Measurement of material properties of steel sheets using laser ultrasonic technology

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Abstract

A non-contact laser ultrasound measuring system for material properties of high-strength steels was developed. This system can measure material properties such as crystal grain size by analyzing high-frequency ultrasound waveforms generated by a pulsed laser. For this purpose, a light equalizing device is applied to the pulsed laser path so that the excited ultrasound can propagate a long distance without being weakened by diffusion. Therefore, the characteristics of the waveform can be captured clearly and analyzed correctly by this system. The advantages of this device were confirmed by numerical simulation of the ultrasonic propagation. The capability of this measuring system was shown by experimental measurement of various high-strength steel specimens. The measured crystal grain sizes showed good agreement with the results of SEM-EBSD observations. The measured crystal grain size also showed good correlation with the tensile test results.

Keywords: Laser-ultrasound; Non-contact measurement; Material property; Grain size; Hot strip mill; Rolling

1. Introduction

For metals like steels, crystal grain size is one of the main factors determining material properties such as strength and formability. It is generally known that the tensile strength and yield point of a metal increases as the
grain size becomes smaller. This has led to the commercialization of fine-grain steels with a grain size less than 10 microns. However, it has not been practical to inspect the material properties of a sufficient number of products because of the several days required to machine a test piece for tensile testing. On the other hand, the laser ultrasonic method provides a means for non-contact inspection. This method uses a pulsed laser to generate ultrasound, and a laser interferometer to detect the ultrasound after it propagates through the specimen. The features of this method are: (i) Quick, non-contact measurement, and (ii) Use of high-frequency ultrasound suitable for inspections of micro-structure and micro-defects. The correlation between ultrasound attenuation and the material properties of metals has been experimentally evaluated. Suzuki et al. (1993) applied laser ultrasonic methods to the detection of ferrite grain size enlarged by annealing. Hutchinson et al. (2002) tested a laser ultrasonic method in a hot strip mill environment. Lévesque et al. (2006) monitored thickness and austenite grain size in a seamless tube making process using laser ultrasound. Lim et al. (2006) measured austenite grain size in a hot rolling pilot plant. Sano et al. (2010) applied laser ultrasonic methods to the measurement of ferrite grain size changed by annealing.

This paper describes the development of a non-contact measuring system for the material properties of high-strength steels using laser ultrasonic methods. This system can measure material properties, such as crystal grain size, by analyzing the high-frequency ultrasound waveform generated by a pulsed laser. Because this requires analysis of the ultrasound waveform characteristics, it is important to detect and record the waveform with greater precision than has been the case for more conventional laser ultrasound uses, such as thickness measurement. Therefore, a light equalizing device was incorporated into the pulsed laser path to ensure that the excited ultrasound waveform can propagate a long distance without weakening by diffusion. With this device, the characteristics of the waveform can be captured clearly and analyzed correctly. The capability of this measuring method was evaluated by experimental measurements of various high-strength steel specimens. Crystal grain size measurements made using this system were compared with the results of SEM-EBSD observations. The correlation with tensile test results was also evaluated.

2. Laser ultrasonic apparatus

2.1. System configuration

Fig. 1 shows the measuring system. The pulsed laser is directed onto the specimen surface where it causes a small explosion. This produces a pulse-like ultrasonic vibration that propagates through the specimen and appears on the opposite surface. The second laser (detection laser) and an interferometer are used to measure this vibration.

Fig. 2 shows the system configuration. A Q-switched Nd:YAG pulsed laser generator is used to excite the ultrasound vibration. The wavelength is 532 nm and the maximum power is 1.25 J/pulse. The power of the pulsed laser is adjusted by changing an oscillator voltage to ensure that the amplitude of the detected waveform is within the measuring range of the interferometer (about 100 nm). A light equalizing device in the beam condensing unit, which is described later, improves the uniformity of the beam profile at the focus spot.
Since the interferometer is based on two-wave mixing in a photorefractive crystal, it can detect vibration at a non-polished rough surface. The frequency detection range of this interferometer is around 10-100 MHz. The separation distances to the specimen surface are 500 mm (pulsed laser) and 200 mm (interferometer).

### 2.2. Light equalizing device

The influence of material properties on waveform becomes greater as the distance of propagation increases. However, the amplitude of the ultrasound waveform is weakened by diffusion, which is caused by shear stress from the surrounding metals. To overcome this, a light equalizing device is used to enlarge the focus spot on the specimen and to produce a more uniform beam profile. This minimizes diffusion of the ultrasound waveform. Fig. 3 shows the configuration of the light equalizing device. This device uses a grid-like lens array which consists of many small lenses. The cross-section of the pulsed laser beam (at point “A” in Fig. 3) is divided into many small regions by the lens array. The beams from these regions are then projected onto the specimen surface through a convex lens. Since beams from many different small regions overlap at the focus spot (point "B"), this results in a uniform (equalized) beam profile at this spot, even if the uniformity of the beam profile of the incoming pulsed laser is poor.

### 2.3. Observed ultrasonic waveform

Fig. 4 shows an example of the observed ultrasonic waveform. The vertical axis shows the amplitude of the ultrasonic vibration detected by the interferometer. The starting point on the time-axis shows the time when the pulsed laser was applied to the specimen. The arrows show the repetitive echoes of a longitudinal wave. The interval of the echoes corresponds to the time taken for the longitudinal wave to propagate through the strip and back.
3. Numerical simulation of ultrasonic propagation

The effectiveness of the light equalizing device was confirmed by numerical simulation of ultrasonic propagation. This simulation was done for a 2-dimensional model, and used the finite difference method. In Case-A, the spot size of the pulsed laser is 0.4 mm and the beam profile is a Gaussian distribution. In Case-B, the spot size of the pulsed laser is 3.0 mm and the beam profile is equalized. The intensity changes as a Gaussian curve and the time width is 10 ns. Fig. 5 shows the contour maps of the von-Mises stress distributions when the propagation time is 0.5 $\mu$s. In Case-A, the ultrasound mainly diffracts spherically, reducing the detected waveform amplitude. On the other hand, in Case-B, the ultrasound mainly propagates forward, thereby maintaining the amplitude of the detected waveform even after the ultrasound has propagated back and forth several times between the surfaces of the specimen.

![Fig. 5. von-Mises stress distributions when propagation time is 0.5 $\mu$s: (a) Case-A; (b) Case-B.](image)

Fig. 6 shows the ultrasonic waveforms at the detection point of the interferometer. It was found that the amplitudes of the longitudinal ultrasonic echo weaken more quickly in Case-A than in Case-B. This difference can be explained by the difference in diffraction behavior shown above.

![Fig. 6. Ultrasonic vibrations obtained by finite difference simulation: (a) Case-A; (b) Case-B.](image)

4. Signal processing

The recorded ultrasonic waveform is divided into frequency components using continuous wavelet transformation. The attenuation rate of each frequency component is obtained by curve fitting the echo amplitudes versus propagation distances. The longitudinal wave component of the ultrasound is attenuated mainly by scattering at grain boundaries. According to the “scattering law”, the frequency $f$ [Hz], attenuation rate $\alpha$ [dB/mm], and crystal grain size $D$ [$\mu$m] are related as follows.

$$D = \left( \frac{\alpha}{1000 \cdot K \cdot f^n} \right)^{\frac{1}{n-1}},$$  \hspace{1cm} (1)

where the coefficients $n$ and $K$ were obtained by analyzing test results of sample plates with known grain size. The grain size is calculated using this scattering law Eq. (1).
5. Experimental specimens

The ferrite grain sizes of various high-strength steel specimens were measured by this method. Specimens were commercial high-strength steel plates, comprising eight different steel grades and manufactured at five different hot strip mills. The specimen thicknesses were in the range 2.85-6.0 mm, and the tensile strength were 400-590 MPa. The specimens were ground to remove the thin oxide layer on the surface. Measurements were performed at between two and five points on each plate, at room temperature.

The measurement results were compared with SEM-EBSD observations. EBSD (electron back scattering diffraction) is a detection method used in scanning electron microscopy (SEM). It can detect the crystal orientation of each pixel in the observed cross section. The grain boundaries are defined as the outlines where the difference in orientation between neighboring pixels is more than 15 degrees. The grain size can be calculated by counting the number of pixels inside each grain. Cross sections were observed by SEM-EBSD across one quarter of the specimen thickness. The average grain size varied in the range 3.5-13.5μm.

6. Experimental results

Fig. 7 shows the relationship between the attenuation rates and average grain sizes measured by SEM-EBSD. The attenuation rates are the 40 MHz components of longitudinal waves. The results show a good correlation.

Fig. 8 shows the correlation between the crystal grain sizes measured by this system and by the SEM-EBSD. It was seen that they showed good agreement.
Fig. 9 shows the relationship between tensile test results and grain sizes measured by this system. The measured grain size (horizontal axis) was based on an average of between two and five points for each specimen. The vertical axis is the tensile strength and the yield point in the rolling direction. The relationship between yield point and grain size shows a tendency similar to Hall-Petch’s law. That is, the yield point is inversely proportional to the square root of the grain size.

Fig. 9. Relation between tensile test results and ferrite grain size measured by this system (Sano et al., 2013).

7. Conclusions

A non-contact system for measuring material properties using laser ultrasound was developed. The system included a light equalizing device using a lens array. The advantages of the light equalizing device for the pulsed laser were shown by a numerical simulation of ultrasonic propagation. This demonstrated that use of the light equalizing device increased the distance that the ultrasound was able to propagate without weakening by diffusion. This makes it possible for the characteristics of the waveform to be captured clearly and analyzed correctly. The capability of this measuring system was demonstrated by making experimental measurements of various high-strength steel specimens. Crystal grain sizes measured by this method show good agreement with the results of SEM-EBSD observations. The measured crystal grain sizes also show good correlation with tensile test results.

References