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LASER-GENERATED SURFACE SKIMMING LONGITUDINAL WAVE MEASUREMENT OF RESIDUAL STRESS IN SHOT PEENED SAMPLES

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Abstract. Shot peening is a surface enhancement technique that produces a compressive residual stress in a thin surface layer to extend the fatigue life and prevent stress corrosion cracking of structural components. A laser-ultrasonic non-contact technique is used for determining residual stresses produced by shot peening. The method is essentially based on the acoustoelastic effect of the laser-generated surface skimming longitudinal wave (LSSLW) propagating just below the surface. The LSSLW is found to be more sensitive to residual stress than the Rayleigh surface acoustic wave. When used in combination with the Rayleigh surface wave, this laser ultrasonic technique is shown to be quite effective and provides results in good agreement with x-ray data. Contributing factors such as surface roughness, crystallographic texture and dislocations have been examined and corrections for a satisfactory assessment of residual stress are proposed.

INTRODUCTION

Surface enhancement processes, such as shot peening, laser shock peening and low plasticity burnishing among others, are used to produce a compressive residual stress below surface structural components to extend their fatigue life and prevent stress corrosion cracking. There is currently a need for a non-destructive technique to measure the residual stress below the surface, beyond the range reached by conventional x-ray diffraction (typically 10-20 μm) for controlling this surface enhancement processes. Such a technique could also be very useful for monitoring stress release effects that can occur during service.

Ultrasonics is one promising nondestructive technique for such a measurement among neutron diffraction, Barkhausen noise and eddy current. Many studies based on the acoustoelastic effect of Rayleigh surface waves (SAW) have been presented in the literature to monitor residual stresses, but with limited success. In a recent work, a laser-ultrasonic technique was described for determining residual stresses in metals based on the acoustoelastic effect of the laser-generated surface skimming longitudinal wave (LSSLW)

also called P-wave [1]. The validity of the approach was demonstrated by measuring quantitatively the near surface stress in a four-point bending experiment and in laser shock peened samples. In this paper, this laser-ultrasonic technique is applied to the determination of the residual stress produced by shot peening. The surface roughness, the crystallographic texture and the dislocations induced by the shot peening process are shown to affect the residual stress measurement. Their effects on LSSLW and SAW velocity variations as function of angle are pointed out and corrections using both velocity measurements are proposed. The results are compared to X-ray measurements.

LASER-ULTRASONIC EXPERIMENT

The laser-ultrasonic set-up is presented in Fig. 1. A pulsed Nd:YAG laser (3rd harmonic: 355 nm wavelength, 35 ps pulse duration) is employed to generate both the LSSLW and the SAW at the same time in the ablation regime. An UV radiation with very short pulse duration is chosen to get good generation efficiency without damaging the sample surface. For the detection, a long pulsed Nd:YAG laser (1064 nm wavelength, 50 μ s pulse duration) is coupled to a photorefractive interferometer by optical fibers.

A line-source and line-detection configuration was chosen to minimize wave spreading as well as microstructure noise since line detection is similar to spatial averaging. The line dimensions are about 10 mm long per 20 μ m wide for both the generation and detection. With this configuration, ultrasonic waves with a 150 MHz bandwidth can be generated and detected in low attenuating materials. A scanning system with a mirror and a translation table controls the source to receiver distance. The sample is mounted on a translation table and a rotating table to perform spatial averaging and measurements in different propagation directions.

In Fig. 2, a typical laser-ultrasonic waveform is shown for an aluminum plate. In this waveform, the discontinuities associated with the LSSLW, the SAW and the longitudinal wave (L-wave) that has propagated through the sample thickness are indicated.

FIGURE 1. The laser-ultrasonic experimental set-up.

FIGURE 2. Typical laser-ultrasonic waveform.

For precise velocity variation measurement, cross-correlation of the discontinuity associated to the LSSLW or SAW arrival is performed with a reference signal obtained on an unstressed sample. The resulting time-of-flight variation is related to the velocity variation by the simple formula $\Delta t/t = -\Delta V/V$, assuming no source-to-receiver distance variation [1]. Moreover, the velocity dispersion is obtained by calculating the phase of the Fourier transform of the cross-correlation result and employing the simple relation $\Delta\phi(f) = 2\pi f \Delta t(f)$ where f is the frequency and ϕ is the phase. In particular, since the penetration depth of SAW (and presumably LSSLW) depends on its wavelength, the stress distribution could then be measured by evaluating velocity dispersion.

Validation of the technique with a four-point bending experiment was conducted in a recent work [1] and LSSLW and SAW velocity variations for an aluminum sample are shown in Fig. 3. It is noticeable that the LSSLW is more sensible to stress magnitude than the SAW. One reason for this behavior is that the SAW is a coupled mode of longitudinal and shear waves so, it presents a lower sensitivity to stress parallel to the surface. Also, very promising results on laser shock peened samples were obtained [1]. A positive LSSLW velocity variation, well indicative and compatible in magnitude with a compressive residual stress beneath the surface was found. For the SAW, no sensitivity to residual stress was observed, mostly due to the surface roughness induced by the laser shock peening process.

RESIDUAL STRESS ON SHOT PEENED SAMPLES

Laser-ultrasonic measurements have been conducted on shot peened aluminum samples prepared using different Almen intensities. In the shot-peening process, the surface is hammered with small ceramic beads. The ceramic beads plastically deform the surface, which is then held in compression by the un-deformed material underneath. In Fig. 4, the residual stress depth profiles measured with X-ray diffraction on these samples are shown. It is noticed that larger Almen intensities induce a similar maximum stress value of about 300 MPa, but the extent of stress is deeper, down to 250 μm in the material.

FIGURE 3. Four points bending test results on aluminum a) LSSLW and b) SAW.

FIGURE 4. Residual stress depth profiles measured with X-ray diffraction.

The velocity variations measured at 10 MHz from dispersion measurement are shown in Fig. 5a. In the following, the reference signal is obtained with the Almen 0 sample. For the SAW, the velocity decreases with Almen intensity and for the LSSLW, the velocity only slightly decreases. Obviously, with the shot peening process, the compressive stress parallel to the surface at shallow depths should produce a velocity increase. Therefore, the observed velocity behavior is due to a combination of factors induced by the shot peening process, including stress (acoustoelastic effect), surface roughness, and cold work (crystallographic texture and dislocation density). To monitor residual stress from such velocity changes, the contributions from other effects must be analyzed and corrected.

FIGURE 5. Velocity variations for LSSLW and SAW measured on a) as received shot peened samples and b) polished shot peened samples.

FIGURE 6. Dispersion of a) SAW and b) LSSLW velocity variations for different roughnesses.

FIGURE 7. LSSLW velocity variations at 10 MHz as function of source-to-receiver distances for different roughnesses.

Surface roughness. In Fig. 5b, the velocity variations at 10 MHz for the LSSLW and the SAW on polished shot peened samples are shown. Without surface roughness effect on velocity, the LSSLW velocity increases with Almen intensity while the SAW velocity still decreases. The effect of surface roughness has been studied on aluminum plates with different roughnesses performed by electro-erosion varying the electric power. In this manner, no additional cold work was induced on the test samples. Fig. 6a shows the results for SAW dispersion. In addition to the expected velocity decrease with frequency, an increase at higher frequencies is observed. This behavior, observed experimentally in this study, has been reported in theoretical work and would be associated to a transition regime [2]. Fig. 6b shows the results for LSSLW dispersion induced by the surface roughness. Its behavior is complex but also presents a minimum. In Fig. 7, the LSSLW velocity variations at 10 MHz are shown as function of the source-to-receiver distance for different surface roughnesses. A similar analysis has been performed for SAW and no such behavior is observed, as expected. The LSSLW appears to be less affected by surface roughness with large source-to-receiver distance. Therefore, the results indicate that the LSSLW would probe different depths according to frequency and source-to-receiver distance and is compatible with a leaky wave propagating within a layer below the surface at a certain depth. However, no definite theoretical description of the LSSLW exists at present (see discussion and references in [1]). Such a model would be useful to validate these measurements and to clearly establish the interaction of the LSSLW with sub-surface material property gradients.

For this application, surface roughness correction could be performed by measuring roughness parameters with an optical technique and evaluating their contributions to velocity variation with a model or calibration.

Crystallographic texture. The crystallographic re-orientation of crystallites due to surface cold work during the shot peening process also affects the ultrasonic velocities [3, 4]. For a rolled aluminum plate, the expressions that include the acoustoelastic and crystallographic re-orientation effects are:

$$(\Delta V/V)_{LSSLW}(\theta) = -43.510^{-6} \Delta \sigma_m - 0.215 \Delta W_{400} + 6.0210^{-5} \Delta \sigma_d \cos(2\theta) - 0.45 \Delta W_{420} \cos(2\theta) - 0.6 \Delta W_{440} \cos(4\theta) \quad (1)$$

$$(\Delta V/V)_{SAW}(\theta) = -4.410^{-6} \Delta \sigma_m + 0.57 \Delta W_{400} + 2.2610^{-5} \Delta \sigma_d \cos(2\theta) + 1.07 \Delta W_{420} \cos(2\theta) - 0.17 \Delta W_{440} \cos(4\theta) \quad (2)$$

where $\Delta\sigma_d = (\Delta\sigma(90) - \Delta\sigma(0))/2$ and $\Delta\sigma_m = (\Delta\sigma(0) + \Delta\sigma(90))/2$, σ is the stress (in MPa), W_{400} , W_{420} and W_{440} are the fourth order texture coefficients or orientation distribution coefficients (ODC) and θ refers to the azimuthal angle or the angle between the rolling direction and wave propagation direction on the surface. It is assumed that the behavior of LSSLW is similar to the bulk longitudinal wave and that the principal axes of stress correspond to those of materials properties (rolling and transverse directions). In these expressions, only variations of each parameter, noted by the prefix Δ , appear. In Fig. 8, the LSSLW and SAW velocity variations as function of azimuthal angle θ are shown for the different Almen intensities, as well as a comparison with the model. A very good agreement is obtained.

The crystallographic texture variation induced by the shot peening process can be isolated solving the system of Eqs. (1, 2). More importantly, measurements at a few angles allow determining residual stress using simple expressions. For both the LSSLW and SAW, the average of velocity variations at 0, 90, 45 and -45 deg., noted B^m , is related to the texture coefficient W_{400} and the mean stress $\Delta\sigma_m$. In addition, half the difference of velocity variations at 0 and 90 deg., noted B^d , is related to the texture coefficient W_{420} and the stress difference $\Delta\sigma_d$. The relations for aluminum are:

$$\begin{aligned} B_{LSSLW}^m &= -43.510^{-6} \Delta\sigma_m - 0.215 \Delta W_{400} \\ B_{SAW}^m &= -4.410^{-6} \Delta\sigma_m + 0.57 \Delta W_{400} \end{aligned} \quad (3)$$

$$\begin{aligned} B_{LSSLW}^d &= 6.0210^{-5} \Delta\sigma_d - 0.45 \Delta W_{420} \\ B_{SAW}^d &= 2.2610^{-5} \Delta\sigma_d + 1.07 \Delta W_{420} \end{aligned} \quad (4)$$

The residual stress is then obtained by measuring the LSSLW and SAW velocity changes and applying roughness correction, and by considering Eqs. (3, 4). The results are shown in Fig. 9a, where the stress difference, $\Delta\sigma_d$, is close to zero and the average stress, $\Delta\sigma_m$, is negative as expected. In shot peening, the stress distribution in the surface plane is isotropic and the stress on and below the surface is compressive.

FIGURE 8. Velocity variations as a function of azimuthal angle: measurements for a) SAW and b) LSSLW; calculation for c) SAW and d) LSSLW.

FIGURE 9. Residual stress assessment including roughness and texture corrections for $\Delta\sigma_m$ and $\Delta\sigma_d$ in a), and further including dislocation density correction for $\Delta\sigma_m$ in b).

Dislocations. An additional effect on velocity variations to be considered is the one produced by the dislocations of the cold work and hardening associated with shot peening. Dislocations are expected to cause a velocity decrease without angular dependence. This effect is difficult to evaluate but it has to be taken into account. For this purpose, we introduce two terms in Eqs. (3) as follows:

$$\begin{cases} B_{LSSLW}^m = -43.510^{-6} \Delta\sigma_m - 0.215 \Delta W_{400} - \alpha |B_{LSSLW}^m| \\ B_{SAW}^m = -4.410^{-6} \Delta\sigma_m + 0.57 \Delta W_{400} - \beta |B_{SAW}^m| \end{cases}, \quad (5)$$

where α and β are parameters to be determined. We have used for α and β the trial values of 0.5 and 0.2, respectively. Residual stress assessment with roughness, texture and dislocation density corrections obtained solving this system with such hypothesis is presented in Fig. 9b. With the additional dislocation density correction, the stress is found to be larger.

In Fig. 10, a summary of the different contributions to LSSLW and SAW velocity variations is presented. For LSSLW, the stress and roughness contributions dominate and the texture and dislocations have opposite contributions. For the SAW, roughness, texture and dislocations contributions dominate and are of opposite sign to the small stress contribution. As a result, the use of the SAW acoustoelastic effect alone for residual stress assessment in shot peened samples is not applicable. Nevertheless, SAW is useful to circumvent other factors when using the LSSLW acoustoelastic effect for this purpose.

FIGURE 10. Different contributions to velocity variation of a) LSSLW and b) SAW on shot peened samples.

FIGURE 11. Comparison of a) averaged X-ray and b) laser-ultrasonic residual stress measurements on shot peened samples.

In Fig. 11, a comparison of X-ray and laser-ultrasonic residual stress measurements on shot peened samples is presented. Each stress value for X-ray in Fig. 11a is calculated considering a weighting average of the stress depth profile of Fig. 4, with the LSSLW penetration depth at 10 MHz as weighting function. We observe a good semi-quantitative agreement between the laser-ultrasonic residual stress measurement and the X-ray averaged over an equivalent depth.

As an additional comment regarding the work previously reported on laser shock peened samples [1], it should be noted that the LSSLW velocity variations were measured in this case with a large source-to-receiver distance for which roughness effects are smaller. In doing so, the sensitivity to residual stress was excellent since in laser shock peening, cold work is also smaller and the stress extends deeper in the sample. For shot peened samples, since the stressed zone is not as deep, the sensitivity to stress would be however reduced by using a large source-to-receiver distance.

CONCLUSION

A laser-ultrasonic technique is proposed for measuring residual stress in shot peened materials using at the same time the laser-generated surface skimming longitudinal wave (LSSLW) and the surface acoustic wave (SAW). The method is based on monitoring the small ultrasonic velocity changes.

The benefits of using LSSLW were recently established with four point bending tests and on laser shock peened samples. For shot peened samples, the effects of additional factors associated with the process, i.e. surface roughness, crystallographic texture and dislocations, were examined and corrections for the assessment of residual stress were proposed. Despite the magnitude of these effects compared to the one produced by the residual stress, we were able to obtain a reasonable agreement with X-ray results.

In conclusion, the proposed technique based on the monitoring and combined use of LSSLW and SAW velocity variations appears quite promising for the measurement below the surface of the residual stress produced by surface enhancement processes like shot peening or laser shock peening and possibly of its depth profile.

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