Novel Technique for Velocity and Thickness Measurements with Laser Ultrasonics

Martin ENGMAN ¹ Magnus FALKENSTRÖM ¹
Swerea KIMAB
Stockholm, Sweden; Phone: +46 84404840, Fax +46 84404535; e-mail: martin.engman@swerea.se, magnus.falkenstrom@swerea.se

Abstract
A technique for independent thickness and velocity measurements, using laser ultrasonics, will be described. Thickness and velocity measurements are highly useful in the metal industrial both for controlling the thickness of the product where other techniques cannot be used but also for material characterisation considering both microstructural and mechanical properties. Longitudinal and transversal ultrasonic velocities can be used as fingerprints of the characteristics of a material provided that sufficient accuracy can be achieved in the measurements. Conventional laser ultrasonic thickness measurements rely on the assumption that the velocity of the investigated material is known and so determining the thickness through simple time-of-flight measurements combined with the already established velocity. The method which will be presented is based on trigonometrical relations between echoes travelling along different paths though the material, resulting in the ability to measure both the thickness and the ultrasonic velocities.

Keywords: Laser ultrasound, velocity, thickness, anisotropy

1. Introduction

Laser ultrasound has been shown to be a practical technique for product monitoring in industrial installations due to its speed and ability to function without physical contact. One successful application has been thickness gauging of extruded seamless pipes since the ability to reach both sides of the pipe wall with a conventional optical measurement is not possible (Levesque et al., 2006). To enable such a measurement the ultrasonic wave velocity has to be first established which is done through calibration where the chemical composition, the microstructural state and the temperature of the steel must all be included and even then the velocity cannot be exactly established.

The longitudinal and transversal wave velocities of ultrasonic waves travelling through a material can directly or indirectly reveal information about the state of the material. Mechanical strain in an elastic material can be directly related to velocity measurement; grain size has shown to correlate well with longitudinal velocity measurement for austenitic steel (Aussel & Monchalin, 1989); mechanical properties such as yield strength and hardness in bainitic and martensitic steel have been shown to correlate well with both longitudinal and transversal velocities (Engman & Falkenström, 2010; Łukomski & Stepinski, 2010).

For monitoring wall thickness of a material where the ultrasonic wave velocity is not established or for measuring ultrasonic wave velocity on a material where the thickness cannot be established accurately enough, the need for an independent thickness/velocity method is obvious.
2. Theory

A method for measuring thickness and velocity has been developed which is based on measuring the relationship between the arrival times of echoes travelling along different paths through the sample. Figure 1. illustrates the experimental set-up which is used for this method where the generation light is split into two parallel beams with a specific separation and the detection light is emitted on to one of the two generation spots. Figure 2. illustrates the paths for the first two consecutive echoes travelling through a plate sample, both when generated at ‘G1’ and at ‘G2’. When considering an isotropic material, the relationship between the arrival times of the ultrasonic wave travelling paths ‘a1’ and ‘b1’ according to Figure 2 depends solely on the relationship between the separation of the two generation spots and the thickness of the sample. Since the distance ‘L’ is known, the thickness can be calculated according to equation 1. The equation reveals that for each echo which arrives from ‘G2’ in Figure 2 the thickness can be calculated. When the thickness is known, the velocity can consequently be calculated through measuring the time difference between consecutive echoes generated at ‘G1’ in Figure 2 combined with the already calculated thickness.

Figure 1. Illustration of the experimental set-up. Left; sample seen from above, red lines indicate focus of the generation laser, green dot represent focus of the detection laser. Right; cross section of a plate sample. The red line represents generation light; the green line represents detection light.

Figure 2. Illustration of the pathway of the first two echoes travelling through a plate sample.

![Diagram](image)

$$R = \sqrt{\frac{L^2}{4n^2\left(\frac{t_n}{t_1}\right)^2 - 1}}$$  \hspace{1cm} (1)

R = Thickness  
L = Separation of generation focuses  
n = numbering of the consecutive echoes  
t = the arrival time of the consecutive echoes travelling from ‘G1’ in Figure 2  
t* = the arrival time of the consecutive echoes travelling from ‘G2’ in Figure 2
2. Materials and methods

2.1 Laser ultrasound 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. The locking of the Fabry-Perot interferometer was regulated by an electronic unit developed by AEA-technology (Hutchinson et al., 2002).

2.2 Sample material

For sample materials, two completely different products were chosen, one a hot rolled low alloyed steel about 4.5mm in thickness and one an extruded and aged aluminium alloy plate about 6mm in thickness. The steel material was polished whilst the aluminium sample was untreated.

2.3 Resistive heat treatment

One of the samples was heat treated through resistive heating with an instrument especially design at the Swerea KIMAB institute. A background gas flow of helium was applied to reduce oxidation during heating.

2.4 Alternative thickness measurement

To verify the results the samples were measured with a micrometer Digitrix II

3. Results and discussion

3.1 Laser ultrasound analysis during annealing

A very demonstrative way of verifying the method is by annealing a sample whilst performing laser ultrasonic measurements. Temperature variation will cause a noticeable velocity change for the ultrasonic waves travelling through the material. The low alloyed steel was used for this experiment. Separation of the generation beams for this test was set to 6.858mm and to verify the results the thickness was measured with a micrometer to be 4.780mm. Figure 3 shows the results of the thickness and velocity measurements. The black dotted line shows the expected thickness change of the sample due to heat expansion, using a thermal expansion coefficient of $13 \times 10^{-6}$ m/mK. The results show that the thickness is accurately measured and that it changes as expected due to thermal expansion. The graph also clearly shows that the velocity of the waves and the measurement of the thickness are completely independent from each other.
Figure 3. Thickness and velocity measured on a low alloyed steel whilst annealing it to 900 °C, the diagram also contains the expected thickness change due to heat expansion.

3.2 Production material

A hot rolled steel can in many cases have a highly anisotropic structure and texture after rolling, especially if it is not subsequently normalised. Figure 4 shows the microstructure of a hot rolled steel, the left image, where the rolling direction is in the horizontal direction, shows that the material has a strongly pancaked structure along the rolling direction. It could be expected that the wave velocity is not constant for all angles when travelling through such a material, both when traveling along or across the rolling direction.

Figure 4. Optical microscopy of a hot rolled low alloyed steel. The left image shows the cross-section of the material when the rolling direction is horizontal and the right image shows the microstructure when the rolling direction is perpendicular to the page.

Figure 5 shows the results of the laser ultrasound measurements of thickness of the hot rolled steel sample when the separation of the generation beams is along the rolling direction of the sample. The sample was attached to a linear stage and measurements were performed along a 35mm length of the sample. The results show good accuracy when compared with the thickness measured using a micrometer and the root mean square deviation was estimated to 11.4 µm.

Figure 5. Laser ultrasound measurements of thickness for a hot rolled steel where the separation of the generation beams is along the rolling direction of the material.
Figure 6 shows the results where the thickness is calculated three times for three consecutive echoes; ‘1st echo’, ‘2nd echo’ and ‘3rd echo’ for each measurement. The accuracy declines for later echoes since the measured time differences become smaller and the signal becomes weaker but it seems as though all three measurements gives the same result. The graph also contains the measured longitudinal velocity based on a mean value of the three thicknesses.

Figure 6. Laser ultrasound measurements of thickness and velocity for a hot rolled steel where the separation of the generation beams is along the rolling direction of the material.

Figure 7 shows the results for the same sample with the exception that the separation of the generation beams are across the rolling direction. The results show that the measured thicknesses for the three different echoes differ by about 100µm between the 1st and the 3rd echo. The reason for this noticeable difference in results probably relates to the anisotropy of the material. The velocity is calculated through the mean value of the three thicknesses and consequently the velocity becomes incorrect when compared with Figure 6. The thickness from the 1st echo is closest to the real value and the thickness from the 3rd echo is furthest away from the real value. This was unexpected since the wave from the 1st echo, having a much larger angle of incidence, might expected to have a stronger effect of any anisotropy in the material.

Figure 7. Laser ultrasound measurements of thickness and velocity for a hot rolled steel where the separation of the generation beams is across the rolling direction of the material.

Figure 8 shows results of thickness measurements from the aluminium material when the separation of the generation beams is across the rolling direction when using only the first echo for the analysis. The results give a root mean square deviation of 28.2µm when compared with the results from measurements with the micrometer. Figure 9 shows similar results from the first three consecutive echoes. Figure 10 shows the results of measurements on the aluminium alloy when the separation of the generation beams was along the rolling direction. Also here there is a slight difference between the results from the three first echoes and a deviation compared with the thickness measured with the micrometer. Contrary to the
results from the steel material the laser ultrasound measurements give a value that is higher than the true value.

![Figure 8](image1.png)

Figure 8. Laser ultrasound measurements of thickness for extruded aluminium plate where the separation of the generation beams is across the rolling direction of the material.

![Figure 9](image2.png)

Figure 9. Laser ultrasound measurements of thickness and velocity for extruded aluminium plate where the separation of the generation beams is across the rolling direction of the material.

![Figure 10](image3.png)

Figure 10. Laser ultrasound measurements of thickness and velocity for extruded aluminium plate where the separation of the generation beams is along the rolling direction of the material.

From the present observations, especially when looking at Figure 7 and Figure 10, the method is seen to be noticeably sensitive to anisotropy in the material. However, by considering the results from several consecutive echoes, the anisotropy can be estimated and possibly used itself as a parameter for material characterization. If the degree of anisotropy can be estimated by measuring the difference between results from waves travelling at different incidence angles, it be possible to compensate for anisotropy and consequently reach more accurate results of the thickness and velocity. The effect of, for example, a hot rolled pancake structure on the ultrasonic propagation ability may be more complex than initially expected considering the results in Figure 7 where the waves propagating with a smaller incidence angle deviate more from the expected values. This needs to be investigated and understood.
When comparing the results from the measurements across and along the rolling direction for the two materials it is seen that the aluminium has a more velocity-anisotropic structure along the rolling direction and steel has a more velocity-anisotropic structure across the rolling direction. This again shows the complexity between the different structures and the elastic properties of the different materials. Another observation from the measurements on the steel and the aluminium plate is that the variation of the results is higher for the aluminium plate. This is expected since the ration between the beam separation and the thickness is smaller. The higher ration, the more accurate the measurement can be done since the difference in arrival times will be more noticeable. If the separation is too large the longitudinal wave traveling from ‘G2’in Figure 2 will become too weak and consequently for each thickness range there will be an ideal beam separation to thickness ratio for best results.

3. Conclusions

A new method for measuring thickness and velocity in plate metals has been investigated in this paper. High accuracy has been observed on isotropic materials with root mean square deviation as low as 7.7µm on a plate thickness of 4.559mm. For samples where velocity is anisotropic, the present results deviate from the true values by as much as ±100µm for the investigated samples but the ability of quantifying the anisotropy also arises. Additional work is needed to understand how an anisotropic material affects the wave velocities for different incidence angles so that this can be taken into consideration. The ability to estimate anisotropy and possibly texture in materials using this method seems possible in view of the fact that small differences in ultrasonic velocities between waves propagating at different incidence angles can be estimated. This measurement in itself could possibly be used for material characterisation.

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References


