In such reports a multi-zone thin rod ultrasonic waveguide was presented in which the arrival time delays of ultrasonic echoes reflected from a series of discontinuities created along the waveguide were used to obtain the average temperature in each zone between the two adjacent discontinuities. The excitation method used magnetostrictive mechanism and the device was bulky. In [4, 5], the cross section dimensions of the waveguide were less than one ultrasonic wavelength. In this investigation,

a screw shape delay line will be used to measure temperature. Its diameter is more than several wavelengths and ultrasonic frequencies high than 10MHz are used. Near the end of the screw, one discontinuity will be created for accurate velocity and hence temperature measurements.

The novelty of this study is that miniaturized UTs made by a sol-gel spray technique [6, 7] will be integrated onto the screw head. On steel integrated UTs (IUTs) can operate up to 500°C [6]. Here IUTs which operate at temperature up to 150°C will be presented.

II. TRANSDUCER FABRICATION AND CHARACTERIZATION

In this investigation, a screw made of mild steel shown in Fig.1 is used. This screw has a length of 76.2mm and its diameter including the thread is 15.9mm. In Fig.2 an IUT was directly fabricated onto the head of the screw by the sol-gel sprayed method [6, 7]. The fabrication consists of six main steps: (1) preparing lead-zirconate-titanate (PZT) solution, (2) ball milling of piezoelectric PZT powders to submicron size, (3) piezoelectric film spraying using slurries from steps (1) and (2) to produce a layer of PZT composite (PZT-c) ceramic film, (4) heat treatment to produce a solid PZT-c film, (5) corona poling to obtain piezoelectricity, and (6) electrode painting. Steps (3) and (4) are used multiple times to produce proper PZT-c film (IUT) thickness for optimal ultrasonic operating frequencies. Silver paste was used to fabricate the top electrode which defines the IUT size. In Fig.2 the IUT has a width of 7mm and a height of 4mm. The PZT-c film thickness is 75 μ m. Typically, for such PZT-c film the measured d_{33} is about 30×10^{-12} m/V, the electromechanical coupling constant K_t about 0.2, the relative dielectric constant 320, the density 4400kg/m³ and the L wave velocity about 2200m/s.

III. IUT TO GENERATE AND RECEIVE L AND S WAVES IN A SCREW

The thick PZT-c film IUT shown in Fig.2 serves as an L wave IUT. In order to propagate L wave along the axial direction of the screw back and forth a 45° reflection interface between steel and air was used as shown in Fig.3. The calculated energy reflection coefficients at the mild steel/air interface provides that the energy reflected from the incident L

wave to the reflected L wave is 16.2% at $\theta = 45^\circ$. It is also reported [7, 8] that the shear (S) waves can be generated and received via the reflection at the steel-air interface. It means that the L wave IUT together with L-S mode conversion caused by the reflection at a steel-air interface can be effectively used as an S wave probe. The steel screw shown in Fig.1 has an L wave velocity of $V_L = 5914\text{m/s}$ and an S wave velocity of $V_S = 3221\text{m/s}$ measured at room temperature. The calculated energy reflection coefficients at the mild steel/air interface provides that the maximum energy conversion rate from the incident L wave to the mode converted S wave is 97.9% at $\theta_{\max} = 67.4^\circ$. Fig.3 also shows a schematic diagram of the special design of a screw in which a mode conversion angle $\theta = 61.4^\circ (\neq \theta_{\max})$ is chosen so that the mode converted S wave will propagate back and forth along the axial direction. Fortunately in this screw when $\theta = 61.4^\circ$, the energy conversion rate is 97.2% which is less than 1% than 97.7% at $\theta = \theta_{\max} = 67.4^\circ$.

Figure 1. A screw made of mild steel for the propagation of both L and S waves.

Figure 2. Zoomed picture of the head of the screw shown in Fig. 1. The IUT has a height of 4mm and a width of 7mm. PZT-c film thickness is $75\mu\text{m}$.

Figure 3. A schematic design of the 45° steel-air interface for the L wave reflection and $\theta = 61.4^\circ$ mode conversion angle so that both L and S waves can propagate back and forth along the axial screw direction using the L IUT deposited at the edge of the screw head.

Fig. 4a shows the measured ultrasonic signals of the screw shown in Fig.1 at room temperature in time domain. The center frequencies and 6dB bandwidth of the L and S waves are 17.0MHz and 13.8MHz and 16.6MHz and 20.6MHz, respectively. L^n and S^n are the nth round trip L and S echoes, respectively, from IUT to the end of the screw. The signals to noise ratios (SNRs) of the L^1 and S^1 waves are above 20dB without any signal processing. The signal appeared at time delay near $41\mu\text{s}$ is a noise which is speculated to be caused by ultrasonic signal traveling one screw length in S wave and another screw length in L wave because of the imperfect mode conversion angle θ machined for the experiment, and limited numerical resolution for this θ used in the calculation. The numerically simulated result in time domain using commercial available software package (Wave3000 Pro, CyberLogic Inc., New York, NY) based on a finite difference method which solves the 3D visco-elastic wave equations is given in Fig.4b. Comparing Figs.4a and 4b a good agreement between the experimental obtained and numerically calculated signals in signal bandwidth and time delay has been achieved. A slight difference in amplitude and time delays between the experimentally obtained and numerically calculated results comes from the texture of the actual screw which is not considered in the theoretical simulation. It is noted that the position and size of the IUT shown in Figs.2 and 3 can be adjusted so that the amplitude ratio between L^1 and S^1 may be varied. For example in Fig.3 if the IUT moves to a lower position, then the amplitude of L^1 will increase and that of S^1 will decrease. The measured ultrasonic signals of the screw shown in Fig.1 at 150°C are presented in Fig.5. The center frequencies and 6dB bandwidth of the L and S waves are 15.0MHz and 14.2MHz and 13.8MHz and 8.5MHz, respectively. The SNRs of the L^1 and S^1 waves are above 12dB without any signal processing. The variation of the amplitudes of L^1 and S^1 from room temperature to 150°C is due to the different ultrasonic attenuation in the screw, and reflection and mode conversion at the steel/air interface. The measurement results shown in Figs.4a and 5 demonstrate that this screw can function well up to 150°C to measure the time delay of L and S wave propagating along the axial direction of the screw simultaneous.

Figure 4. (a) Measured and (b) numerically calculated ultrasonic signals in time domain at room temperature in the probe as shown in Fig.1.

Figure 5. Measured ultrasonic signals in time domain at 150°C in the probe as shown in Fig.1.

IV. AXIAL LOAD MEASUREMENT TECHNIQUE

In [3] the value of axial load, F , can be calculated from the following first order approximated relationship

$$\frac{t_{dS}^{\sigma}}{t_{dL}^{\sigma}} \cong \frac{V_L^0}{V_S^0} \left[1 - \frac{L_e}{L_i} (A_S - A_L) \frac{F}{S_e} \right] \quad (1)$$

where t_{dL}^{σ} and t_{dS}^{σ} are the time of flight of the L and S waves, respectively, in the screw in the stressed state; V_L^0 and V_S^0 L and S waves velocities, respectively of the screw in the unstressed state; $L_i = L_0 + L_e$ and L_e the effective length and L_0 the unstressed portion of the screw; A_L and A_S the longitudinal and transverse acoustoelastic coefficients, respectively; and S_e the effective cross-sectional area of the screw. The capability to measure both the time delay of L and S waves in the screw allows the elimination of time-of-flight measurement of both waves in the unstressed state. Therefore the tightening tension can be evaluated without loosening the assemblies bolted with this screw and the measurement of the axial load [3] can be made on-line. In addition to the necessity to determine the parameters S_e , L_i , L_e , A_L , A_S , V_L^0 and V_S^0 before the on-line determination of axial load, high accuracy in time delay measurement is critically required. The high center frequency, large bandwidth and high SNR of IUT integrated onto the screw will enable the high precision time delay measurement for both L and S waves [9].

In addition, this probe can be used to measure L and S waves of solid specimens via a proper ultrasonic couplant so that the Young's modulus, bulk modulus and Poisson ratio of the specimen may be measured at the same time, location and elevated temperatures.

V. TEMPERATURE MEASUREMENT TECHNIQUE

In order to demonstrate that the screw shown in Fig.1 can be made for the temperature measurements, one step, D1, has been made near its end as shown in Fig.6. The length of this step is designed so that the reflected echoes from this discontinuity and the screw end can be well separated in time domain. Such step also permits the determination of V_L and V_S of the screw. The diameter of this step is also designed so that the echoes, L^{D1} , and/or S^{D1} reflected from the step D1 is strong enough but the echoes L^1 and S^1 can be still strong enough for the measurement of axial load. Fig.7 shows that measured

signal of the screw design shown in Fig.6 at 150°C. One can see that the echoes, L^{D1} and L^1 , S^{D1} and S^1 are clearly observed and separated. Since the ultrasonic velocity (time delay) in the screw section between D1 and the screw end is a function of temperature which can be measured in an off-line calibration setup, the average temperature of the screw in this section can be obtained on-line and real-time using the time delay difference between the echoes L^1 and L^{D1} or between S^1 and S^{D1} [4, 5]. The thermal expansion coefficients of the screw material must be included for the temperature measurements. It is noted that the IUT in Fig.1 can function up to 150°C but the screw end location near the step can be at higher or much higher temperatures depending on the screw length and heating region. Using the step size, 1.72mm, between D1 and the screw end and the time delay differences between L^{D1} and L^1 and S^{D1} and S^1 , the L and S velocities of the screw in this step region at room temperature and 150°C are 5911m/s and 3107m/s, 5858m/s and 3030m/s, respectively.

Figure 6. One step, D1, made near the end of the screw shown in Fig.1 for temperature measurement illustration.

Figure 7. Measured ultrasonic signals in time domain at 150°C in the probe as shown in Fig. 6. L^{D1} and L^1 , and S^{D1} and S^1 are the reflected L and S wave echoes, respectively, from the discontinuity D1 and screw end.

VI. CONCLUSION

Miniature IUT has been directly deposited onto a mild steel screw head. L and S waves were able to propagate simultaneously along the axial direction of the screw using a 45° reflection and 61.4° mode conversion angles, respectively. This IUT can work up to 150°C. Due to more than 12dB SNRs for both L and S wave echoes it is expected that the axial load of the this screw can be measured on-line using the time delays of these two waves. Such screw probe can be also used to measure L and S waves of solid specimens via a proper ultrasonic couplant so that the Young's modulus, bulk modulus and Poisson ratio of the specimen may be measured at the same time, location and elevated temperatures. One discontinuity was made near the end of the screw and the clear separated L

and S echoes reflected from this discontinuity and screw end can be used for the on-line average temperature measurements providing that an off-line calibration of the velocity versus temperature of the screw has been made.

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