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Thickness and grain size monitoring in seamless tube-making process using laser ultrasonics

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Abstract

The seamless tube-making process often causes wall-thickness variations generally in a helical pattern along the tube length. A laser-ultrasonic system installed immediately after the final operation in tube making provides process monitoring. Tube wall thickness and temperature measurements guide the mill adjustments to achieve the desired tolerances. Using the same ultrasonic signals, additional functionality provides the ability to measure the size of austenite grains. A signal processing approach based on a single echo analysis is used for determining wall thickness and austenitic grain size in relatively thick materials. Discussions review challenges specific to on-line conditions such as limited signal-to-noise ratio. A statistical comparison with metallographic results shows that the laser-ultrasonic grain sizes determined on-line have at least the same accuracy.

Keywords: Thickness; Austenite grain size; Laser ultrasonics; Seamless tube

1. Introduction

Seamless tubes are used for numerous applications, such as hydraulic cylinders and power transmission components (gears and bearing races), where microstructural variation due to a weld seam is not acceptable. The seamless tube-making process can cause wall thickness variations, which often follow a helical pattern. Thickness measurements during the production is not easy, firstly because of the relatively high tube temperature (of about 1000 °C), and secondly because the tube is not precisely guided.

Laser ultrasonics [1], which uses lasers for the generation and detection of ultrasound at a distance, was the elected technique to develop the mill-worthy system. Although there has been previous in-plant demonstration of this technique for on-line tube gauging [2–4], this is the first system continuously used in production. Using the same ultrasonic signals, added functionality provided the ability to measure the size of the austenite grains, which largely determine the final microstructure, and consequently the mechanical properties of steels. While the time propagation of an ultrasonic echo can provide information about the thickness of the tube, ultrasonic attenuation can provide information about the grain size in the austenitic phase [5], which is the standard phase for hot-rolling steel products. Continuous in-line monitoring of grain size facilitates a controlled process that leads to an optimized microstructure, avoiding post-production modifications usually performed through costly heat treatments.

After a brief description of the system, the paper presents the signal processing approaches involved in the measurements of wall thickness and austenitic grain size using a single echo and a reference, for use in relatively thick materials (up to 30 mm). Discussions review the challenges specific to on-line conditions, in particular limited signal-to-noise ratio (SNR). The laser-ultrasonic system, which has been running at The Timken Company in Ohio, USA,

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for more than 3 years, is performance evaluated for the continuous monitoring of both wall thickness and austenite grain size.

2. Description of the system

Generation of ultrasound is performed in the ablation regime by a sufficiently strong laser pulse. The recoil effect following material ejection off the surface (essentially surface oxide) and plasma pressure produces strong longitudinal (compressional) ultrasonic wave emission perpendicular to the surface. The ultrasonic waves, after reflection by the inner wall of the tube, cause a small surface motion on the outer surface (see Fig. 1a). Detection of the ultrasound uses a second laser with pulse duration sufficiently long to capture the ultrasonic signal of interest. The surface motion associated with the arrival of the ultrasonic signal produces a Doppler frequency shift on the scattered light that is demodulated by an optical interferometer. Fig. 1b shows an ultrasonic signal obtained on-line on a steel tube at high temperature. Specially designed laser Doppler velocimeters (translation and rotation) and two-color pyrometer allow the measurement of the position and temperature at the measurement location (see Ref. [6] for details). An off-line cabin houses the laser-ultrasonic system including all delicate equipments (lasers, interferometer, etc.) in a clean air-conditioned environment. Optical fibers transmit the light beams for the three functions (laser ultrasonics, pyrometry and velocimetry) to a front coupling probe located right on the production line. The lasers include the generation short-pulsed Nd:YAG laser and the detection laser, which is long-pulse Nd:YAG with a high-frequency stability. The repetition rate is 100 Hz, which gives, depending upon the processing conditions and the tube outer diameter, 5–15 data points per tube circumference. The demodulator is a stabilized confocal Fabry–Perot interferometer also located inside the cabin.

3. Tube wall thickness measurement

For determination of wall thickness, a signal processing approach based on a single echo was developed to measure time-of-flight (TOF) from the acquired laser-ultrasonic signals in the presence of ultrasonic backscattered noise. Numerical cross-correlation is performed between the first ultrasonic echo reflected from the inner surface of the tube and a reference pulse. The cross-correlation technique, an optimal matched-filter, traditionally uses two successive echoes in the signal and has shown success in determining precise TOF with sufficiently high SNR of the second echo [7]. Such a second echo may be too weak in laser-ultrasonic signals from hot seamless steel tubes. As reference pulse, a synthetic pulse is built taking an average of several signals and fitting the obtained pulse with a model of the pulse.

The use of split spectrum processing (SSP) for the case of very low SNR was also considered. SSP consists in the decomposition of a signal into multiple signals by applying a set of narrow-band Gaussian filters. The set of signals is then processed with a non-linear operator to yield a composite signal having a better SNR. For a given non-linear operator, the efficiency of SSP depends on three parameters: the filter width, the filter separation and the number of filters. It as been shown that optimum values of the filter width and filter separation can be found [8]. The optimum value for the number of filters is more complicated, but is related to the effective frequency bandwidth of the ultrasonic echoes. Therefore, after proper windowing of the echo and the reference as input to cross-correlation, a strategy was implemented to use SSP on the cross-correlation output. Considered as matched-filter, the cross-correlation result should strengthen the coherent part of the original signal and SSP could help locating the true maximum in the cross-correlation output to determine the TOF.

Fig. 2 shows an example of using the single-echo approach described above from a signal having a low SNR. On the left, the signal on top is the reference pulse and the signal between cursors on bottom is used for interrogation of the first echo. Notice that the horizontal axis is the time in μs and that the amplitude of each signal is normalized to one. On the right, the result from cross-correlation is shown on top, the horizontal axis being the time lag with respect to the beginning of each signal portions. Also, the result from SSP is shown on the bottom, which clearly indicates the presence of a coherent signal in the cross-correlation output. We have observed that in many occasions the signal has a sufficient SNR to avoid the additional step of performing SSP on the cross-correlation output. The wall thickness is then determined

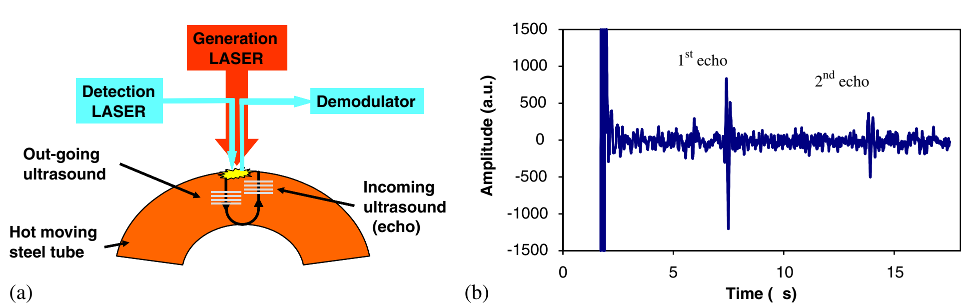

Fig. 1. (a) Principle of laser-ultrasonic generation and detection in a tube and (b) signal acquired on-line for a 16-mm-thick steel tube at 940 °C.

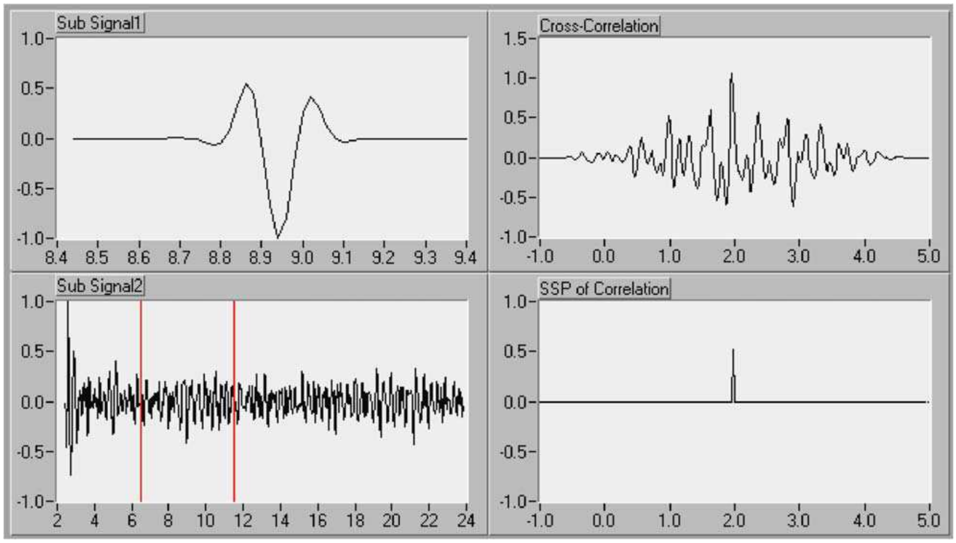

Fig. 2. Example of cross-correlation with SSP on the first echo of a signal having a low SNR.

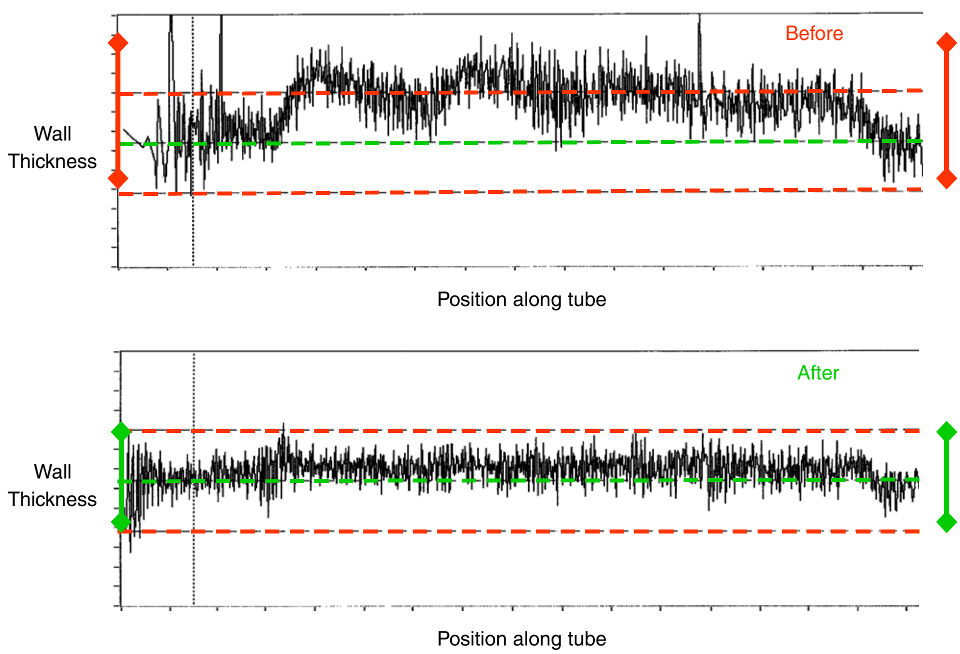

Fig. 3. Example of a tube detected within specification only at its very ends and then, after corrective measures brought to the line, the next tube produced within specifications along the entire length.

from the TOF using the ultrasonic velocity at a given measurement location with the temperature given by the pyrometer. Also, eccentricity can be determined from several wall thickness values around the tube circumference using a statistical estimator.

Accuracy of the system in gauging hot tubes properly was verified by selecting several tubes and measuring them at room temperature with a conventional ultrasonic gauging system. The results obtained at high and room temperatures were found in very close agreement (within $\pm 0.5\%$). The system providing in real-time wall thickness information over the whole tube length allows adjustment of the mill to get a product within specifications. It also allows detecting worn or defective mechanical parts of the mill. Fig. 3 presents one example of corrections that were made possible with a tube that was out-of-specifications except at its very ends. Without the system, using the conventional method of cutting from time-to-time tube endings and manually measuring them, such defective tubes would have been processed with exceeding wall thickness unnoticed, resulting in additional costs for additional machining.

4. Austenite grain size measurement

For determination of austenite grain size, a signal processing approach also based on a single echo was developed to obtain a relative attenuation spectrum from laser-ultrasonic signals in the presence of backscattered noise. The approach was used to quantitatively determine austenite grain size over a wide range (20–300 μm) and for relatively thick materials (up to 30 mm). The method consists in proper windowing of the first echo and calculation of its amplitude spectrum for both the signals from the tube and from a reference material. The frequency-dependent attenuation curve is then calculated by the ratio between the spectrum of the reference and that of the tube material to be characterized. A scattering parameter, b, related to austenite grain size is determined by fitting the experimental attenuation curve to a model for the attenuation mechanisms involved such as

$$\alpha(f) = \alpha_o + af^m + bf^n, \qquad (1)$$

where m and n are the frequency powers, respectively for absorption and scattering. According to well-accepted models for these mechanisms, m is between 0 and 2 and n is between 0 and 4. For robustness, m and n could be kept fixed during fitting, and should not be too close. Otherwise, a single power–law term should be used with an effective frequency power for both mechanisms involved. Then a calibration curve is established between the scattering parameter and the austenite grain size measured by metallography on many steel samples. Fig. 4 illustrates the method showing an example of the material and reference echo spectra, and the resulting ultrasonic attenuation measured and fitted with a model. In this approach, the normalization by a reference material signal allows the correction for system response and diffraction but does not take into account fluctuations in signal strength from one measurement to another. Normalization for such variations is made unnecessary by fitting the experimental attenuation curve to a model that accounts for this, e.g. including a constant factor α_o as in Eq. (1). This method is particularly efficient for broadband ultrasonic systems with sufficiently good response as low frequencies.

For calibration, steel samples of different grades were heated in a Gleeble thermomechanical simulator in the range of 900–1250 °C and held to saturate grain growth. During the whole thermal cycle, laser-ultrasonic measurements were performed and, after proper quenching (varying with the steel grade), the former austenitic grains were revealed by etching and quantitatively characterized by image analysis. Measurements were also performed on a reference sample of steel having low attenuation to obtain the attenuation spectra. Fig. 5a depicts an example of a calibration curve, where the scattering parameter, b, obtained from fitting the attenuation spectrum of the first echo is plotted against the grain size obtained from

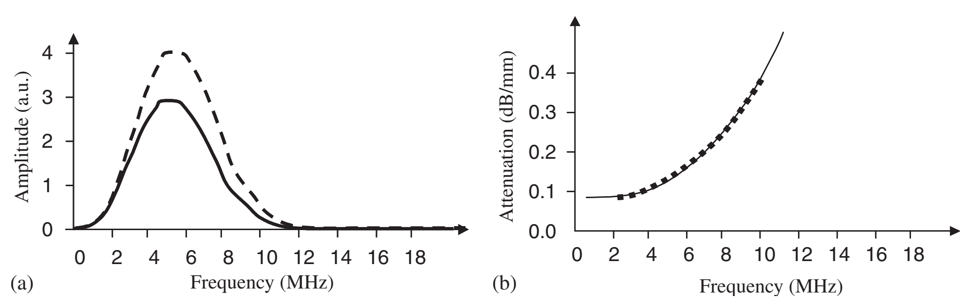

Fig. 4. (a) Example of the material (solid line) and reference (dashed line) spectra, and (b) resulting attenuation spectrum measured (dots) and fitted (line) with a model.

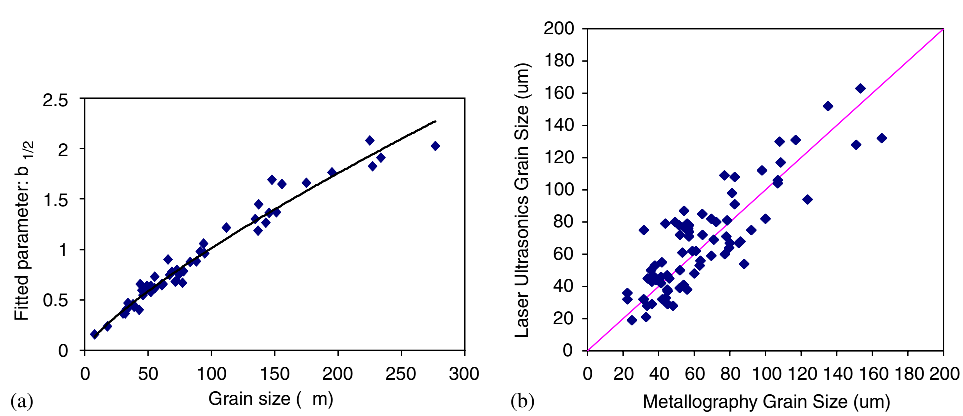

Fig. 5. (a) Calibration of the fitted attenuation parameter 'b' and metallographically measured austenite grain size and (b) austenite grain sizes measured on-line by the laser ultrasonic system as a function of those obtained by metallography on the same tubes after proper quenching.

metallography. For on-line measurements, many challenges specific to such conditions were addressed. To improve the attenuation spectrum quality, ultrasonic signals obtained at many positions along the tube are averaged, and the grain size is evaluated over a segment of the tube or over the whole tube. Also, the effects of tube eccentricity and roughness were found to be somewhat small and no correction was applied. Fig. 5b shows the comparison between austenitic grain size measured on-line by the laser ultrasonic system and that obtained by metallography on the same tubes after proper quenching. Due to the on-line conditions, the ultrasonic measurements are expected to be less accurate than those performed in the laboratory. The metallographic values are also less accurate due to the challenge of applying, in the production environment, the proper cooling procedure that allows the visualization of former austenitic grain sizes. With estimated metallographic grain size accuracy between 0.5 and 1 ASTM, a statistical analysis shows that the laser-ultrasonic grain sizes determined on-line have at least the same accuracy as those obtained from standard metallography methods.

5. Conclusion

A laser-ultrasonic system was developed and implemented to gauge thickness and determine the austenite grain size on-line in a seamless tube production plant. A signal-processing approach based on a single echo is used in the presence of backscattered noise and moderately low SNR after propagation in relatively thick materials. This system also includes a pyrometer to measure tube temperature and a coordinate measuring system to determine the measuring locations. This system provides thickness information all along the tube length unlike the conventional technique of cutting and measuring end sections. It eliminates such an imprecise and tedious practice and contributes to increased productivity. The real-time determination of the austenitic grain size provides an extraordinary tool towards controlling microstructure by a closed loop controlled thermomechanical processing. A statistical analysis with metallographic results shows that the laser-ultrasonic grain sizes determined on-line have at least the same accuracy. With more than 1,000,000 tubes inspected since its March 2002 deployment, the system has demonstrated its reliability and usefulness and is leading to significant productivity increase.

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