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Determination of residual stresses using laser-generated surface skimming longitudinal waves

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ABSTRACT

A laser-ultrasonic technique is described to non-destructively determine residual stresses in metals such as those produced by shot peening. The method is based on monitoring the small ultrasonic velocity change of the laser-generated surface skimming longitudinal wave (LSSLW) propagating just below the surface. The main advantage of using LSSLW is that the effect of surface roughness induced by shot peening is greatly reduced compared to using surface acoustic waves (SAW). To improve resolution in the measurement of small velocity changes, a cross-correlation technique is used with a reference signal taken on the same but unstressed material in similar conditions. Also, the low-frequency SAW can be used to correct the LSSLW results when affected by minute changes in the path length during the measurements. The validity of the approach is demonstrated by measuring quantitatively the near surface stress in a four-point bending experiment with different levels of surface roughness. Then, scanning results on properly and improperly laser shock peened samples are reported. In particular, the LSSLW velocity variations for the properly peened samples clearly show an increase in the laser-peened area well indicative of a compressive stress.

Keywords: laser-ultrasonics, residual stress, surface skimming longitudinal wave, shot peening

1. INTRODUCTION

The measurement of residual stresses is important for quality control of various industrial processes, such as welding, shot peening and low-plasticity burnishing. This is because residual stresses directly affect the overall performance of structural components. For shot peening in particular, a compressive surface stress is induced using high speed small hard ball shots or intense laser short pulses to extend the fatigue life and prevent stress corrosion cracking. Such compressive stress parallel to the surface at shallow depths is accompanied by a reaction-induced tensile stress beneath this layer. Generally, the compressive stress at the surface should be several times greater than the subsurface tensile stress. There is a need to measure residual stress state non-destructively to verify the actual stress levels to ensure that the part is properly peened. Also, such measurement could be useful for inspection during service to check if the part has lost its protection via unpredictable stress release.

Ultrasonics is one promising nondestructive technique, among X-ray diffraction, neutron diffraction, Barkhausen noise and others, for such a measurement. One advantage of the ultrasonic method is that it is not limited to measurements in the few nm near the surface, not indicative of the internal stresses. Under certain conditions, ultrasound can provide stress information at different depths by varying the frequency content. The method is based on measuring the small velocity change of any ultrasonic wave which has polarization or at least a displacement component in the stress direction. Velocity variations of an ultrasonic wave can be related to the residual stress state through the linear relation[1]:

$$V_m^{st} = V_m^0 + K_m \sigma \tag{1}$$

where V_m^{st} is the m-mode ultrasonic velocity under stress, V_m^0 is the m-mode ultrasonic velocity without stress, K_m is the acoustoelastic coefficient for ultrasound propagation of the m-mode and σ is the stress.

Many studies have been reported based on the analysis of the velocity change of bulk waves and Rayleigh surface waves (SAW). Among methods tested, there are 1) a polarimetric approach with through thickness measurement of two orthogonally polarized S-waves, 2) the ultrasonic microscopy, so-called V(z) approach, using the SAW. As mentioned, any ultrasonic mode can be used as long as the wave produces a displacement in the stress direction. However, waves propagating along the surface are preferred since bulk waves would average all stresses throughout the thickness. Also, the penetration depth of SAW is well known and depends on its wavelength; therefore the stress distribution could be measured by evaluating velocity dispersion. Nevertheless, limited success was obtained to monitor the residual stress produced by shot peening with SAW[2-4]. In aluminum, it is found that peening induced roughness leads to erroneous SAW velocity variations attributable to stress since it produces an apparent decrease of the SAW velocity. In Waspaloy, the change on velocity is larger than the one predicted by the stress alone and the effect of dislocation density (cold work) is suggested as the main reason. In a case of steel, the change observed is larger than the one predicted by stress alone, and is of opposite sign. Indeed, the velocity decreases at higher frequencies whereas the stress is more compressive at the surface.

One reason for such a limited success is that the SAW is a coupled mode of longitudinal and shear waves with opposite velocity changes, the combination of which may present a low sensitivity to stress. Another reason is that SAW mainly travels on the surface with most of its energy propagating within one wavelength depth. SAW is therefore very sensitive to surface roughness and dislocation density, which are often associated with the process inducing stresses and can also affect the velocity. Recently, the critically refracted longitudinal wave propagating within a layer below the surface at a certain depth, was found more sensitive to the stress[5-7]. Such a wave has compression wave characteristics and penetrates more than one wavelength deep, with an effective layer thickness that appears to be dependent on the transducer frequency[5,8]. However, the relation between the penetration depth and the detection at the surface of the so-called surface skimming longitudinal wave (SSLW) has not been fully established. The SSLW is generated with transducers mounted on plastic wedges in physical contact with the inspected part. Care must be taken to avoid any couplant thickness changes at the interface and a precise mechanism is needed for attachment of the probe (two plastic wedges with emitting and receiving transducers) to the tested part.

Laser-ultrasonics is an emerging non-contact inspection technique using lasers for the generation and detection of ultrasound, and presents several advantages over other nondestructive techniques[9]. Generation of ultrasound is performed at a distance, which in practice can range from a fraction of a meter to several meters. The source of ultrasound is the surface of the material itself and detection of ultrasonic motion is performed off the material surface, which eliminates the need for coupling liquid and the alignment requirements of conventional ultrasonics. Therefore, laser-ultrasonics can be used on parts of complex shape and at elevated temperature. For optical detection, the small phase or frequency shift in the scattered light induced by the ultrasonic surface motion is detected by an interferometric system. A passive approach based on time-delay interferometry can be used or one can rely on an active one using nonlinear optics for wavefront adaptation. Also, the laser-ultrasonic technology has been demonstrated to be applicable to real industrial conditions[10]. Accordingly, laser-ultrasonics could offer a much simpler way to produce a surface skimming wave having compressional characteristics that could provide a more accurate and reliable stress measurement. This technique indeed produces a SSLW, but its physical origin is clearly different of the origin of a critically refracted wave produced by a transducer mounted on a wedge. We will call it laser-generated surface skimming longitudinal wave (LSSLW) or P-wave.

In this paper, a laser-ultrasonic technique is described for determining residual stresses in metals such as those produced by shot peening. The method is based on the acoustoelastic effect measurement by monitoring the small ultrasonic velocity change of the LSSLW propagating just below the surface. The main advantage of using LSSLW is that the effect of surface roughness induced by shot peening is greatly reduced compared to using SAW. Taking into account that the expected velocity change due to stress is very small, therefore innovative steps and accurate signal processing methodology are required to achieve adequate accuracy. The validity of the approach is demonstrated by measuring quantitatively the near surface stress in a four-point bending experiment with different levels of surface roughness. Then, scanning results on properly and improperly laser shock peened samples are presented. In particular, the LSSLW velocity variations for the properly peened samples clearly show an increase in the laser-peened area well indicative of a compressive stress.

2. LASER-ULTRASONIC APPROACH

2.1 Laser-ultrasonic setup

Fig. 1 shows the laser-ultrasonic setup used. The system comprises one laser with a short pulse for generation, such as Nd-YAG laser, and another one, long pulse or continuous, coupled to an optical interferometer for detection. As already mentioned, the source of ultrasound is the surface of the material itself and detection of ultrasonic motion is performed on the same surface, at a given distance from the generation location. The generation of ultrasound on the metal surface is performed in the ablation regime, where a sufficiently strong laser pulse provides vaporization or slight ablation of the surface. The recoil effect following material ejection off the surface and plasma pressure produce strong longitudinal wave emission, and shear waves as well as SAW are also emitted. When the source is small (smaller than the acoustic wavelength), the generated acoustic field is almost uniform in all directions, which includes the direction parallel to the material surface corresponding to the LSSLW. For detection, a long pulse produced by a laser is launched onto the material surface and the small phase or frequency shift in the scattered light induced by the ultrasonic surface motion is detected by a confocal Fabry-Perot or a photorefractive interferometer. For residual stress measurement, sufficient energy of the long pulse detection laser, of order 100 mJ for 60 µs pulse duration, is required for better sensitivity. This allows single shot measurement at each scanning position to prevent any surface modification since generation is in the slight ablation regime.

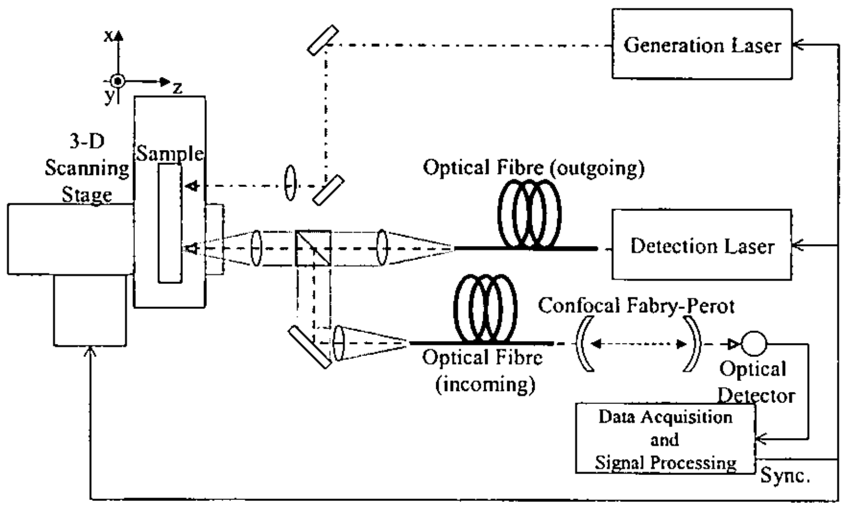

Figure 1: Setup of a laser-ultrasonic inspection system.

To efficiently generate and detect LSSLW, each laser beam is focused onto the surface using a cylindrical lens to produce a thin line source, typically 3 mm long and 50 µm wide, and a small line detection, 0.5 mm long and 50 µm wide. A line source is preferred over circular spot in order to have a more directional wave with more energy. Line detection is used to have some contributions averaged, but is kept small compared to the source to avoid alignment problems and diffraction effects by the edges of the line source. This increases the signal-to-noise ratio (SNR) of the LSSLW as well as its frequency content. In these conditions, the LSSLW (or P-wave) is clearly observed in laser-ultrasonic signals, such as in Fig. 2. However, its amplitude remains small compared to the amplitude of the SAW also produced. It is expected that the LSSLW propagate within a layer below the surface at a depth increasing with the distance from the source. Therefore, the selection of an adequate distance between generation and detection is a tradeoff between a sufficient SNR and time resolution associated with small velocity change. Even if less critical than for SAW, such a distance has also to be chosen to avoid interference with bulk wave signals also generated by the laser. The recorded signal, see Fig. 2, also includes a spike-like signal indicative of the generation laser light to clearly identify initial time for ultrasonic wave propagation and get precise time-of-flight measurement. This is made possible by intentionally collecting part of the light scattered from the surface with the optical detector without going through the interferometric system.

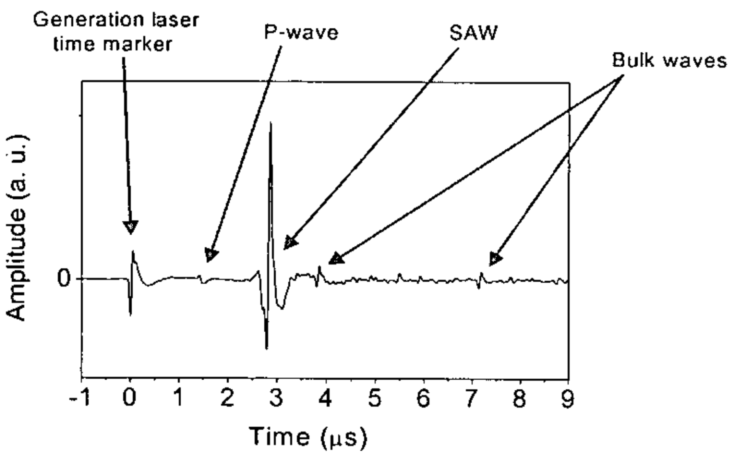

Figure 2. Typical laser-ultrasonic signal showing the different wave arrivals.

2.2 Characteristics of the LSSLW

A formal theoretical description of the LSSLW is subjected to some controversy in the literature. Refs. 11 and 12 reported the existence of a leaky surface mode arising from the complex roots of a modified (rationalized) form of the Rayleigh equation. This gives rise to a wave that propagates along the surface and is coupled to a shear wave in the medium. Due to the coupling, the surface wave leaks energy into the medium and is inhomogeneous. Mostly of compressional nature, the corresponding peak energy propagation of this mode is at about 2 wavelengths, while the SAW mainly travels on the surface within 1 wavelength depth. Also, it is found that the wave velocity can be smaller than that of the longitudinal wave propagating in bulk material for Poisson's ratio $\nu > 0.26$. On the opposite, Refs. 13 and 14 reject these findings and argue that these roots do not strictly satisfy the Rayleigh equation. They can ultimately play a role when using a different choice of Riemann sheets for calculating the elastic response, but the elastic response can be solved correctly by considering only the contributions from the branch cuts associated to the proper Riemann sheets. The disturbance propagating on the surface could be related to the head wave propagating with the longitudinal velocity on the surface and with the shear velocity at the critical angle in the volume. Notice that a similar result has been reported for the case of a transducer on a finite wedge[8]. From these references, the P-wave has no physical explanation in terms of one single inhomogeneous surface wave. This would preclude a simplistic estimation of the effective penetration depth as for SAW.

We have investigated the surface response to an impulsive line source with a calculation based on the Cagniard-de Hoop method[15]. As an example, a comparison of the calculated and measured waveforms in aluminum for a 4.8 mm distance between generation and detection is shown in Fig. 3. Note that the signal is different than the signal in Fig 2 since a photorefractive interferometer has been used in this case. A quite close agreement is found for the arrival times and shapes of the P-wave and SAW. Also, Fig. 4 shows different shapes of P-wave calculated for different ratios of the shear velocity over longitudinal velocity, c_T/c_L. In all cases, one can see a fast rising leading edge, with slope depending on the velocity ratio, followed by a tail associated to low frequency content. Notice that the fast rising leading edge has an arrival time corresponding to the bulk longitudinal velocity, while the low frequency portion appears at a longer time with a lower velocity. From waveforms calculated for two distances between generation and detection, the P-wave velocity is found smaller than that of the bulk longitudinal wave for $c_T/c_L < 0.57$ or a Poisson's ratio $\nu > 0.26$, in apparent agreement with the above theory of a specific surface mode. Notice that steel and aluminum have a ratio c_T/c_L of 0.54 and 0.48 respectively. More work and experimental validation with different materials are needed to assess the effective penetration depth of LSSLW. Also at the present time, the theoretical basis establishing a possible frequency dependence of the penetration depth of the LSSLW to provide stress information at different depths is uncertain. A velocity dispersion is observed in the simulation results of Fig. 4 at least for $c_T/c_L < 0.57$, but its relation with depth remains vague. Such a difficulty is also true for the SSLW produced by a transducer on a wedge.

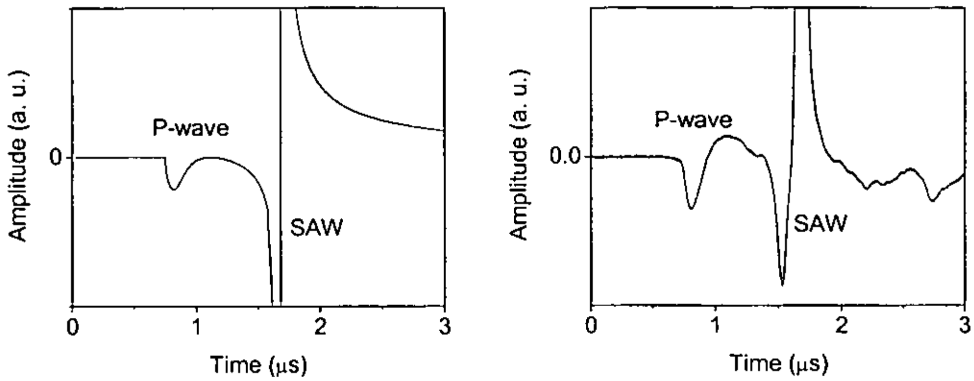

Figure 3. Comparison between calculated waveform (left) and actual signal in aluminum, for a 4.8 mm distance between generation and detection.

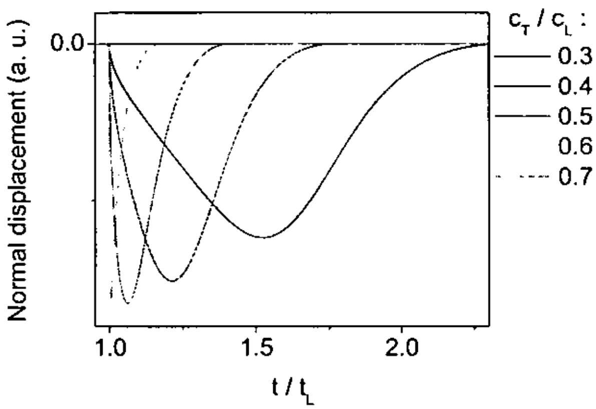

Figure 4. Calculated pulse shape of the P-wave for different ratios of c_T/c_L.

An experiment has been performed to obtain the acoustoelastic coefficient of the LSSLW. Samples were made of type 304 stainless steel and were specially designed to be used in a Gleeble thermomechanical simulator. A laser-ultrasonic system was setup to perform ultrasonic measurements on the sample during tensile tests. The generation and detection spots were separated by 8 mm and measurements were performed while applying a tensile stress from 0 MPa to 250 MPa and also during unloading from 450 MPa to 80 MPa. The LSSLW was recorded as well as an output signal of a strain gauge mounted on the sample. The relation between applied stress and measured strain is shown in Fig. 5a. Two lines obtained by loading and unloading show essentially a linear relation between strain and stress, the slope of which gives the Young's modulus estimated to be about 150 GPa, compared to a value of 190 GPa for this material in data books. The line obtained following unloading does not go through the origin, while the other line does, because a permanent strain remains in the material. The arrival time of the LSSLW was measured on each signal and the relation between stress and the LSSLW velocity is shown in Fig. 5b. Although there is some fluctuations in the data, the velocity is linearly decreasing with the increase of stress, having a slope of nearly 10 m/s per 100 MPa, similar to the value found for 316L stainless steel in the literature[5].

Hence, the velocity change due to stress is small, even if it is 10 times larger than that for SAW. Assuming a propagation path length between the generation and the detection of 10 mm, the travel time differences are only about 3 ns for a stress of 100 MPa. Therefore, the time resolution required is quite high and for example, a change of the path length of 10 μm, which may easily arise without taking enough precautions, causes a travel time difference of about 2 ns. Also, despite that strong effects such as surface roughness is avoided by using LSSLW, velocity changes produced by other factors such as temperature, texture, grain scattering, could interfere with those produced by residual stress.

Therefore, an accurate signal processing methodology, including the choice of a proper reference, is required to achieve adequate accuracy and to measure the small velocity change attributable to stress.

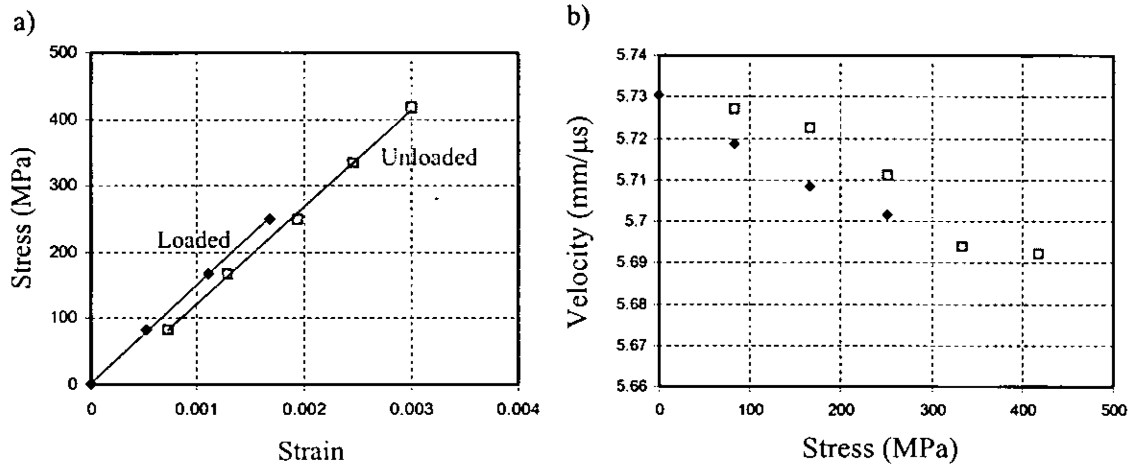

Figure 5. a) Relation between strain and stress on 304 stainless steel and b) relation between applied stress and velocity change of LSSLW.

2.3 Signal processing methodology

As shown in Fig. 2, a spike-like signal indicative of the generation laser light is present to clearly identify initial time for ultrasonic wave propagation and get precise time-of-flight measurement. In this case, the use of two cross-correlations is proposed, one for the light pulse and one for the ultrasonic pulse (LSSLW) with those of a reference signal, maintaining the same distance between generation and detection. The reference signal is obtained with a high SNR ultimately on the same but unstressed material in similar conditions, to remove the possible effects of temperature, texture, grain scattering, which may significantly contribute to the small measurable velocity dispersion. Also, the fixed distance between generation and detection allows removing any effect from ultrasonic diffraction. The time delay between light pulses provides the change in the triggering jitter and that between ultrasonic pulses provides the change of travel time uncorrected for jitter while scanning the inspected area. The difference between the two is the change in time delay for the effect of residual stress independent of the triggering jitter. In each cross-correlation, an interpolation of the maximum is performed, corresponding for example to a time interval of 0.5 ns for a sampling rate of 100 MSamples/s (time interval of 10 ns). Notice that such a sampling rate is consistent with a system cut-off frequency of say 15 MHz and that the use of cross-correlation including interpolation is very effective to obtain accuracy better than the sampling time interval. This also explains the usefulness of performing cross-correlation with the light pulses.

The time difference, Δt, obtained from the above procedure is related to the velocity change, ΔV, through the general relation:

$$\frac{\Delta t}{t^0} = \frac{\Delta d}{d^0} - \frac{\Delta V}{V^0} \tag{2}$$

where d^0 and Δd are respectively the path length and possible variations during the measurement. Also, the superscript "0" denotes the corresponding values without stress but, for small deviations, the current values with stress can alternatively be used. Therefore, assuming negligible change in the path length, the conversion into ultrasonic velocity change is given by the simple relation:

$$\frac{\Delta V}{V^0} \approx -\frac{\Delta t}{t}. \tag{3}$$

If the changes in the path length cannot be neglected, the arrival of the SAW can be used as a reference to get a measurement independent of path length changes using the following relation:

$$\frac{\Delta V_P}{V_P^0} \approx \frac{\Delta t_R}{t_R} - \frac{\Delta t_P}{t_P} \tag{4}$$

where the subscript denotes the wave mode (R: SAW or P: LSSLW). The path length changes may be caused either by instabilities of the assembly holding the generation and detection lasers (or the optical fibers guiding these laser beams) or a probed surface that is tilted (not perpendicular to the probing beams) or is curved. Notice that this approach can be used even if the SAW velocity is found to a certain extent sensitive to stress. Using Eq. 1, one has the expression:

$$\frac{\Delta V_P}{V_P^0} - \frac{\Delta V_R}{V_R^0} = \left(\frac{K_P}{V_P^0} - \frac{K_R}{V_R^0}\right)\sigma \tag{5}$$

and therefore, the effective acoustoelastic coefficient in parenthesis establishes the relation between the difference of velocity changes (calculated from Eq. 4) and the stress. This coefficient can be calculated from measured properties or it can be obtained experimentally as calibration. As a further improvement, since the SAW is dispersive, the frequency at which the velocity change of the SAW is measured should ultimately be chosen for the same penetration depth as the LSSLW, which means typically at one-third of the center frequency. This is also a frequency where the SAW is less affected by surface roughness.

As an example of the accuracy achieved, LSSLW velocity variations on a bare stainless steel sample for two perpendicular directions and for a separation of 8 mm between generation and detection were investigated. A sampling rate of 100 MSample/s consistent with the cut-off frequency of the system near 15 MHz was used. The fluctuations in the profiles, mostly considered to be attributable to the measurement accuracy are found to be within ±0.05%. Also, a theoretical limitation of the time resolution in the measurement using cross-correlation is given by[16]:

$$e_t = \sqrt{\frac{3}{8\pi^2 T}} \cdot \frac{\sqrt{1+2\cdot SNR}}{SNR} \cdot \frac{1}{\sqrt{f_H^3 - f_L^3}} \tag{6}$$

where T is the pulse duration, f_L and f_H are the minimum and maximum frequencies of the available bandwidth. A better SNR and a larger bandwidth could give a better time resolution, especially a higher value for the upper frequency cut-off.

As already discussed, the velocity dispersion of the LSSLW (frequency dependence of the velocity change), if any, could provide residual stress information at different depths. Such dispersion can be obtained from the phase after calculating the Fourier transform (using the FFT algorithm) of the cross-correlation result[16]. Such a phase obtained with a reference signal on a sample having no stress is related to the change in travel time using:

$$\Delta\phi(f) = 2\pi f \Delta t(f) \tag{7}$$

where $\Delta\phi(f)$ is the phase of the cross-correlation, $\Delta t(f)$ is the travel time (or the jitter), and both of them depend on the frequency, f. The velocity dispersion, $\Delta V(f)$, of the LSSLW is then calculated using Eq. 3 or Eq. 4 for each frequency. Similarly to the previous analysis, the procedure is applied to the light pulse and the ultrasonic pulse with their respective reference signal. The dispersion between light pulses provides the change in the triggering jitter and is expected to be nearly constant. The dispersion between ultrasonic pulses provides the change of travel time uncorrected for jitter while scanning the stressed area. The difference between the two is the velocity change as function of the frequency for the effect of sub-surface stress independent of the triggering jitter. Notice that the limit of zero velocity change with increasing depth is a very useful criterion for validating the procedure. Again, the reference signal used should ultimately be taken on the same material but unstressed and with the highest SNR possible. This is particularly critical when calculating velocity dispersion.

Other configurations are possible using the LSSLW to measure residual stresses. Among them, one could use two generation (or two detection) spots at different distances and apply the above cross-correlation technique to the two received signals. While making the scanning more difficult, the cross-correlation result would be affected by the fact that the LSSLW propagates deeper with increasing distance from the source. Another aspect relates to the precise initial time for ultrasonic wave propagation to get precise time-of-flight measurement. If jitter-free laser triggering and acquisition electronics is available, only cross-correlation of the LSSLW with that of a reference signal is needed.

3. QUANTITATIVE ASSESSMENT OF STRESS USING LSSLW

As a demonstration of the validity of the approach for a quantitative evaluation of near surface stress using the LSSLW, the laser-ultrasonic approach above was tested on aluminum and steel bars under four-point bending. Fig. 6 shows the four-point bending assembly used to apply well-controlled state of stress on a sample about 8 mm thick. A special design for bending the sample was made with openings for beam passage to allow measurements on each side of the sample. In this setup, the stress distribution is linear throughout the thickness, going from a uniform maximum positive value (tension) on one face to a uniform maximum negative value (compression) at the other face and a zero stress condition at the center line. Different level of stress can be applied on the sample by screwing the bolts shown in the figure. The system has been calibrated by attaching a strain gauge between the generation and detection locations. From the measurement of strain, stress can be readily derived knowing Young's modulus. A laser-ultrasonic signal, averaged and used as reference, was acquired on each sample prior to applying stress. Velocity variations were averaged from 50 positions with a 4.8 mm distance between generation and detection. Also, all velocity variations were corrected with SAW velocity using Eq. 4 in the zero frequency limit. This is because the small changes in the path length cannot be neglected in this four-point bending experiment.

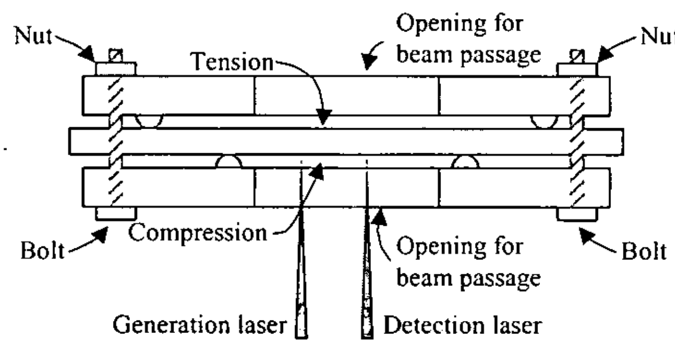

Figure 6. Four-point bending assembly to apply controlled stress on a sample.

Fig. 7 shows the results for aluminum and steel from both sides of each sample. For aluminum, the measured LSSLW velocity variations clearly show a linear trend with applied surface stress as expected, in a symmetric manner from 0 to -3% for tensile stress and from 0 to +3% for compressive stress. For comparison, velocity variations of SAW, not shown here, exhibit a much smaller and erratic behaviour as function of surface stress, with values not exceeding 0.5 %. With the respective velocities of LSSLW and SAW, this means a larger sensitivity for the LSSLW by a factor of 13, without considering their effective probing depth. For steel (type 52100), the LSSLW velocity variations show a clear dependency with surface stress, even if not so linear and symmetric, from 0 to -1.5% for tensile stress and from 0 to +1.0% for compressive stress. With respect to Fig. 5, such variations are of the correct order of magnitude for stresses of up to 800 MPa. For comparison, SAW velocity variations exhibit a somewhat smaller and erratic behaviour as function of surface stress with values not exceeding 0.4 %, which means a larger sensitivity of the LSSLW by a factor of 7.5.

To evaluate the effect of surface roughness on stress measurement, aluminum samples were sand-blasted using grits of various sizes and different pressures. Fig. 8 shows velocity variations for LSSLW (left) and SAW (right) as function of surface stress, with surface roughness corresponding to Ra=6 μm (a, b) and Ra= 12 μm (c, d). Clearly, the LSSLW velocity variations are not so much affected by surface roughness, nearly showing the behaviour in Fig. 7a. For comparison, velocity variations of SAW, also corrected for path length with the zero frequency limit, show a non-symmetric and erratic behaviour as function of surface stress. The surface roughness decreases the SAW velocity by a factor from 0 to -0.5 %, cancelling out the effect of compressive stress and overestimating the effect of tensile stress. These results clearly indicate the advantage of LSSLW over the SAW.

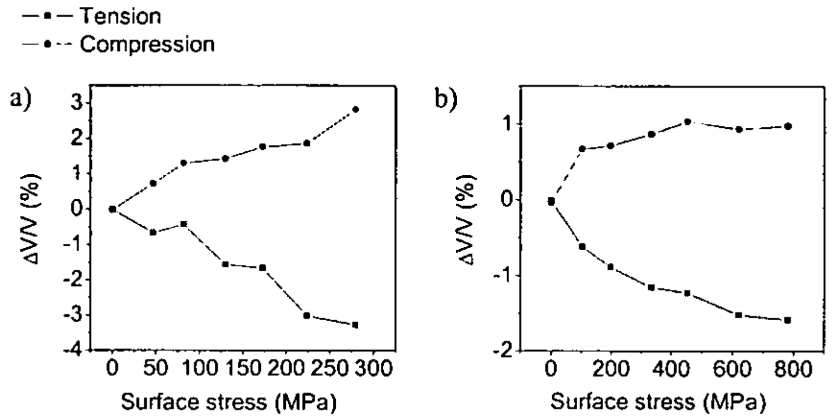

Figure 7. Velocity variations for LSSLW as function of surface stress in aluminum (left) in steel (right).

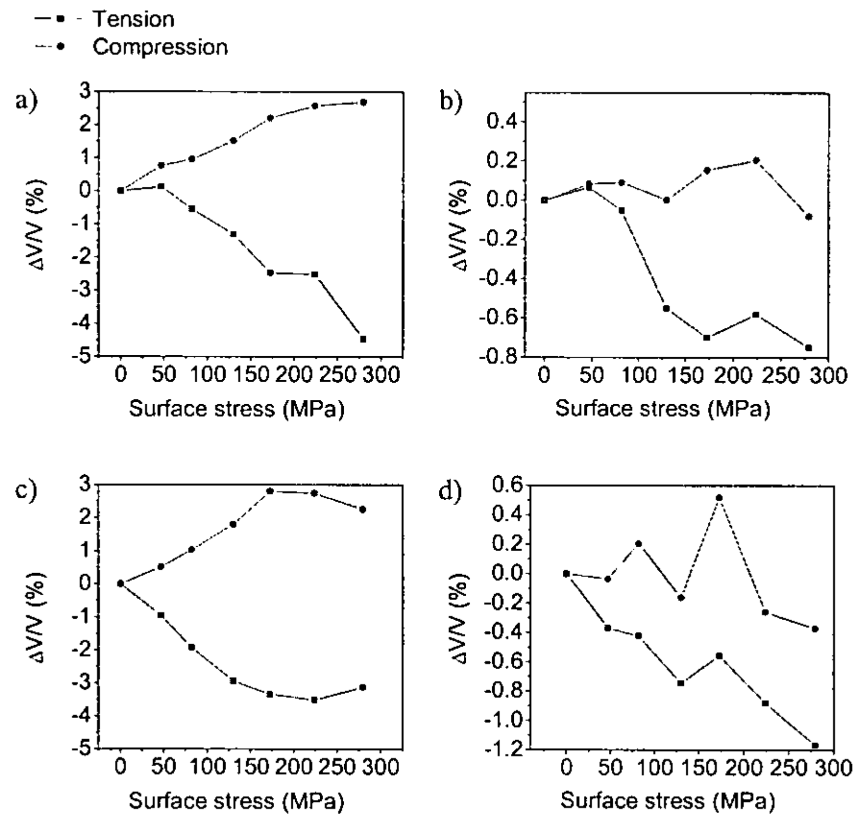

Figure 8. Velocity variations for LSSLW (left) and SAW (right) as function of surface stress in aluminum. Influence of surface roughness of Ra=6 μm in a) and b), and Ra= 12 μm in c) and d).

With this four point bending experiment, no LSSLW velocity dispersion is clearly observed although stress varies with depth. As mentioned before since the theory of the LSSLW is unclear, this should not have been necessarily expected. Another reason could be the rather weak stress gradients involved that may be too small to be detected within the available ultrasonic frequency range (from 1 to 15 MHz). Indeed, the extent of stress in depth is over 4 mm in the present experiment. This may be different for shot peening experiment since the extent of stress is typically from 0.2 to 0.5 mm with similar surface stresses, i.e. one order of magnitude difference for the stress gradients.

4. MEASUREMENT OF RESIDUAL STRESS PRODUCED BY LASER SHOT PEENING

Results obtained on samples that have been properly and improperly shot peened by laser are presented. Refs 17-19 give a description of the technique of laser shock peening along with typical depth profiles of the stresses produced in the material. Three samples made of 304 stainless steel were tested for each of the peening conditions, proper with a small laser spot or improper with a large spot. Peening was performed by scanning the laser beam along a series of lines with overlapping spots along the lines and between adjacent lines. The estimated near surface stresses in the directions parallel to line scanning (axis x) and perpendicular to it (axis y) are given in Table 1. These values were measured using X-ray diffraction on samples with similar treatments. Also, surface roughness before and after laser-peening was found to be typically 1 μm, which is small compared to ultrasonic wavelength. Each peened sample was scanned along a line of length 44 mm in two directions, one corresponding to wave propagation parallel to the x axis and the other with wave propagation parallel to y axis. The signals were acquired at every 50 μm with a sampling rate of 100 MSamples/s (10 ns). The line source and line detection were separated by 8 mm and were both in the laser-peened area or outside it. The beginning and the end of each scan correspond to probing an unpeened area. With the setup used, the frequency content was found between 1 and 15 MHz.

Table 1. Surface stresses determined by X-rays on laser-peened materials.

Description	σ_x (MPa)	σ_y (MPa)
Properly peened	-190	-630
Improperly peened	+360	+370

Fig. 9 shows the LSSLW velocity variations on a properly peened sample, for wave propagation along the x and y directions, thus scanning along the y and x directions, respectively. The results clearly show a velocity increase in the laser-peened area, for positions ranging from 5 to 35 mm. The velocity change is about +0.6 % for propagation in the two directions. Similar results are observed for the other two properly peened samples. First, the increase of velocity is well indicative of a compressive stress. However, the velocity changes in the two directions suggesting similar stress levels are to be compared to the quite different values on the surface measured by X-rays indicated in Table 1. Notice that the LSSLW may be probing the material at a depth where the stresses in the two directions are almost the same. Taking into account the acoustoelastic coefficient of 10 m/s per 100 MPa, the observed velocity change of 0.6 % corresponds to a compressive stress of –300 MPa at same probing depth, which appears quite reasonable[19]. Also not shown here, velocity variations corrected with the low frequency SAW using Eq. 4 to compensate for changes in the path length have shown very similar results.

Fig. 10 shows the LSSLW velocity variations in the x and y directions for an improperly peeened sample. Only small positive velocity variations are observed and similar results are found for the other two improperly peeened samples. At the surface from Table 1, the improperly peened samples have large tensile stresses of same order in the two directions. However, the LSSLW is probing below the material surface where the stress of these samples can be tensile or compressive. From these results, at the LSSLW probing depth, the stress in the peened area seems to be only slightly in compression. Therefore, clearly different results are obtained on properly and improperly peened samples.

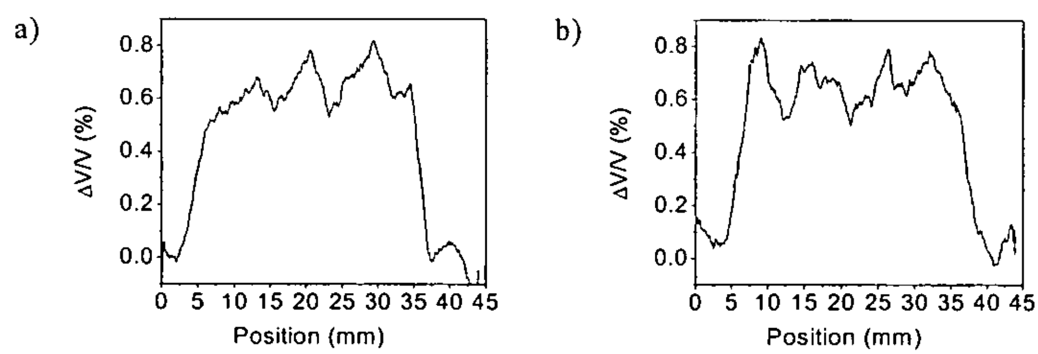

Figure 9. LSSLW velocity variations for a properly peened sample for propagation along a) x-direction and b) y-direction.

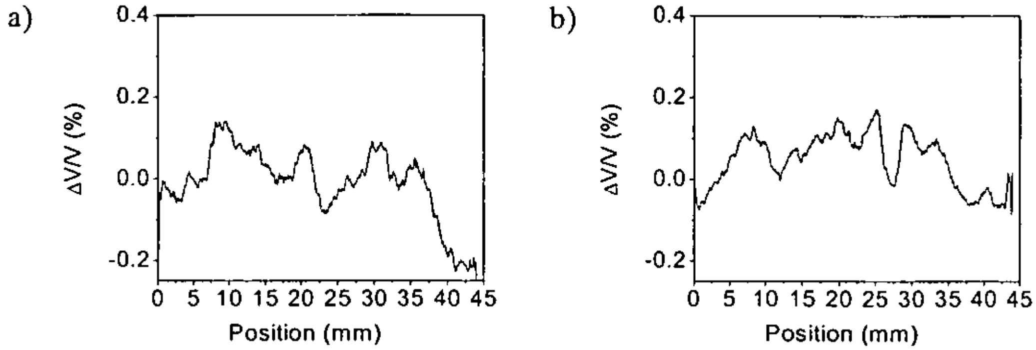

Figure 10. LSSLW velocity variations for an improperly peened sample for propagation along a) x-direction and b) y-direction.

Regarding velocity dispersion, Fig. 11 shows the LSSLW velocity variations for different frequencies (3, 6, 9, 12 MHz) on the same properly peened sample. These results have been obtained from the dispersion curve of each signal in a line scan. Compared to Fig. 9, this can be seen as a detailed view of the LSSLW velocity variations at different depths, the high frequencies probing closer to the surface. A similar behaviour is found for the dispersion curves of the other two properly peeened samples. For the same improperly peened sample not shown here, some dispersion is observed but the stress depth profiles of these samples are not well known.

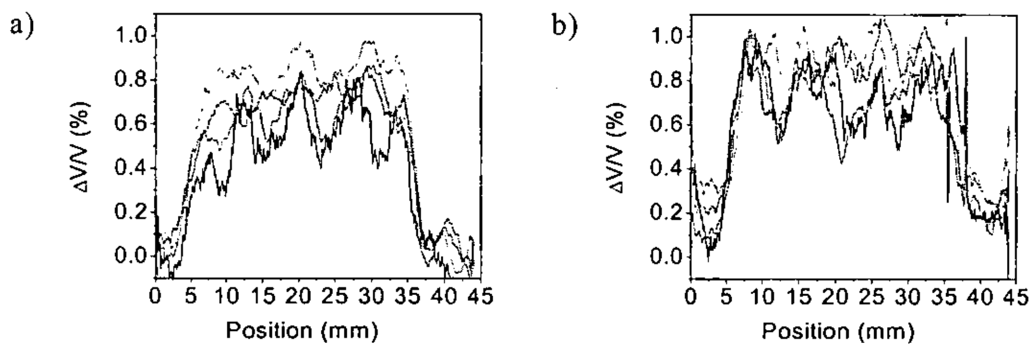

Figure 11. LSSLW velocity variations for the same properly peened sample at different frequencies for propagation along a) x-direction and b) y-direction (3 MHz ——— ; 6 MHz ———; 9 MHz ——— ; 12 MHz ———).

CONCLUSION

A laser-ultrasonic approach is described for residual stress measurement using the laser-generated surface skimming longitudinal wave (LSSLW). As a non-contact technique, it removes the difficulty of any couplant thickness changes and the need for probe attachment with a precise location control. Good sensitivity is obtained with sufficient energy of the long pulse detection laser, thus allowing single shot measurement at each scanning position. The method is based on monitoring of the small ultrasonic velocity change caused by stress. A cross-correlation technique is used with a reference signal taken on the same but unstressed material in similar conditions. The use of two cross-correlations, one for the light pulse and one for the ultrasonic pulse with reference signals, is proposed to avoid problems associated with jitter of the laser firing or triggering of the data acquisition system. We have also shown the effectiveness of using the low frequency SAW to correct the LSSLW results, which can be affected by minute changes in the path length during measurements. The validity of the approach is demonstrated by measuring quantitatively the near surface stress in a four-point bending experiment. Also, very conclusive results are shown on samples that have been properly and improperly shot peened by laser. For properly laser-peened samples, a consistent velocity increase is observed well indicative of a compressive stress and of the correct order of magnitude. We have also observed velocity dispersion of the LSSLW in these samples. It is however presently unclear how velocity dispersion relates to the depth profile of the residual stress. Further theoretical and experimental work is required to clarify this point. It is however expected that information on stress profile could be obtained since the LSSLW goes deeper with propagation distance. Anyhow, the reported method should be applicable to measurement of applied stress or residual stress caused by a variety of fabrication processes, such as welding, machining, grinding, shot peening including its variant of laser-peening and low plasticity burnishing.

REFERENCES

1. R.M. James and O. Buck, "Quantitative nondestructive measurement of residual stresses", CRC Crit. Rev. Solid State Mater. Sci. 9, pp. 61-105, 1980.
2. A. Lavrentyev and W.A. Veronesi, "Ultrasonic characterization of near-surface material properties in shot peened Waspaloy", *Review of Progress in Quantitative Nondestructive Evaluation Vol. 21*, ed. by D.O. Thompson and D.E. Chimenti, AIP Conf. Proc., Melville, pp. 1659-1666, 2002.
3. A. Lavrentyev and W.A. Veronesi, "Ultrasonic measurement of residual stress in shot peened aluminum alloy", *Review of Progress in Quantitative Nondestructive evaluation Vol. 20*, ed. by D.O. Thompson and D.E. Chimenti, AIP Conf. Proc., Melville, pp. 1472-1479, 2001.
4. S.E. Kruger, O. Bouesnard, J. Charlier, J.M.A. Rebello, L. Segers, "Shot peening treatment characterization by surface acoustic waves", *Review of Progress in Quantitative Nondestructive evaluation Vol. 19*, ed. by D.O. Thompson and D.E. Chimenti, AIP Conf. Proc., New York, pp. 1479-1486, 2000.
5. D.E. Bray and W. Tang, "Subsurface stress evaluation in steel plates and bars using Lcr ultrasonic wave", Nucl. Eng. and Design **207**, pp. 231-240, 2001.
6. D.E. Bray, N. Pathak and M.N. Srinivasan, "Residual stress mapping in a steam turbine disk using the Lcr ultrasonic technique", Mater. Eval. **54**, pp. 832-839, 1996.
7. E. Tanala, G. Bourse, M. Fremiot and J.F. De Belleval, "Determination of near surface residual stress on welded joints using ultrasonic methods", NDT&E Int. **28**, pp. 83-88, 1995.
8. K.J. Langenberg, P. Fellenger, R. Marklein, "On the nature of the so-called subsurface longitudinal wave and/or the surface longitudinal 'creeping' wave", Res. Nondest. Eval. **2**, pp. 59-81, 1990.
9. C.B. Scruby and L.E. Drain, *Laser-Ultrasonics: techniques and applications*, Adam Hilger, Bristol, 1990.
10. J.-P. Monchalin, "Laser-ultrasonics: from the laboratory to industry", *Review of Progress in Quantitative Nondestructive Evaluation Vol. 23A*, ed. by D.O. Thompson and D.E. Chimenti, AIP Conf. Proc., New York, pp. 3-31, 2004.
11. C.T. Schröder and W.R. Scott, "On the complex conjugate roots of the Rayleigh equation: The leaky surface wave", J. Acoust. Soc. Am. **110**, pp. 2867-2877, 2001.
12. L.V. Yuozonene, "Elastic longitudinal surface waves and their applications to nondestructive testing", Defektoskopiya **8**, pp. 29-38, 1980.
13. J.G. Harris and J.D. Achenbach, "Comment on "On the complex conjugate roots of the Rayleigh equation: The leaky surface wave"", J. Acoust. Soc. Am. **112**, pp. 1747-1748, 2002.
14. V.N. Danilov, "Calculations of parameters of longitudinal surface waves on a free planar boundary of a material", Russian J. Nondestr. Testing **37**, pp. 700-707, 2001.
15. C. Bescond C. and M. Deschamps, "Dynamical surface response of a semi-infinite anisotropic elastic medium to an impulsive force", J. Acoust. Soc. Am. **103**, pp. 114-124, 1998.
16. J.-D. Aussel and J.-P. Monchalin, "Precision laser-ultrasonic velocity measurement and elastic constant determination", Ultrasonics **27**, pp. 165-177, 1989.
17. Y. Sano, N. Mukai, O. Koki, M. Obata, "Residual stress improvement in metal surface by underwater laser irradiation", Nucl. Instr. and Meth. Phys. Res. B **121**, pp. 432-436, 1997.
18. N. Mukai, N. Aoki, M. Obata, A. Ito, Y. Sano, C. Konagai, "Laser processing for underwater maintenance in nuclear plants", *Proc. of 3rd JSME/ASME Joint Int. Conf. Nucl. Eng. Vol. 3*, Kyoto, pp. 1489-1494, 1995.
19. A.H. Clauer and J.R. Koucky, "Laser shock processing increases the fatigue life of metal parts", Materials & Processing **6**, pp. 3-5, 1991.