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Measurement of texture in steel by laser-ultrasonic surface waves

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Abstract. A laser-ultrasonic approach based on the propagation of surface skimming longitudinal wave (P-wave) and Rayleigh wave (SAW) is investigated for the measurement of texture in moderately thick steel plates. The angular dependence of the P-wave and SAW velocities presents different patterns, both of amplitude of a few % attributed to texture. Moreover, the difference of the P-wave and SAW profiles is shown to be very robust against small path length changes or other detrimental effects. For measurements on large plates, a solution based on the rotation of a generation line using an axicon lens is tested. Texture variations across the width of steel plates and the influence of residual stress are discussed.

1. Introduction

In the continuous production line for hot-rolled steel sheet, thick input material is transformed to much thinner steel sheet in the form of coil by several processes. The stresses generated during these processes are usually transformed into energy for shaping the steel strip. But a small amount of stress usually remains in the steel sheet after the whole processing. Also, crystallographic texture change is expected to occur for similar reasons. Therefore, the control of texture and reduction of residual stress are important and necessary for high quality steel product.

Laser ultrasonics can be a good candidate for such measurements. Successful results were obtained in recent years for residual stress in aluminum using an approach based on the laser generated surface skimming longitudinal wave (LSSLW or P-wave) [1-3]. For steel, the effect of stress on the ultrasonic velocity is small, with an acoustoelastic coefficient of about -0.1 % / 100 MPa for the P-wave, i.e. four times less than in aluminum. Also, this coefficient is only about -0.01 % / 100 MPa for the Rayleigh wave (SAW).

In this paper, a laser-ultrasonic approach based on the propagation of P-wave and SAW is investigated for the measurement of texture in steel plates. The angular dependence of the velocity of these modes presents different patterns of amplitude of a few % attributed to texture. Also, the difference of the P-wave and SAW profiles is found to be very robust against small path length changes. For measurements on large plates, a solution based on the rotation of a generation line is tested. Texture variations across the width of steel plates and the influence of residual stress are discussed.

2. Laser ultrasonic P-wave approach

A laser-ultrasonic setup was assembled for precise velocity measurements of P-wave and SAW. A pulsed Nd:YAG laser is employed to simultaneously generate the ultrasonic modes. For the ultrasonic detection, a long pulse Nd:YAG laser is coupled to a photorefractive interferometer by optical fibers. A line-source and line-detection configuration is used to minimize wave spreading and microstructure noise. Also, a scanning system is mounted to allow measurements for different separation distances between the generation and detection locations. The setup further includes a rotation stage for the analysis of the angular dependence of velocity variations due to both texture and stresses.

For signal processing, a cross-correlation method is used between the measured signal and a reference signal for each separation distance between the generation and detection. One has the simple relation between velocity and time delay variations:

$$\frac{\Delta V}{V^0} = \frac{\Delta d}{d^0} - \frac{\Delta t}{t^0} \tag{1}$$

where V is the velocity, t is the time delay and d is the path length. Since variations are small, the index 0 (for zero stress) is unnecessary and if the change in path length (e.g. separation distance between generation and detection line) can be neglected, one has the simple relation:

$$\frac{\Delta V}{V} \approx -\frac{\Delta t}{t} \tag{2}$$

One improvement is to use the P-wave and SAW in combination to correct for small changes in the path length with respect to Eq. (1) and possibly other effects. Taking the difference between velocity variations of the two modes results in the relation:

$$\frac{\Delta V_P}{V_P} - \frac{\Delta V_{SAW}}{V_{SAW}} = -\left(\frac{\Delta t_P}{t_P} - \frac{\Delta t_{SAW}}{t_{SAW}} \right) \tag{3}$$

where the subscript denotes the wave mode. In this manner, the path length change is numerically cancelled out.

Using the rotation stage, the angular dependence of the velocity or time delay in a sample is a combined effect of texture and stress [2]. The equations for P-wave and SAW with coefficients for steel were calculated and are given by:

$$\begin{aligned}(\Delta V/V)_P(\theta) &= -10.210^{-6}\ \sigma_m - 1.12\ W_{400} - 12.810^{-6}\ \sigma_d \cos(2\theta) \\ &\quad + 2.35\ W_{420}\cos(2\theta) + 3.11 W_{440}\cos(4\theta) \\ (\Delta V/V)_{SAW}(\theta) &= -1.210^{-6}\ \sigma_m + 2.2\ W_{400} - 3.210^{-6}\ \sigma_d \cos(2\theta) \\ &\quad - 4.17 W_{420}\cos(2\theta) + 0.74\ W_{440}\cos(4\theta)\end{aligned} \tag{4}$$

where θ is the angle with respect to rolling direction, W_{400}, W_{420} and W_{440} are the texture coefficients in the Roe's notation, $\sigma_m = (\sigma_0+\sigma_{90})/2$ is the mean stress and $\sigma_d = (\sigma_0-\sigma_{90})/2$ is the difference (in MPa) between the rolling (0 deg) and transverse (90 deg) directions. Also with a reference signal at 0 deg, one should subtract terms corresponding to 0 deg from Eq. 4. When using a reference with rotation at a different location, the variation in each physical quantity with respect to the reference is obtained. Also, for the P-wave / SAW combination, the expression for the difference is easily derived.

3. Measurement results

A series of measurements was performed using the rotation stage on samples cut across the width of a large plate. It is expected that the stress should be actually zero due to the small sample dimensions. Also, measurements are made after slight surface polishing. First results showed velocity variations clearly oscillating in a different manner for P-wave and SAW, with an amplitude of more than 1 % attributed to texture, much larger than the 0.1 % variation expected for a 100 MPa stress.

Figure 1 shows the results (time delay) from simultaneously fitting the profiles of P-wave and SAW using Eqs. (4) with parameters W_{420}, W_{440} and a fixed separation distance of 14 mm. Notice that the reference is the signal in the rolling direction at 0 deg. The fit is quite good with texture coefficients $W_{420} = -3.56 \times 10^{-3}$ and $W_{440} = 3.37 \times 10^{-3}$ in the valid range, with stress values forced to zero. Figure 2 shows the results of fitting the difference profile of the P-wave / SAW combination for samples at the edge and at the center. For the edge, a very good fit is obtained with texture coefficients $W_{420} = -3.65 \times 10^{-3}$ and $W_{440} = 2.91 \times 10^{-3}$ close to the previous values obtained. For the center, a good fit is also obtained with smaller texture coefficients $W_{420} = -1.46 \times 10^{-3}$ and $W_{440} = 1.80 \times 10^{-3}$. The difference profile shows similar behavior when making measurements with a rough, as received, surface finish.

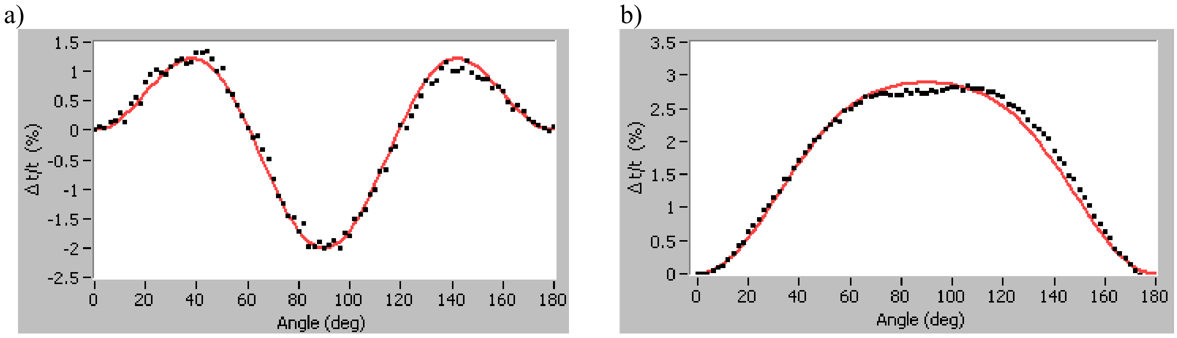

Figure 1. Simultaneous fit of the profiles for a) P-wave and b) SAW on a sample near the edge.

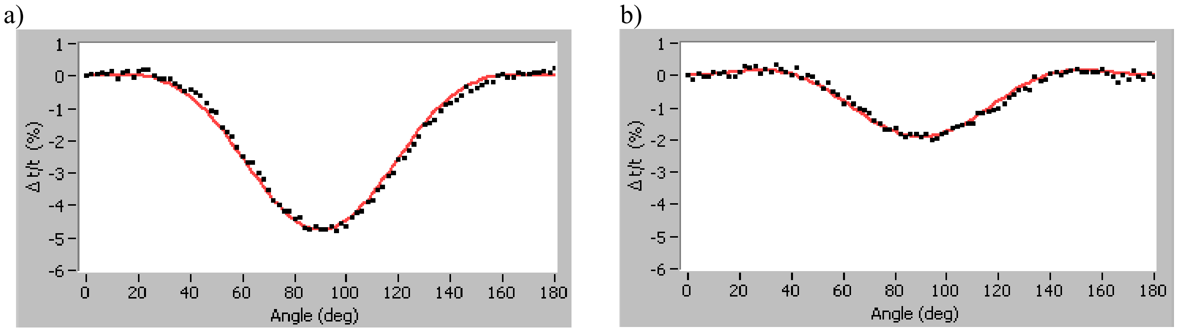

Figure 2. Fit of the profile of the P-wave / SAW combination for a sample a) at the edge and b) at the center.

Another analysis is to use the center as reference location and apply cross-correlation for the P-wave and SAW with corresponding signals at each angle. With this reference choice, the contribution of W_{400} can be obtained as well from fit. The difference profiles of the P-wave / SAW combination for samples at both edges were obtained. For the same edge as before, a very good fit is obtained with texture coefficient variations $\Delta W_{400} = -0.36 \times 10^{-3}$, $\Delta W_{420} = -2.26 \times 10^{-3}$ and $\Delta W_{440} = 0.87 \times 10^{-3}$. The changes in texture coefficients ΔW_{420}, ΔW_{440} are quite consistent with the distinct values obtained from the two samples in Figure 2. For the other edge, the good fit is obtained with almost the same texture coefficient $\Delta W_{400} = -0.35 \times 10^{-3}$, but smaller values of the others, $\Delta W_{420} = -1.34 \times 10^{-3}$ and $\Delta W_{440} = 0.79 \times 10^{-3}$. These results indicate an asymmetry across the width of the strip.

4. Measurements on large samples

Using the P-wave approach on large hot-rolled samples, an optical setup was developed to perform rotation of the generation line, with a point detection at the center of the circle formed. One solution is to use an axicon lens to map the laser spot onto a circle and a mask to only have an arc rotating on the sample surface. Two large hot-rolled samples of dimensions sufficient to sustain residual stresses across the width were prepared by POSCO. From strain gauge measurements, it was found that one sample had residual stresses reaching -80 MPa (in compression) near the edges, compared to -20 MPa for the other sample.

Figure 3a shows a profile and fit of the P-wave / SAW combination near the edge on the sample with largest residual stresses, using an axicon lens of 16 mm radius and the reference signal at 0 deg. The profile shape is nearly symmetric with time delay variations of about 6 %. Such large variations should be attributed to texture. To reduce the effect of texture and possibly make more emphasis on stress, a strategy discussed before is to use a reference location far enough from the edge with almost no stress. Figure 3b shows the profile of the P-wave / SAW combination using a reference location at 175 mm from the edge. The profile is nearly symmetric, but large variations are still observed. Therefore, taking a reference location far enough from the edge does not cancel out the texture effect. According to the fit, variations of the texture coefficients between the two locations are $\Delta W_{400} = 4.00 \times 10^{-3}$, $\Delta W_{420} = -3.06 \times 10^{-3}$ and $\Delta W_{440} = 0.56 \times 10^{-3}$.

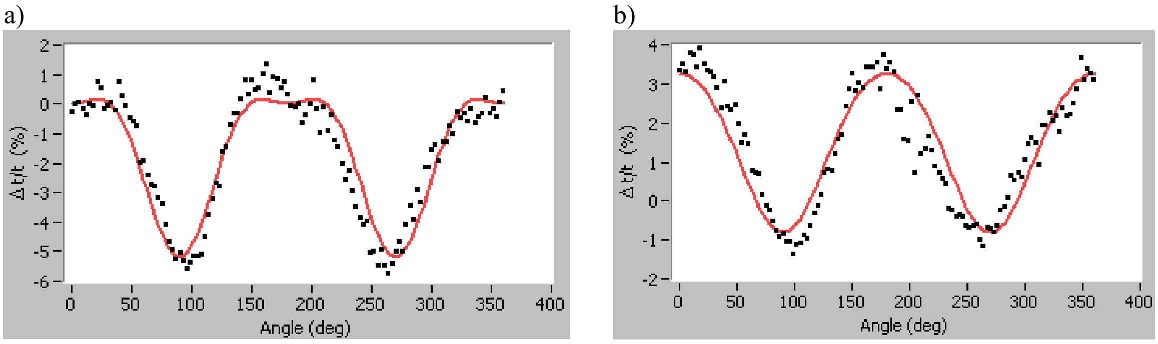

Figure 3. Profile of the P-wave / SAW combination near the edge on a large sample a) with the reference at 0 deg and b) using a reference location at 175 mm from the edge.

5. Conclusion

A laser-ultrasonic approach based on the propagation surface waves was studied for the measurement of texture in steel plates. The difference of the P-wave and SAW profiles is shown to be very robust against small path length changes or other detrimental effects. For actual measurement on large plates, a solution based on the rotation of a generation line using an axicon lens was tested. Texture variations across the width of a plate are obtained. Taking a reference far enough from the edge does not cancel out the texture effect to have variations mostly due to stress. This texture change could prevent measuring residual stress in hot-rolled steel strip with ultrasound. However, the potential of measuring the texture on-line by laser ultrasonics is demonstrated.

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