Ultrasonic Assessment of Metal Microstructures, Modelling and Validation

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Abstract. The uniformity of strip rolled steel and its mechanical properties are intrinsically linked to the complex microstructure along the strip length. Ultrasonic methods are sensitive to differences in grain size, grain distribution and texture. This with the intention to provide suitable tools to inline monitors the properties of hot rolled steel.

In this paper, we present a comparison of results from numerical and analytical simulations of the elastic wave propagation in deterministic and stochastic models of the microstructures. Modelled microstructures are used to provide the flexibility of assessing single microstructural parameters of different steel grades and rolling conditions. The individual simulations are validated against laser ultrasonic measurements on metal sheets in thickness range of 2mm-5mm, which were independently characterized metallurgically.

The correlation to parameters as texture, grain size and dual phase composition was addressed. The simulation facilitates the development of methodologies to identify quantitative values that will enable to non-destructively assess the quality of a component. Different methods are developed based on changes in attenuation and velocity. These were tested against the simulated as well as the experimental data.

Introduction

The uniformity of the microstructure of steel strip over the entire coil length and between different coils of the same grade is key to stable and consistent material behaviour. The primary objective of the PUC (Product Uniformity Control) project [1] is to achieve enhanced and sustained product uniformity of steel strip and associated benefits, by improved interpretation of data from inline measurement techniques and systems that aim real-time and non-destructive characterisation of microstructure parameters.

In this paper we focus on laser ultrasonic characterization. Traditionally main focus has been on calculating attenuation and wave velocities, but also backscattering is considered.
In general the attenuation in amplitude (i.e. decrease in energy) as the ultrasonic wave propagates through some media can be subdivided into four different mechanisms, i.e., absorption, scattering, dispersion, beam spreading. There are three different regions of wave scattering as a function of grain size and wavelength. If the grain size is much smaller than the wavelength, this is called the Rayleigh regime. Scattering in this region is approximately omnidirectional. When the grain size is much larger than the wavelength, it is called the geometrical regime. The intermediate range is called the stochastic regime.

The effects of grains boundaries on the propagation of ultrasonic waves have been investigated using perturbation methods, mostly the Born approximation (assuming that the incoming field that is scattered by a grain is the unperturbed field). An early example is the work by [2-4] where weak anisotropy and equally-sized and spherical grains are assumed.

A different type of approach is to regard the grain scattering as a multiple scattering problem for the grains in a homogeneous host material. The multiple scattering by isolated scatterers is a classical problem, going back to the classical papers by a number of authors [5-9].

It should be noted that in all methods mentioned so far the shape of the grains is not taken into account; the shape is simply assumed to be spherical or spheroidal at most.

The numerical modelling used within the PUC project involves generating synthetic microstructures based on a Voronoi-model developed by TATA steel [10-12]. An example of a modelled microstructure is shown in Fig. 1. Each grain is described by its phase, for example ferrite or martensite and its crystallographic orientation, indicated by the three Euler angles. The orientation can be fully random or some preferential direction may be assigned.

![Fig. 1 Example of modelled microstructure from TATA steel.](image)

Within the scope of the project, two types of modelling approaches are followed, one numerical scheme based on a finite difference time domain implementation and one semi-analytical approach. The numerical scheme offers full flexibility in modelling the microstructure in both 2D and 3D, but this is computationally intensive. On the other hand the semi-analytical approach has limitations with respect to the level of microstructural detail that can be modelled but it is computationally more friendly. This makes it more suitable for parametric studies.

The models are described in more detail below. Modelled results are compared to actual measurements for validation. The measurements are performed using two different laser ultrasonic systems one at Swerea KIMAB and a second one at Salzgitter Mannesmann Forschung.
1. Numerical modelling

Wave propagation in an elastic medium can be accurately modelled using the finite-difference approach. Physical phenomena such as mode conversion and frequency dependent scattering from grain boundaries are included automatically. To calculate wave propagation, the elasto-dynamic equations are used, where the stresses and the particle velocities in the medium are described. Three sets of equations are required: the equation of motion, the strain-displacement equation, and the constitutive relation.

Equation of motion:
\[
\frac{\partial \tau_{ij}}{\partial x_j} + F_i = \rho \frac{\partial^2 v_i}{\partial t^2},
\]
where \( \tau_{ij} \) is the stress tensor for the direction \( [x_i, x_j] \), \( F_i \) is the external force applied in direction \( x_i \), \( \rho \) is the density tensor of the medium, and \( v_i \) is the displacement in direction \( x_i \).

Strain-displacement equation:
\[
\varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} \right),
\]
where \( \varepsilon_{ij} \) is the strain tensor for direction \( [x_i, x_j] \).

Constitutive relation
\[
\tau_{ij} = C_{ijkl} \varepsilon_{kl},
\]
Where \( i, j, k, l = 1,2,3 \), for a 3D Cartesian geometry and \( C_{ijkl} \) is the elasticity matrix. These equations are solved numerically using a rotated staggered grid[13]. Laser ultrasonic measurements can be modelled by defining an extended vertical velocity source at the surface.

2. Analytical modelling

The SUNDT and simSUNDT software packages have been developed to efficiently model ultrasonic wave propagation in solids. It contains a complete mathematical model of the ultrasonic measurements and can therefore be used to simulate various NDT configurations. The development has been on-going since almost twenty years and has been validated and described in journals and conference contributions (see e.g. [14-16]). The model includes a general model of an ultrasonic contact probe working as transmitter and/or receiver and the interaction of the ultrasound with the microstructure in an isotropic or anisotropic medium. The probes are modelled by boundary conditions instead of as above an external force, the elastodynamic vector wave equations can be solved by using displacement potentials. Expanding the two states in spherical vector wave functions and using the Betti identities the signal response can be provided as a close expression with all information about the scatterer captured in its transition matrix. The characterization of the probe acting as a transmitter is encapsulated in the expansion coefficients for the incident field and to evaluate its behaviour as a receiver we use an electromechanical reciprocity argument by Auld[18].

In this model, grain scattering is simulated as a the superposition of ultrasonic scattering with a large number of elastic spherical inclusions. No multiple scattering effects are considered in the noise signal but only a superposition of direct scattering from each defect. The number of defects is based on the assumption of constant volume fraction and satisfies the central limit theorem according to previous validations [18-19]. The inclusions have the
same density as the surrounding material but provided with slightly deviating wave speeds (corresponding to 20% increase in stiffness). The position of each scatterer is randomly distributed in a uniform manner in the modelled volume but the sizes have been distributed with four different distributions (uniform and three different normal distributions). In Fig. 2 the backscattered amplitude based on a LUS point source (1 mm in diameter) have been normalized with a SDH. The amplitude correlation in the figure follows quantitatively with what have been reported in literature[20].

![Fig. 2 Backscattered amplitude (dB) as function of nominal grain size and distribution of sizes](image)

3. Experimental set-up

Within the scope of PUC project both Salzgitter Mannesmann Forschung and Swerea KIMAB are involved in conducting laser ultrasonic measurements to characterize samples. A typical laser ultrasonics set-up consists of a generation laser and an interferometry based detection system. The laser used to generate the ultrasound was the fundamental, 1064 nm, pulsed output (8 ns) from a Quantel Bigsky 100mJ Nd:YAG-laser. The generation occurred in the ablation regime to guarantee high amplitude bulk waves. As a detection source, a continuous single mode Coherent Verdi 5 laser, 532 nm, was used. The vibrating surface velocity at the detection point was measured by converting the single mode probe light in a Fabry-Perot interferometer from a frequency modulated signal to an amplitude modulated signal. A schematic overview of the system is shown in Fig. 3.

![Fig. 3 Schematic drawing of a typical laser ultrasonic measurement set-up](image)

4. Model validation

To validate the modelling results, measurements are performed on an aluminium plate with a thickness of 2.84 mm. The ultrasonic wave is generated on one side of the plate and the
generated wave field is recorded on the opposite side. At the first position the generation and detection laser beams are directly opposite of each other. Eight measurements are performed, each time moving the detection laser beam 1 mm away. Using the numerical modelling approach a simulation in 2D and 3D is performed. The amplitude of the 2D simulation is corrected for the geometrical spreading difference between 2D and 3D. The wavelet of the second compressional wave arrival at position 1 is used to match the wavelets. The result is shown in Fig. 4. The black curves indicate the arrival times of the compressional wave echoes. The measured data is shown in Fig. 4a, the first echo is not clearly visible, because the laser generation pulse temporally affects the detection sensitivity of the interferometer. Obviously this is not modelled because it is specific behaviour of this instrument. The models only described the propagation of elastic waves in solids. Overall the modelled results agree well with the measurements with some minor differences. The timing of the echoes in the analytical result is slightly different due to a small difference in material properties used in the model. All echoes observed in the measurements can also be identified in the simulated results and there amplitude as function of position (horizontal distance between source and receiver) is very similar. Therefore the differences are not considered relevant within the scope of the PUC project.

![Fig. 4](image)

**Fig. 4 Comparison between measurements and various modelled results, a) measurement, b) 2D numerical simulation, c) 3D numerical simulation and d) analytical model.**

**5. Measurement and modelling of the influence of grain size**

Grain size is an important parameter affecting the mechanical behaviour of steel. A series of 2D microstructural models have been created by TATA steel. The grain size increases from 5 µm to 50 µm (see Fig. 5). Each model is 3 mm thick and 12 mm wide. A laser ultrasonic source is modelled with a spot size of 1 mm. The black lines at the top, bottom and the centre of Fig. 5 are the locations at which the wavefield is recorded for analysis. Snap shots for each of these models is shown in Fig. 6. The snap shots show the vertical velocity component of the wavefield. The amplitude is colour coded, red is a positive amplitude and blue a negative amplitude. The time at which the snap shot is taken is 0.7 µs. At this time the compressional wave just reflected from the back wall. The shear waves have not yet reached the back wall. Along the top surface a Rayleigh surface wave can be seen.
Fig. 5 Models with increasing grain size generated by TATA steel, a) grain size: 5 \( \mu \)m, b) grain size: 10 \( \mu \)m, c) grain size: 20 \( \mu \)m, d) grain size: 30 \( \mu \)m and e) grain size: 50 \( \mu \)m.

Fig. 6 Modelled snap shots (time is 0.7 \( \mu \)s) for an increasing grain size, a) grain size: 5 \( \mu \)m, b) grain size: 10 \( \mu \)m, c) grain size: 20 \( \mu \)m, d) grain size: 30 \( \mu \)m and e) grain size: 50 \( \mu \)m.

From these snapshots it is clear that the scattering rapidly increases with increasing grain size. The shear wave scattering dominates in this case. Characterizing grain scattering in these thin samples is quite challenging. Inline measurements can only be conducted from one side. This means that the reflected wave from the back wall will interfere with the scattered shear waves. In thin samples this effect is more pronounced due to the short repetition time of multiple reflections. Within this short amount of time, the shear wave scattering has not yet died-out.

Similar effects are also observed in measurements. Special heat treated samples have been prepared by CEIT. These samples have an increasing average grain size from 20 \( \mu \)m to about 76 \( \mu \)m. The thickness of these samples is about 14 mm. Transmission measurement have been conducted by Salzgitter Mannesmann Forschung. The recorded field is shown in
Fig. 7. The measurements are performed in transmission, the first arriving event at 2.4 µs is a compressional wave. The second event at 4.5 µs is the direct shear wave. The results for the larger grain sizes clearly show a grain scattering reverberation trail behind the first compressional wave and shear wave arrivals. The frequency content of the laser ultrasonic measurements in these thick samples is significantly lower (up to 7 MHz in measurements and 30 MHz in the simulations) than in the simulations on the thin samples. This explains why there is still a good signal for the 76 µm average grain size. Qualitatively similar effects are observed in the both the modelled and measured wave field. Further qualitative comparisons between measurements and modelled results will be made in the PUC project.

Conclusions

The PUC project aims at developing and validating models for ultrasonic wave propagation in steel, taking the microstructure into account. This provides a more in depth understand which parameters can be used and reliably measured for inline microstructural characterization.

The numerical scheme offers full flexibility in modelling the microstructure in both 2D and 3D, but this is computationally intensive. On the other hand the semi-analytical approach has limitations with respect to the level of microstructural detail that can be modelled but it is more computationally friendly. This makes it more suitable for parametric studies. Comparison between actual laser ultrasonic measurements and modelled results shows a good agreement. Further simulations studies are performed evaluating the influence of texture and second phase fraction.

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References


