Laser Ultrasonic Characterisation of Rolled Steel Strip: Wave Propagation in Inhomogeneous Thin Sheets

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Abstract. For the production of hot rolled steel it is of special interest to assess the homogeneity of the material along the length of the strip. Being couplant free, laser ultrasound as a method is especially suited for the task because it opens up the opportunity of measuring material parameters early in the production process. Detailed models of the ultrasonic signal are needed though in order to extract robust figures from the experimental data, which give information about the elastic constants and damping rates resulting from the underlying microstructure.

Micro-alloyed and dual-phase steel sheets in the thickness range between 3.5 mm and 4 mm were used in a test case for the propagation of Lamb waves in a weakly inhomogeneous and damping medium. Using a scanning setup we are able to determine the full dispersion relation of the in-plane sound field and thereby determine the contribution of the varied vibrational modes to the sound field. In particular we are able to determine the frequencies of the non-dispersing surface modes. These are closely related to the Poisson’s ratio of the steel, which is a reliable figure for the homogeneity of the strip and independent of the thickness of the sheet. Likewise we determined damping rates for different surfaces modes taking into account the geometric spread of the sound waves.

Inhomogenities of the material, e.g., texture from rolling or scattering from grains, break the symmetry of the sheet geometry and necessitate numerical treatment of the wave propagation problem. Numerical simulations of ultrasonic wave propagation are used to investigate the influence of grain size and texture.

Introduction

Laser ultrasonic systems are based on the generation and detection of ultrasound by exciting a wide frequency ultrasonic pulse in a material using a short pulse (nanosecond) laser and a single frequency laser to interrogate the resultant vibration of the surface. In the field of steel production, laser ultrasonic methods are employed if conventional ultrasonic methods cannot be used because of the temperatures involved in the process or a couplant free alternative is needed for other reasons. Laser ultrasonic setup - as a general rule - provide large flexibility of their parameters, which need to be chosen to meet the needs of the particular application. Typical setups in the steel industry are capable of detecting ultrasound in the megahertz frequency range (1-30 MHz) [1-3].
The work presented in this paper is embedded in the PUC (Product Uniformity Control) project whose objective is to achieve enhanced and sustained product uniformity of steel strip, by improving existing inline measurement techniques. Within the project samples are characterised using electromagnetic, (laser) ultrasonic and destructive methods, which are combined to generate a better understanding of the interplay between process parameters, inline measurement data, mechanical properties and ultimately the steel’s microstructure [4].

![Fig. 1. Simplified experimental setup for laser ultrasonic measurements of Lamb wave dispersion.](image)

1. **Samples, Experimental Setup and Theoretical Background**

1.1 **Samples**

A total of 80 samples were cut from four different coils of two different steel grades (a micro-alloyed and a dual-phase grade) at ArcelorMittal Eisenhüttenstadt GmbH. The samples were selected in order to reflect special processing conditions, which were most likely to lead to inhomogeneities in the strip. The samples were approximately 500 mm by 500 mm wide, and were ranging from 3.5 mm to 4 mm in thickness. The sheets were sampled from the head and the tail section of the coils; aligned in two tracks on each side of the strip (5 samples per track).

1.2 **Laser Ultrasonic Setup**

For the laser ultrasonic measurements, a laser ultrasonic setup (LASUS) provided by Salzgitter Mannesmann Forschung GmbH similar to the one shown in Fig. 1 was used [5]. A Q-switched, flash lamp pumped Nd:YAG pulse laser was used for the generation of ultrasound in the ablation regime. The laser was able to deliver pulses of 7 ns and an energy of up to 800 mJ per pulse. The generation laser was focused onto the sample generating a spot with a diameter of 1.7 mm.

A 5W cw laser operating at 532 nm was used for detection. The light of the detection laser was coupled into a 50 µm multi-mode fibre and focused onto the sample resulting in a detection spot size of 0.6 mm. The light was collected by a lens with an optical aperture of 25 degrees at a distance 110 mm from the sample surface and injected into a multimode optical fibre of 0.8 mm diameter and a numerical aperture of 0.28. The detection head could be scanned over the surface in one direction keeping the excitation spot fixed.
A 500 mm scanning confocal Fabry-Pérot interferometer (FPI) with a free spectral range of 150 MHz and an approximate finesse of 30 was used for the phase demodulation of the signal. An avalanche photodiode was used for detection.

A proprietary control scheme was used to dynamically lock the FPI to the frequency of the detection laser [6].

1.3 Theoretical Background

1.3.1 Lamb waves

In a thin steel sheet and as a general rule elastic waves are guided by the geometrical boundaries of the solid. In a thin sheet the resulting Eigenvalue problem is solved by sinusoidal waves propagating in the plane [7].

For an isotropic solid without texture Rodriguez et al. [8] calculate the displacement for the symmetric and antisymmetric modes using cylindrical coordinates, giving equations for the displacement in the radial and the z-direction

\[
\begin{align*}
    u_r^{A,S} &= J_1(kr)e^{i\omega t} f_{r,k}^{A,S}(z) \\
    u_z^{A,S} &= J_0(kr)e^{i\omega t} f_{z,k}^{A,S}(z)
\end{align*}
\]

where \( k \) is the wave number, \( \omega \) is the angular frequency, \( J_0(kr) \) and \( J_1(kr) \) are the first two Bessel functions and the \( f(z) \) are mode dependent functions determined by the free surface boundary conditions. The total displacement field is given by a superposition of the above solutions and is itself radially symmetric.

1.3.2 Data Analysis

The signal obtained by laser ultrasonics is sensitive to the displacement \( u_z \) at the surface. Scanning the detection spot through the epicentre of the excitation measures the radial part of a radial symmetric function, \( s(r,t) = s(\mathbf{r},t) \). We are interested in the Fourier transform of the 2-dimensional field \( S(k,\omega) = S(\mathbf{k},\omega) \). It is given by the zero-order Hankel transform

\[
S(k,\omega) = 2\pi \int_0^\infty s(r,\omega) J_0(kr) r dr
\]

where \( J_0(kr) \) is again the Bessel function and \( s(r,\omega) \) is the regular time Fourier transform of the laser ultrasonic signal.

In a recent publication Nagata et al. introduced a material property measurement system based on the measurement of certain frequency components in a laser ultrasonic signal. In particular they identified a close relation between Poisson’s ratio and the ratio \( \beta \) of the fundamental frequency \( \Delta f \) of the longitudinal waves and the frequency \( S1f \) of the S1 Lamb mode at a special point of vanishing group velocity [9]. They could show that this method produced reliable results for thin steel sheets even under inline conditions. The two frequencies required are readily extracted from a frequency-wavenumber plot, where regions of zero group velocity stand out because the slope \( d\omega/dk \) vanishes.

1.3.3 Grain Scattering

Grain scattering causes the redistribution of vibrational energy into modes that would otherwise not be present in the signal. Fig. 2 shows laser ultrasonics data simulated for microstructures with different average grain sizes from 5 µm to 50 µm. For the smallest
grain size the modal structure that is expected from the unperturbed Lamb wave picture remains intact and the individual modes can be resolved. In such a case the effect of scattering is quite similar to the one caused by, e.g., hysteresis damping, in that energy is removed from the primary mode. Scattering then results in an exponential decrease of the signal $A(t, k) = \exp(-\alpha t) \exp(i\omega_0 t) f(k_0)$ with an attenuation coefficient $\alpha(\omega_0, k_0)$. In the frequency domain we expect to see a Lorentzian like spectral broadening of each mode

$$A(\omega, k) \propto \frac{1}{\sqrt{\alpha^2 + (\omega - \omega_0)^2}}$$

For the frequency range relevant in this paper, the frequency dependence of the attenuation coefficient is often modelled as

$$\alpha(f) = b_1 f + b_2 f^4$$

where $b_1 f$ represents a contribution from hysteresis damping, and $b_2 f^4$ is damping by Rayleigh scattering [10]. For larger grain sizes the picture becomes increasingly perturbed and eventually the signals may not be well described by an exponentially decaying harmonic. Indeed there might be regions of the spectrum that actually gain amplitude.

Fig. 2. Frequency-wavenumber plots for different average grain sizes.

2. Measurements and Data Analysis

2.1 Measurements

Fig. 3 shows a typical laser ultrasonic signal for 4 mm hot rolled micro-alloyed steel. The detection spot was initially positioned directly opposite to the excitation spot and then scanned over the surface in steps of 0.1 mm. The position of the excitation spot was kept fixed during the measurement. The backwall echos of the longitudinal waves can be readily identified because of the constant time difference between successive arrivals. In addition a large contribution of a travelling surface wave can be observed. The data are offset by a constant time which was caused by a delay in the triggering circuit.
For the right part of Fig. 3 the same data have been transformed into frequency-wavenumber space using regular FFT in the time domain and the zero-order Hankel transform for the special coordinate. The small periodic signals in the frequency direction are an artefact of the finite length FFT. A rectangular window had been used for the analysis because other windowing techniques, while advantageous for a frequency analysis, would hamper the determination of attenuation rates from the Fourier transformed data.

Fig. 4 shows a cut through the frequency-wavenumber space for \( k = 0 \) (blue) and at the minimum position \( k = 0.5 \) 1/mm (red) for this sample thickness. The \( \beta \) ratio has been extracted from similar plots for each of the 80 samples.

**Fig. 3.** Typical laser ultrasonic signal from a 4 mm hot rolled steel plate (micro-alloyed steel). The ultrasonic generation and detection spots were on opposite sides of the sample.
2.2 Data Analysis

Fig. 5 shows the variation of the $\beta$ ratio for the MA and DP samples. For the red squares the detection head was scanned in transverse direction, blue diamonds denote data measured on the same sample but in rolling direction.

![Graph showing variation of the $\beta$ ratio for the micro-alloyed and dual-phase sample set.](image)

Even though the data scatter appreciably, it is noticeable that measurement results from the same sample are remarkably reproducible. Indeed, no significant difference between the measurements in the rolling direction and the ones in the transverse direction could be observed. The variation between samples therefore clearly characterizes the individual sample and may hint toward different microstructures as result of the different processing conditions.
Characterising the grain scattering in the samples has proven to be challenging because the laser ultrasonic signal is heavily influenced by the geometric spread of the wave package. We therefore limit our analysis to pure pressure waves with zero wavenumber, corresponding to vibrations that are in phase over the entire plate. They are characterised again by a group velocity of zero. Equivalently this states that these wave packages are not transported out of the detection area during the measurement, and that transport effects do not further influence the analysis.

Fig. 6 contains attenuation coefficients that have been determined for a 4 mm DP sample. Each data point has been extracted from a Lorentzian fit to the individual pressure wave resonance. A linear relation between the attenuation coefficient and the resonance frequency is observed.

![Fig. 6. Frequency dependence of ultrasonic attenuation for a 4 mm DP sample.](image)

Conclusion

We have demonstrated that laser ultrasound can be used to identify inhomogeneous regions of hot rolled strip steel. Using a scanning laser ultrasonic detector, we could identify the contribution of the individual Lamb modes to the signal. The laboratory results show that the method is capable of measuring the frequency of the S1 Lamb wave mode of zero group velocity (S1f) alongside the fundamental longitudinal resonance frequency with sufficient accuracy. Our data analysis shows that the system was capable of discriminating between different steel grades and is able to resolve differences between samples of the same steel grade.

The linear relation between the attenuation coefficient and the resonance frequency implies that damping within the samples is dominated by hysteresis effects and not by grain scattering, suggesting that the effective grain size of the samples was too small to have an impact on the damping of the longitudinal waves. In fact effects from grain scattering have been readily observed for heat treated samples with average grain sizes from 20 µm to 76 µm using the same setup that was used for this publication [11], and numerical calculations carried out by Volker et al. show that the scattering of shear waves is more pronounced even for smallest grain sizes [11]. It may therefore be argued that other parts of the frequency-wavenumber spectrum should be more strongly influenced by grain scattering than the ones looked at so far.
Acknowledgment

The research leading to these results has received funding from the European Union’s Research Fund for Coal and Steel (RFCS) research programme under grant agreement nr. RFSR-CT-2013-00031.

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