Dynamic Material Property Measurement of Steel Thin Sheets using Laser-Based Ultrasonics

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Abstract. A material property measurement system for steel sheets using laser-based ultrasonics was developed. The system consists of a pulsed Nd:YAG laser for ultrasonic generation and multi-channel interferometer coupled with a CW single frequency laser for ultrasonic detection. The system can measure the frequency of the S1 Lamb wave mode of zero group velocity (S1f) as well as the longitudinal resonance frequencies without ablative damage to the steel surface. It was confirmed that Poisson’s ratio could be directly obtained by combining the measured S1f value and the longitudinal resonance frequencies. To evaluate the applicability of this system in an actual steel production setting, the system was installed in a hot rolling pilot plant that produces steel samples. As a result, it was demonstrated that the system can measure dynamic changes in Poisson’s ratio values within steel sheets, even in the hot rolling pilot plant environment. Material property data, such as Poisson’s ratio, during the thin sheet production process will be very useful for manufacturing high value-added steel, such as sheets with uniform quality.

1. Introduction
Laser-based ultrasonic technology, where the ultrasonic waves are generated and detected by lasers, is a promising technology for non-destructive and non-contact evaluations of the material properties of moving and/or high temperature targets. Especially in the field of steel production, laser-ultrasonic technology is considered to be a very attractive solution for in-process measurements of the properties of the steel on the production line. Even though fundamental technologies have already been developed and have resulted in huge progress in application technologies, several improvements are still needed to be made in order to realize in-process measurements of the microstructure of steel materials in an actual production line setting.

Material property data, such as Poisson’s ratio, during the thin sheet production process would be very useful for manufacturing high value-added steel, such as sheets with uniform quality. However, until now, no in-process system for measuring Poisson’s ratio in steel sheets existed. In this study, the development of a system using laser ultrasonics to measure Poisson’s ratio was explored. In particular, ultrasonic generation techniques in the thermoelastic region were developed in order to avoid ablative damages to the surface of the sheets.
Furthermore, the robustness of the measurement system in an actual production line setting was explored. To confirm the robustness, a prototype measurement system was installed in a hot rolling pilot plant, and its performance was tested.

2. Preliminary experiments to detect the Lamb waves of zero group velocity

In order to apply laser ultrasonics to steel samples without causing surface damage, the energy of the pulsed Nd:YAG laser used for ultrasonic generation should be controlled at a relatively low level, and the generation scheme should be in the thermoelastic region rather than the ablation region. Clorennec D. et al. reported on using pulsed laser generation in the thermoelastic region for efficiently generating first-order symmetric Lamb mode (S1) in Duralumin plates under laboratory conditions [1]. It was reported that this S1 mode exhibited an anomalous behavior at the frequency (S1f) in which the group velocity vanished.

At first, preliminary experiments and analyses were conducted in order to investigate whether S1f measurements were possible for steel sheets as well as whether such measurements were effective for evaluating the material properties. A Q-switched Nd:YAG laser of the wavelength of 1064 nm was used for the ultrasonic generation, and 1W CW single frequency laser of the wavelength of 532 nm was used for the ultrasonic detection. Both of ultrasonic generation and detection laser beams were adjusted to the same spot on the sample surface. In this experimental system, a multi-channel interferometer was adopted [2]. According to our experiments, the interferometer showed better robustness about a liftoff deviation, compared with a conventional Fabry-Pérot interferometer combined with the 1W detection laser. Therefore, the multi-channel interferometer was adopted (liftoff: distance between sample surface and the front part the probe head).

The experiments were conducted for a 2 mm thick plain carbon steel sheet at room temperature, and the fluence of the ultrasonic generation laser beam was controlled at 1.8 mJ/mm², which is in the thermoelastic region. Figure 1 shows a FFT spectrum of the detected waveform, and a spectrum peak at 1.3 MHz was clearly observed. Figure 2 shows the theoretically calculated relationship between the frequency and the group velocity of Lamb waves in the case of a 2 mm thick steel sheet. In the calculations in figure 2, the longitudinal and shear wave velocity values were assumed to be the typical values of 5900 m/s and 3200 m/s, respectively. According to figure 1 and figure 2, it was confirmed that the spectrum peak in figure 2 corresponded to the S1 Lamb wave mode of zero group velocity (S1f).

It was reported that S1f can be expressed theoretically as follows, where \( V_L \) is longitudinal wave velocity, \( d \) is sample thickness, and \( \beta_1 \) is a function related to Poisson’s ratio [3]. It was additionally reported that \( \beta_1 \) values can be deduced from the dispersion curves of Lamb waves. Figure 3 shows the theoretical relationship between the \( \beta_1 \) coefficient and Poisson’s ratio, and it shows that \( \beta_1 \) varies from 0.975 to 0.60 as Poisson’s ratio varies from 0 to 0.451 [3].

\[
\text{S1f} = \beta_1 \cdot \frac{V_L}{2d}
\]

Since Poisson’s ratio is related to longitudinal and shear wave velocities, S1f is also related to longitudinal and shear wave velocities. If S1f values can be obtained dynamically, it will be possible to monitor the dynamic changes in material characteristics.

Figure 1. FFT spectrum of the detected waveform.
(FFT was conducted for a 90 \( \mu \)s temporal period of the waveform after the generation timing.)
3. Development of a technique to measure Poisson’s ratio

We have developed a system for measuring $S_{1f}$ values in the thermoelastic region, and the developed system was installed in hot rolling pilot plant. Figure 4 shows the schematic diagram of the pilot plant trial. Samples were heated in a furnace, and after descaling by the descaling machine, they were then hot rolled several times and ultrasonic measurements were conducted. The spot diameter of the focused generation beam was about 4 mm, and the power density at the irradiation spot was kept low in order to generate ultrasonics in thermoelastic region (fluence: 2.0 mJ/mm$^2$). A compact head component for ultrasonic generation and detection was developed for the pilot plant trials.

It emerged from these results that while the frequency peak of the lowest peak corresponds to $S_{1f}$, the other frequency peaks correspond to the resonant frequencies of the longitudinal waves since the space between each of the frequencies are all equal. The space between the resonant frequencies of the longitudinal waves $\Delta f$ is theoretically calculated by $\Delta f = V_l/(2d)$. Consequently, it also emerged that $\beta_1$ can be calculated with the $S_{1f}$ and $\Delta f$ values using equation (1), and Poisson’s ratio can thus be obtained using the data in figure 3. Figure 7 shows the results of consecutive Poisson’s ratio measurements using a measurement method at high temperatures, including temperatures in the vicinity of phase transformation as the steel sample naturally air-cooled. The above results enabled us to confirm that it is possible to dynamically measure Poisson’s ratio at high temperatures. In order to evaluate the validity of the developed technique, five steel samples of different steel kind were prepared and each Poisson’s ratio was measured by the developed technique at room temperature. Additionally, longitudinal and shear
wave velocity of each sample were measured by using contact probes, and each Poisson’s ratio was calculated by the following theoretical equation, where \(V_S\) is shear wave velocity.

\[
\text{Poisson’s ratio} = \frac{1}{2} \left[ 1 - \frac{1}{(V_L/V_S)^2} - 1 \right]
\]  

(2)

Figure 8 is the comparison of Poisson’s ratio measured by contact probes and developed laser ultrasonic technique. It was confirmed that Poisson’s ratio measured by laser ultrasonic technique showed a good agreement with the values measured by contact probes.

4. Conclusions
The developed system is capable of measuring Poisson’s ratio in steel sheets using the frequency data of S1 Lamb wave mode of zero group velocity (S1f) and longitudinal wave resonance frequencies without ablative damages on the steel surface, even in a hot rolling pilot plant environment.

References
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