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Research Article

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Development of evaluation method of residual stress measurement for gear tooth root based on ultrasonic actuation by piezoelectric wafer

Qinxue Pan[1,2*], Xin Jin[1], Dingguo Xiao[1,2] and Shuai Liu[1]

[1]School of Mechanical Engineering, Beijing Institute of Technology, China
[2]Key Laboratory of Fundamental Science for National Defence for Advanced Machining Technology, China

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ABSTRACT

Gears are widely used as machine transmission parts to transfer power and change the speed and direction of rotation. The main failure modes of the gear are broken teeth and tooth surface wear, caused mainly by large residual stress. Traditional inspection methods, such as X-rays, cannot measure tooth root residual stress accurately due to the special structure of the tooth root. In this paper, an ultrasonic method involving the longitudinally critically refracted (L_{CR}) wave was used to measure the gear tooth root residual stress. The special sensor was actuated by a piezoelectric wafer. An examination of the transmission principle of ultrasonic waves in the gear revealed that measurements of the residual stress of the gear's tooth root using L_{CR} waves were feasible.

Keywords: Gear tooth root; piezoelectric wafer; residual stress; ultrasonic

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INTRODUCTION

Gears are widely used in machine transmission parts to transfer power and change the speed and direction of rotation[1]. The measurement of the gear tooth root is critical due to the potential for tooth fracture from large residual stress.

Residual stress is an inherent stress that tends to maintain an internal balance in the component in the absence of external influences. During fabrication, residual stress is created in the gear by forging, turning, carburizing and quenching, and grinding [2–3]. The residual stress can lead to serious outcomes, including broken teeth, tooth surface wear, tooth surface erosion, and the formation of tooth surface glue. However, the service life of a gear can be enhanced when compressive stress exists in the gear. As a result, it is very important to improve the state of residual stress in the gear by exploring effective methods for testing residual stress.

To successfully control and make use of residual stress, a method for accurate detection and assessment is required. Rossini et al.[4] provide a detailed summary of testing methods for residual stress in mechanical components. The pipe weld stress are simulated by Jun Liu et al.[5]. Shu Jie Liu predicted life due to residual stress under condition monitoring[6].

Ultrasonic stress detection possesses high spatial resolution and penetration. This approach can be used to determine the residual stress value and state of tension and compression in the component's surface and sub-surface. Additionally, ultrasonic detection is safe for the operators and parts being tested, and is easily adaptable to detection in more complex environments. Thus, ultrasonic detection is expected to provide a more effective, efficient means to detect residual stress in components.

Ultrasonic stress testing is based on the linear relationship between the ultrasonic wave velocity and stress. Within the elastic limit of the materials, the relationship can be expressed in terms of the acoustoelastic effect[7–8]. In this study, acoustoelastic theory was examined to develop a test method based on the relationship of the velocity and the direction of ultrasonic propagation with stress in a component using the critically refracted longitudinal wave (L_{CR} wave). Based on our analysis, an ultrasonic residual stress testing system was constructed and calibrated for evaluation of the residual stress in the gear tooth root.

Theoretical background

Acoustoelastic theory

Acoustoelastic theory is based on finite mechanical deformation of a continuous medium. It has been studied in terms of the stress state of elastic solids and the velocity of the elastic wave in the solid at some macro-angle. Theoretical analysis has shown that the velocity of the elastic wave depends on the material density, second-order elastic constant, third-order elastic constant, and the initial stress state in the solid. When the longitudinal wave propagates along the stress direction, the relationship between the wave velocity and stress is given as follows[9–10]:

$$\rho_0 V^2 = \lambda + 2\mu + \frac{\sigma}{3\lambda+2\mu}\left[\frac{\lambda+\mu}{\mu}(4\lambda + 10\mu + 4m) + \lambda + 2l\right] \tag{1}$$

where V is the longitudinal wave propagation velocity of the stress, ρ_0 is the density of the material, λ and μ represent the second-order elastic constants in the material, l and m are the third-order elasticity coefficients, and σ is the stress value. Positive values indicate tensile stress, whereas negative values denote compressive stress.

If the derivative of both sides of Eq. (1) is obtained, then the relationship between the variation in the ultrasonic velocity and the variation in the stress can be written as follows[11]:

$$d\sigma = -\frac{2}{kt_0}dt \tag{2}$$

where $d\sigma$ is the residual stress change, dt is the acoustic time difference, k is acoustic elasticity coefficient, t_0 is acoustic time of zero stress, $K = -2/kt_0$, with K denoting the stress constant.

Equation (2) describes the measurement method used in this study to determine the relative residual stress values. Variations in the acoustic wave facilitate determination of the relative residual stress, providing the key measurement principle of gear residual stress.

2.2 Basic principle of L_{CR}

Within the elastic limit, ultrasonic stress evaluation relies on the linear relationship between the stress and the velocity or travel time change. The critically refracted longitudinal wave (or L_{CR} wave) is a longitudinal ultrasonic wave that is used to measure the residual stress. The L_{CR} wave can spread tens of centimeters in a medium and retain a good waveform. Figure 1 shows the L_{CR} wave, which propagates parallel to the surface at a shallow depth. The depth depends on the frequency of the ultrasonic transducer.

According to Snell’s law, the ultrasonic longitudinal wave experiences refraction as it propagates from a medium having a lower wave velocity (slower medium) to a faster medium (*e.g.*, from organic glass to steel). If the longitudinal wave refraction angle is 90°, then the longitudinally refracted wave will spread along the surface of the second medium; this describes the L_{CR} wave. The incident angle is called the first critical angle. The calculation formula is given below:

$$\theta_{cr} = sin^{-1}(V_1/V_2) \tag{3}$$

where V_1 is the ultrasonic longitudinal wave propagation velocity of the slower medium (m/s^{-1}), V_2 is the ultrasonic longitudinal wave propagation velocity of the faster medium (m/s^{-1}), θ_{cr} and is the first critical angle (°) in which the L_{CR} wave angle $\theta_L = 90^o$.

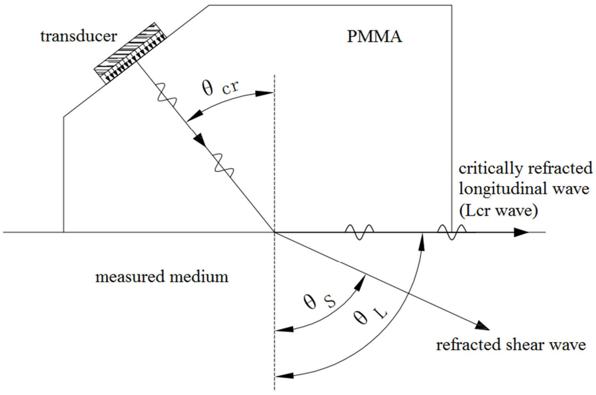

FIGURE 1. Generation principle of L_{CR}

EXPERIMENTAL SECTION

3.1 Sensor design

In this study, the gear tooth root was measured using the method of chips on a wedge. According to the nature of the involute gear and Snell’s theorem, the angle of the wedge was calculated with respect to limiting wafer movement. The frequency of the wafer was 5 MHz, and the length and width of the wafer were 10 and 5 mm, respectively. The wedge was separated in the middle to eliminate interference. Using the ultrasonic pulse echo method (figure 2), we obtained the acoustic velocity of the organic glass and gear, as described by Eqs. (4) and (5), respectively. The first critical angle is given by Eq. (6), from Eq. (3). The sensor design is shown in figure 3.

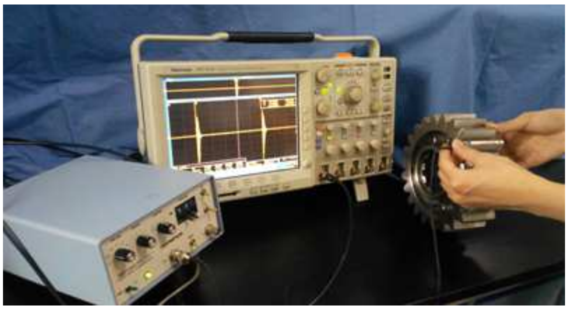

FIGURE 2. Acoustic velocity measurement

FIGURE 3. Fabricated sensor

$$V_{\omega edg\varepsilon} = 20 \times 2/15.06 = 2656\,m/s \qquad (4)$$

$$V_{gear} = 60.4 \times 2/20.558 = 5876\,m/s \qquad (5)$$

$$\theta_{cR} = \arcsin(2656/5876) = 26.87^{o} \qquad (6)$$

3.2 L_{CR} transmission mechanism in the gear tooth root

To verify the feasibility of residual stress ultrasonic measurement of the tooth root, we used a similar procedure to test the root of a sample specimen (figure 4). To validate the propagation rule of ultrasonic waves near the root, two specimen thicknesses were used, 37 and 17 mm. In the position of different or transitional thickness, the ultrasonic transmission time was the same as when the distance of the two sensors was constant. The resulting waveform (received) is shown in figure 5. The transmission mechanism of L_{CR} near the root is shown in figure 6.

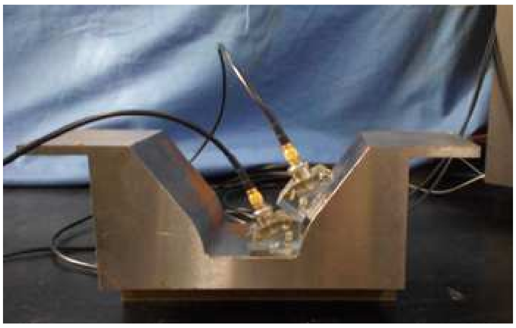

FIGURE 4. Ultrasonic transmission validation

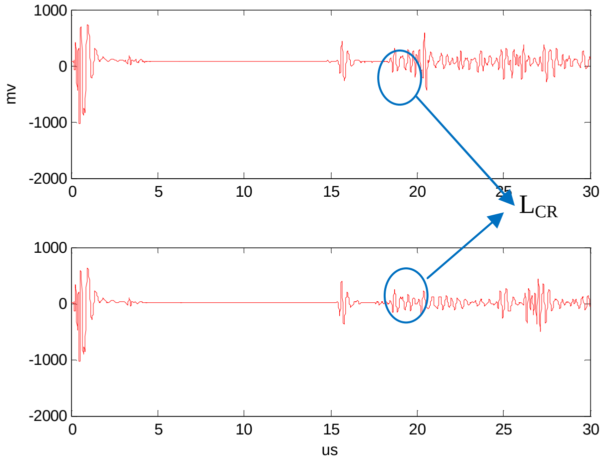

FIGURE 5. Time required for LCR to be received in the two different thicknesses of the specimen

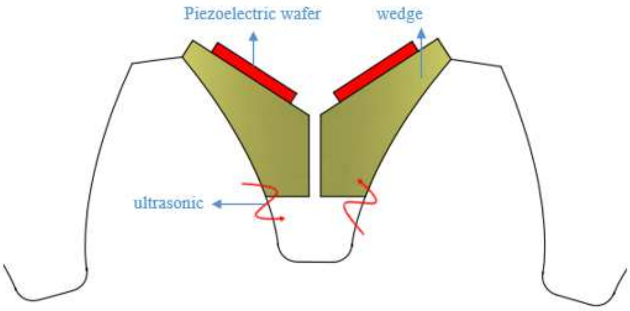

FIGURE 6. Ultrasonic propagation path near the root

3.3 Measurement system

The measurement set-up (shown in figure 7) consisted of a computer and two ultrasonic transducers with piezoelectric wafers. The computer set-up includes a data acquisition card and an ultrasonic sending and receiving card. Different frequencies were used to evaluate the residual stresses throughout the gear thickness. The piezoelectric wafer (length: 10 mm; width: 5 mm) was assembled on a united poly(methylmethacrylate) (PMMA) wedge. The data acquisition card consisted of a 100 MHz ultrasonic testing device with pulsar signal–internal clock synchronization capabilities to control an analog-to-digital (A/D) converter, which controls the A/D converter.

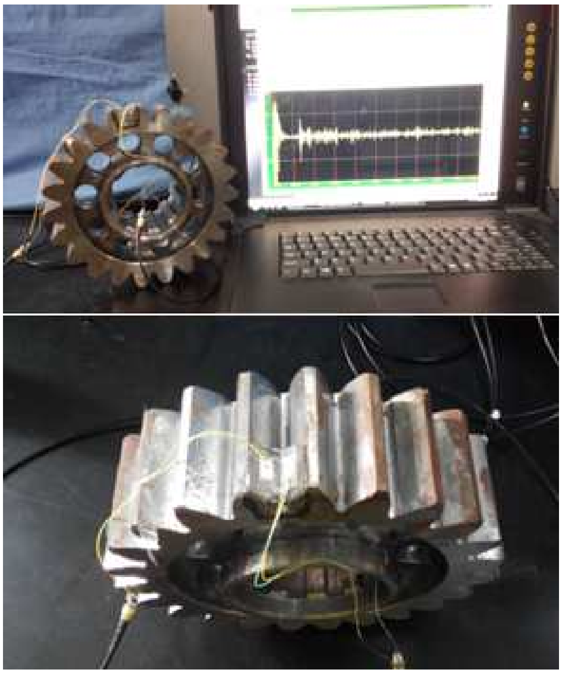

FIGURE 7. Measuremental setup

3.4 Gear tooth root residual stress measurement method validation

To verify the accuracy of the ultrasonic measurement of the tooth root residual stress, we machined specimens having the same gear shape. The relationship between stress load and acoustic time are shown in figure 9.

FIGURE 8. Gear-tooth tensile experiment

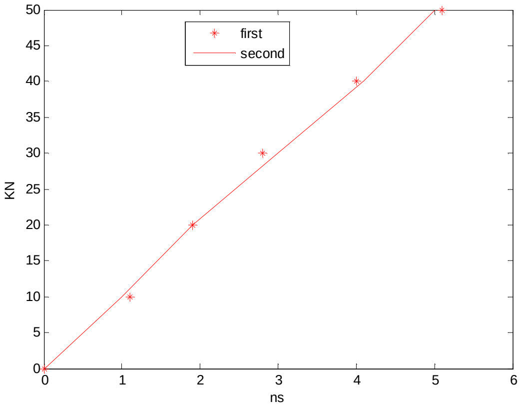

FIGURE 9. The relationship between stress load and acoustic time

3.5 Evaluation of the stress constant between the two sensors

We prepared a tension specimen to evaluate the stress constant. The tension sample material was the same as the material used for the measured gear. The tensile stress cannot exceed the material yield strength. The distance from the ultrasonic transducer was approximately 30 mm. To evaluate the residual stress from Eq. (2), the value t_0 was measured directly from the stress-free sample, and the stress constant was deduced experimentally from a uniaxial tension and compression test associated with the ultrasonic measurement, as shown in figure 7. The stress can be calculated according to Eq. (9) under different tensile stress. The load on the specimen ranged from 0 to 300 MPa, using 30-MPa step increments. The experiment was repeated twice. The stress constant was obtained from the slope of the relative variation curve using time-of-flight measurements and the applied stress values (as shown in figure 12). For the tensile specimen, K_0 was 10.68 MPa ns^{-1}, and t_0 was 14.32 μs (as shown in figure 11). Equation (2) was used to obtain $k = 1.2775 \times 10^{-5} MPa^{-1}$. The ultrasonic propagation time in the gear was t_1 = 12.51 (as shown in figure 13). The stress constant in the gear is given by

$$\sigma = F/S \tag{9}$$

where F is the stress, and S is the cross-sectional area.

$$K_1 = \frac{2}{kt_1} = 12.52\, MPa/ns \tag{10}$$

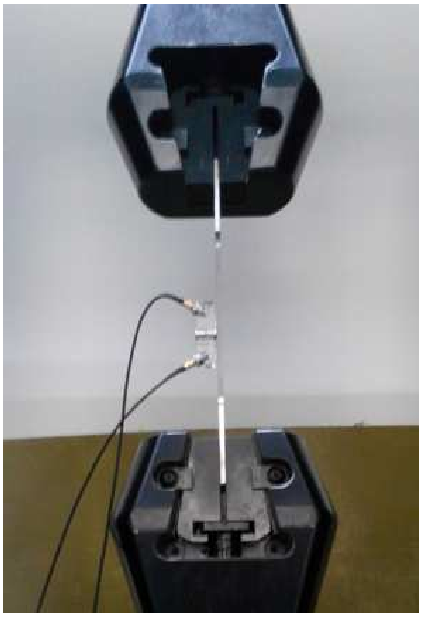

FIGURE 10. Tension test to evaluate the stress constant

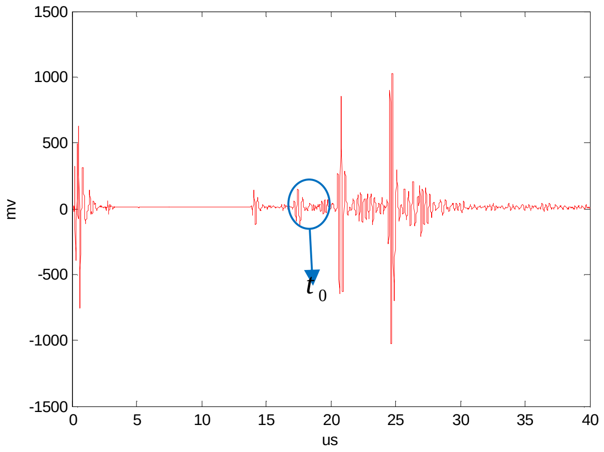

FIGURE 11. Time of flight under stress-free conditions in the flat

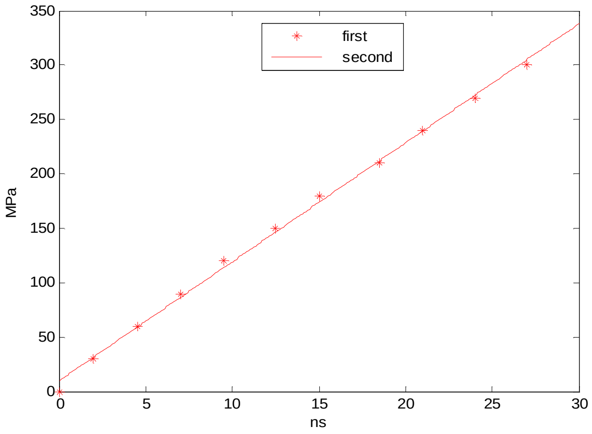

FIGURE 12. Result of tension test

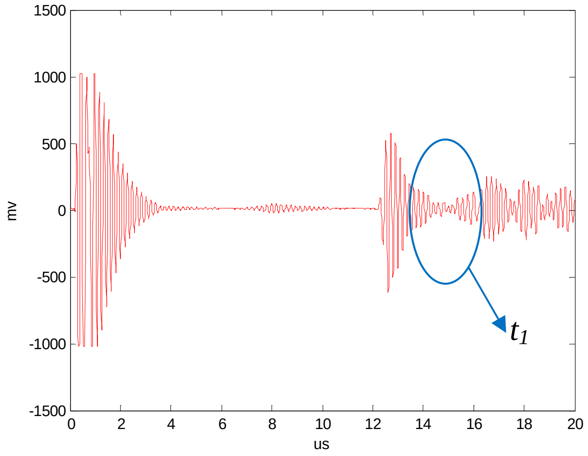

FIGURE 13. Time of flight under stress-free conditions in the gear

RESULTS

In this study, we evaluated the residual stresses in the gear tooth root using an ultrasonic measurement method. The residual stress was calculated using Eq. (2). The gear tooth root was divided into six equal sections in the axial direction. Each regional stress value was measured twice. The results are shown in figure 14. The measurement results of 23 teeth are shown in figure 15.

Repeated measurements were performed in the same location. Figure 15 shows that the measurement results were consistent among the 23 teeth tested. Thus, our results indicated that the ultrasonic method for gear tooth root residual stress was viable. We chose six measurement points on the same tooth. The results indicated that the stress was different in the same tooth, with both tensile stress and compressive stress evident in the measurements.

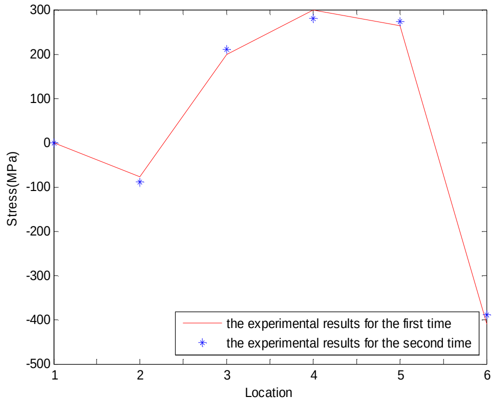

FIGURE 14. Axial direction of the gear stress distribution in the tooth root

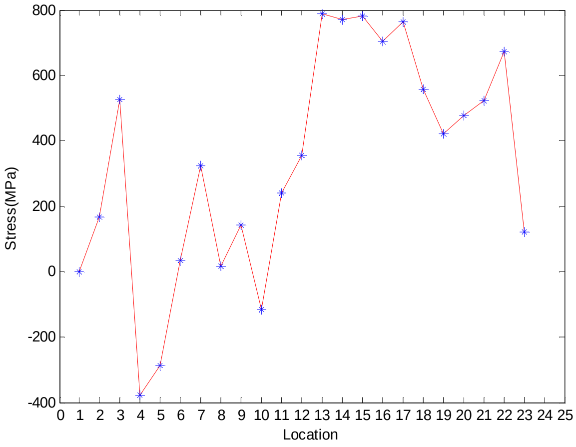

FIGURE 15. Teeth root stress distribution in 23 tooth gear

CONCLUSION

This study verified that the ultrasonic method can be used to measure the residual stress in a gear tooth root. The transmission path of a L_{CR} wave can be obtained between the teeth using the method described. The stress constant in the gear was obtained numerically. Our results are summarized below.
1) The L_{CR} wave propagated near the gear tooth root.
2) The L_{CR} wave was capable of measuring complex curved surface residual stress, such as that associated with gears.
3) Ultrasonic stress testing is a reliable method for stress indication.
4) The stress constant in the gear was obtained from numerical calculations.
5) The residual stress and the sound change in the gear exhibited a linear relationship.
6) The gear stress distribution was nonuniform without heat treatment.

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