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On-line Monitoring of Wall Thickness and Austenite Grain Size on a Seamless Tubing Production Line at the Timken Company

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INTRODUCTION

For almost 40 years, since the principle of the generation and detection of ultrasonic waves by lasers has been demonstrated, there was great hope that this technology would be used in metallurgical production lines. The expectations were not without reason: ultrasound is well known to be able to measure thickness, detect flaws and provide information about the microstructure of materials. But the contact or near-contact character of conventional ultrasonic techniques prevents its use as a sensor on production lines where materials are moving and are often at high temperature. The unique remote character of laser-ultrasonics, where ultrasound is generated and detected by optical means, make this technique particularly fitted to real-time monitoring products in the metallurgical industry. During the 80's, important developments on powerful detection lasers and speckle-insensitive interferometers made the technique ready for use on rough and low-reflection surfaces. During the 90's the technology became fully commercial in the aerospace industry to inspect large composite panels with complex geometry. But for the metallurgical industry the application of the technology was limited to on-line demonstrations for the same reasons most sophisticated new technologies fail to become commercial success: high cost and lack of proven robustness for long term use. But by the end of the 90's, the Timken Co with partial funding from US Department of Energy decided to build a laser-ultrasonic system to measure the wall thickness of tubes for one of their seamless tube production line. The laser-ultrasonic system (called LUT) was designed, built and installed at Timken in the spring of 2002 by a team from the Industrial Materials Institute of the National Research Council of Canada, a group that has been pioneering the industrial use of laser-ultrasonics for many years. Since then, the system has been working continuously, providing production people key information about the thickness profile of each tube in real-time. By the summer 2004, more than one million tubes had been inspected. More recently a new functionality was added to the system, the measurement of austenite grain size, providing new exciting possibilities on controlled thermo-mechanical processing (CTMP) of Timken's tubes.

THE LASER-ULTRASONIC GAUGE

In laser-ultrasonics, the ultrasonic waves are generated and detected at a distance (typically several tens of centimeters to one meter) by lasers. The physical foundations of the technique are described in Apendix I and a more complete description of the technique can be found in reference 1. Robustness is the most important challenge in the design of a system to work permanently in the harsh environment of a tube mill where severe vibrations, large temperature variations and high levels of water vapor and dust are present. These challenges were addressed by locating the generation and the detection lasers as well as the interferometer in a trailer outside the building and by connecting them to the 'laser-ultrasonic head' (LUT head) located above the production line with fiber optics. Figure 1 shows the LUT head attached to the 'laser shield', a metal structure designed to guide the tube and assure laser safety. The LUT head is installed just after the rotary sizer, which is the last stage of tube production as illustrated in Figure 2. The hot tube exiting the rotary sizer goes through the laser shield while being subjected to both translation and rotation movements that are measured optically by two Doppler velocimeters integrated to the system. Additionally, the temperature is measured optically by a two-color pyrometer.

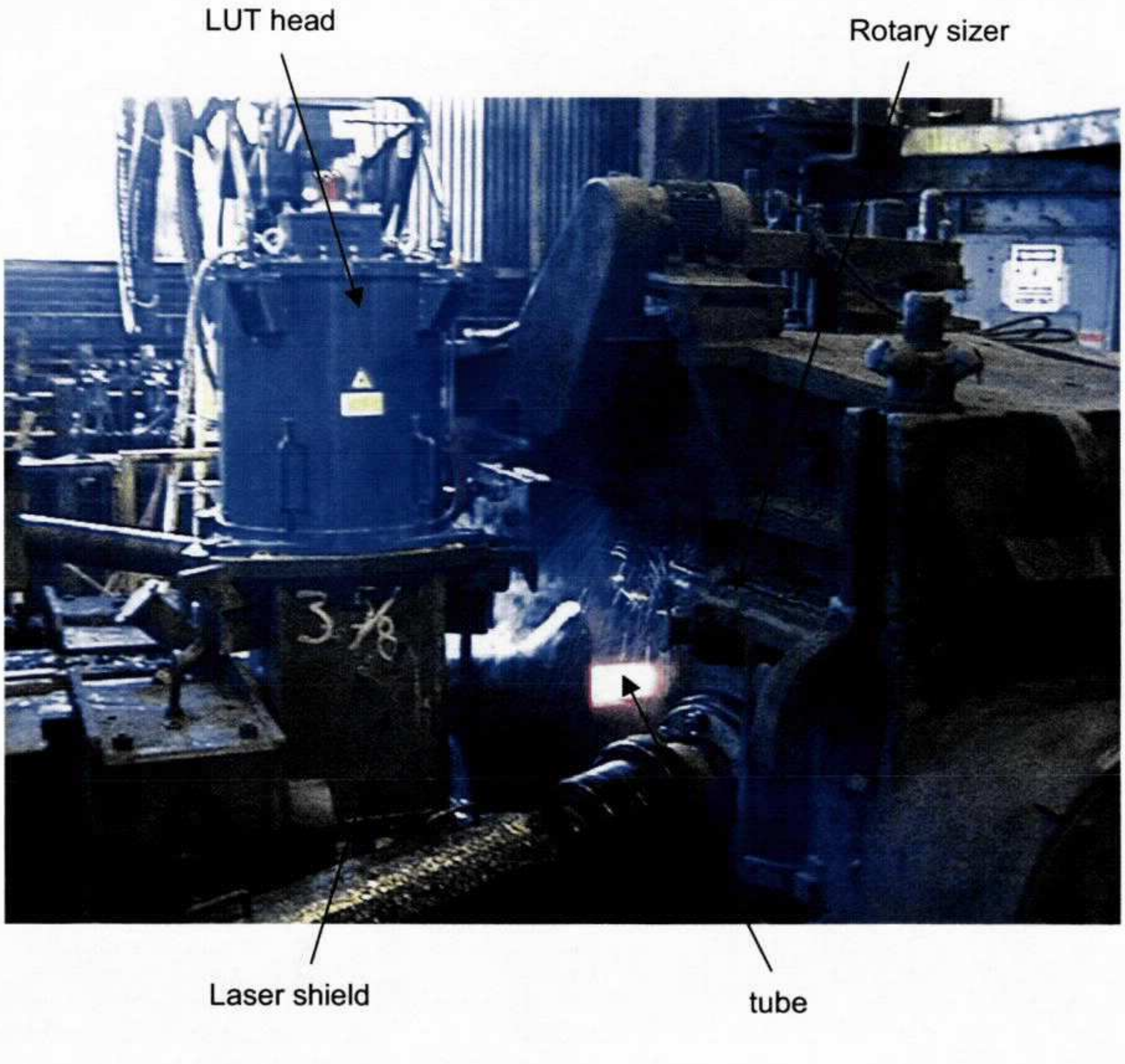

Figure 1. Laser-ultrasonics head installed on Timken's production line.

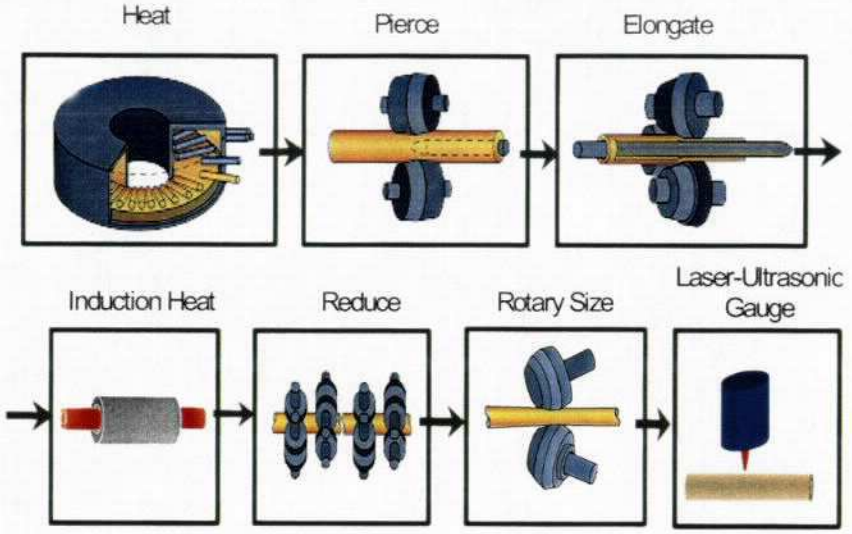

Figure 2. Stages of a seamless tube fabrication process.

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 produce strong longitudinal 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 (typically in the nanometer range) (see Fig. 3a). Detection uses a second laser with a pulse duration sufficiently long to capture all the ultrasonic echoes of interest (typically 50 μs) and very stable in frequency and intensity. The ultrasonic surface motion produces a Doppler frequency shift on the scattered light that is demodulated by an interferometer. Figure 3b shows an ultrasonic signal obtained online. The time delay between echoes is a measure of thickness (if velocity is known) and the echo amplitude decay is a measure of attenuation, which in the present case was demonstrated to be intimately related to the austenite grain size.

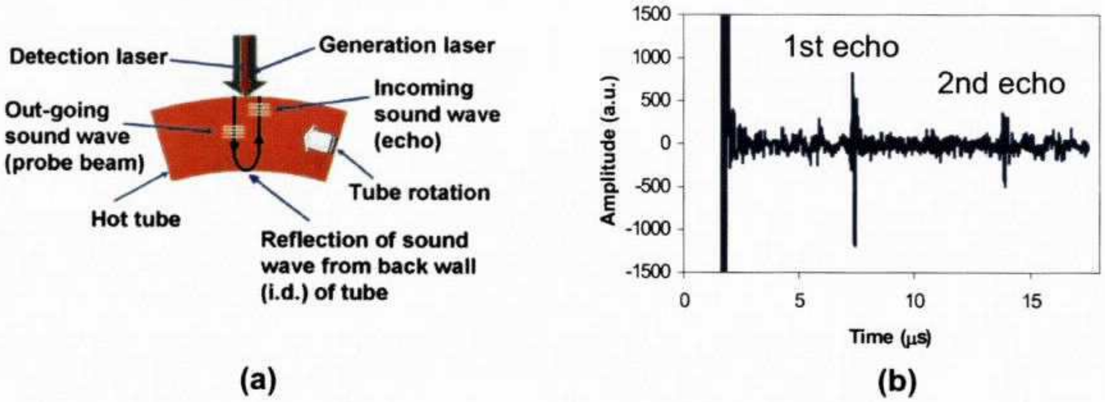

Figure 3. (a) Principle of laser ultrasonic generation and detection in a tube and (b) signal acquired on-line for a 16 mm thick tube at 940 °C.

WALL THICKNESS MEASUREMENTS

The tube making process oftentimes causes wall thickness variations in a helical pattern along the tube length. Therefore, additional clean-up stock is added to the tube as illustrated in Figure 4. Process control to reduce this variation would achieve considerable savings through improved material utilization and reduced tubing scrap and re-work. For components machined from tubing, additional savings are realized from reduced machining time and tool wear. The need of a sensor to close the control loop of the process was accomplished by placing the laser-ultrasonic sensor measuring wall thickness immediately at the end of the production line.

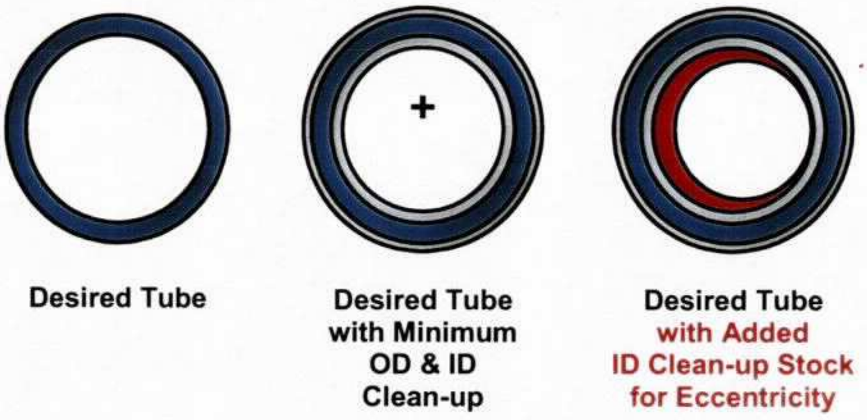

Figure 4. Clean-up addition to tube dimensions due to eccentricity.

Accuracy of the laser-ultrasonic system in gauging hot tubes 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 +/- 0.5%). The system providing real time wall thickness information over the whole tube length allows adjustment of the mill machinery to manufacture product within specifications. It also allows detecting worn or defective mechanical elements of this machinery. Figures 5 and 6 present two examples of corrections that were made possible by the system and which avoided the production of large quantities of out-of-specification product. Since the tubes are rapidly rotating, the short-scale variations of the thickness are due to eccentricity (the inner and outer circumferences are not concentric). Figure 5 shows a case where high eccentricity was observed and corrected afterwards. Figure 6 shows the case of a tube that was out-of-specifications except at its very ends. Without the system, using the conventional method of occasionally cutting tube ends and measuring them, such defective tubes would have been processed unnoticed, resulting in additional machining costs.

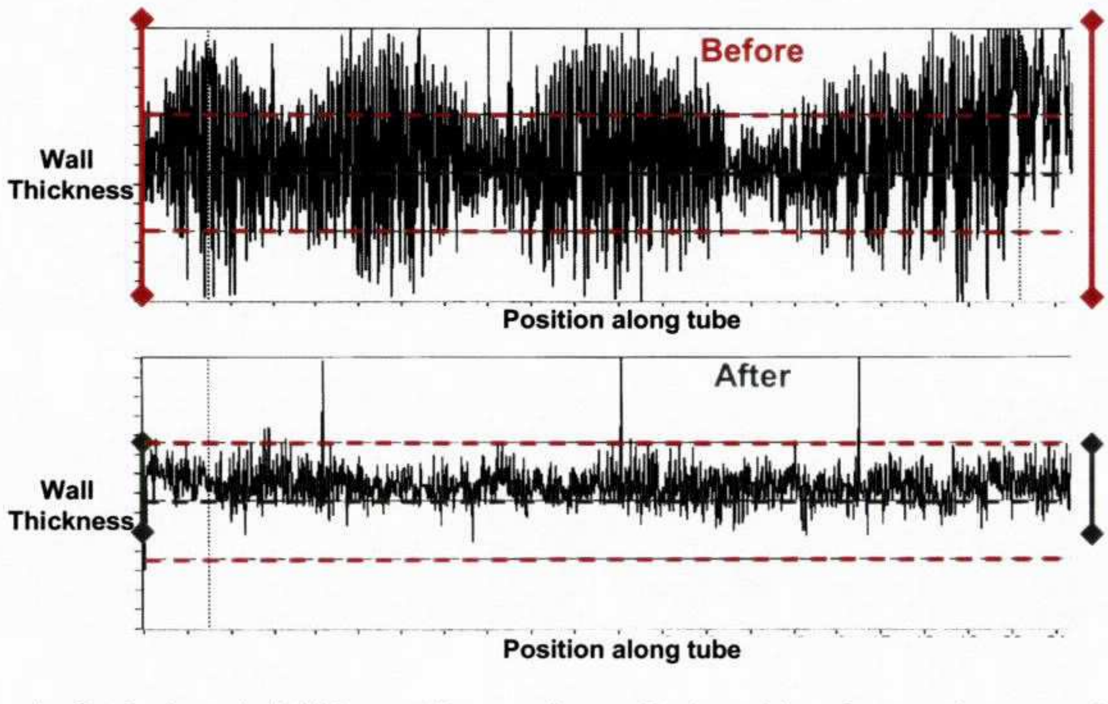

Figure 5. Example of a tube detected with high eccentricity exceeding specification and then, after corrective measures brought to the line, the next tube produced within specifications.

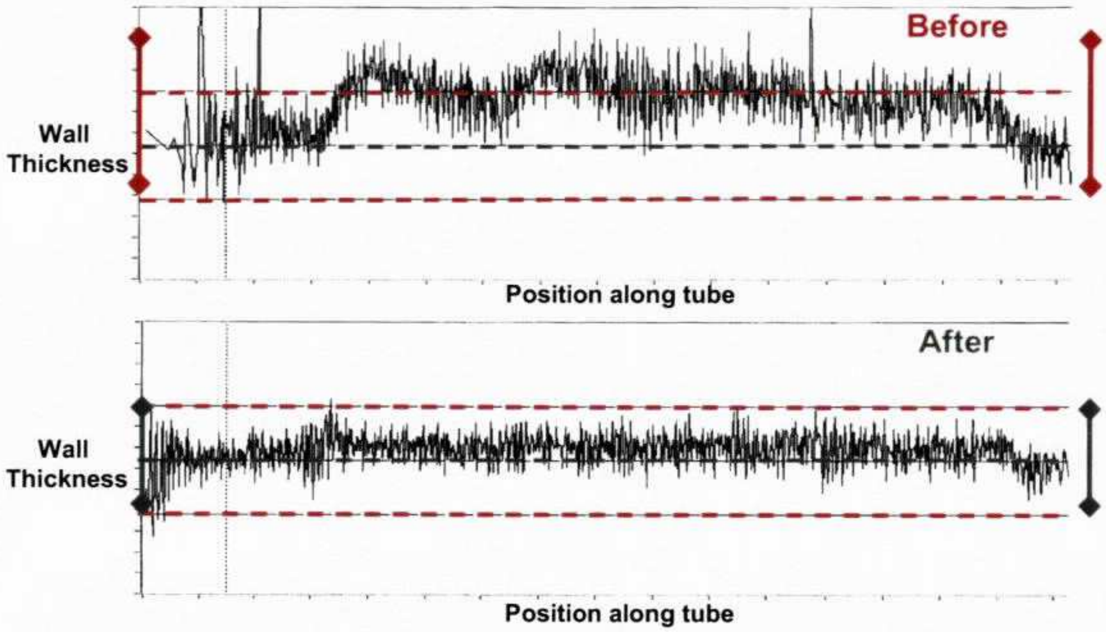

Figure 6. Example of a tube detected within specification only at its very ends and then, after corrective measures, the next tube produced within specifications along the entire length.

AUSTENITE GRAIN SIZE MEASUREMENTS

Austenite grain size associated to the austenite decomposition during cooling is the most important metallurgical parameter that determines the mechanical properties of the products as illustrated in Figure 7. The possibility of measuring the austenite grain size and further control the cooling process, provides a powerful tool for the controlled thermo-mechanical processing (CTMP) of tubes.

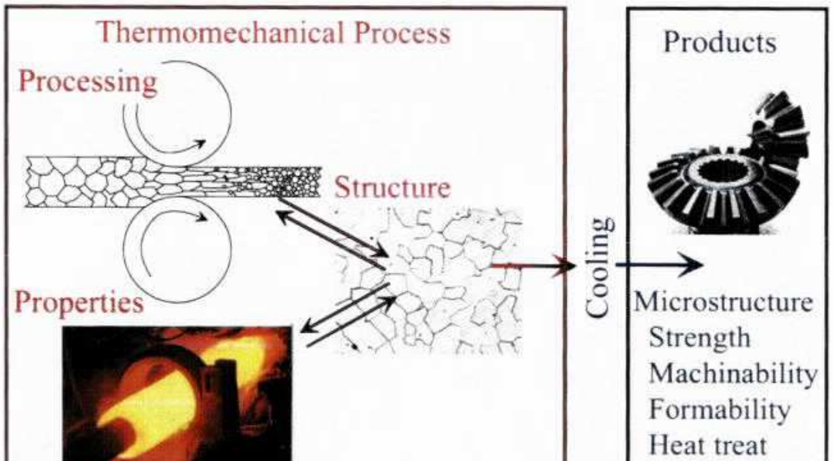

Figure 7. Relationship between the microstructure of steels at austenite phase and its subsequent austenite decomposition during cooling and the final product mechanical properties.

The attenuation of ultrasound was demonstrated to be highly dependent on the austenite grain size [2]. The approach adopted for establishing the quantitative relationship between austenitic grain size and ultrasonic attenuation for a wide range of grain sizes (20 to 300 μm) and for relatively thick materials (up to 30 mm) was to experimentally determine calibration curves between the frequency dependent ultrasonic attenuation and the grain size measured by metallography.

Steel samples of different grades were heated in a Gleeble thermomechanical simulator in the range of 900 to 1250 °C and held for about 10 minutes 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. Figure 8 depicts an example of a calibration curve, where the ultrasonic scattering parameter 'b' obtained from a fit of the attenuation as a function of ultrasonic frequency is plotted against the grain size obtained from metallography. The effect of the temperature on such a calibration curve due to temperature dependent absorption and scattering mechanisms was also determined experimentally. This calibration curve obtained in the laboratory was implemented in the signal-processing software used to determine the austenitic grain size from online ultrasound attenuation.

In transferring this knowledge to online measurements, many challenges specific to online conditions were addressed: eccentricity, roughness, diffraction, system response, and limited signal-to-noise ratio. To improve the attenuation curve quality, ultrasonic signals obtained at many positions along the tube are averaged, which means that the grain sizes are not evaluated at a single point but over a segment of the tube or over the whole tube. The effect of tube eccentricity and roughness were found to be negligible and/or coupled to the diffraction correction and no correction was applied. The diffraction has a major effect on the measured attenuation and correction was made based on tube thickness and temperature. This correction was determined experimentally with tubes of various thicknesses.

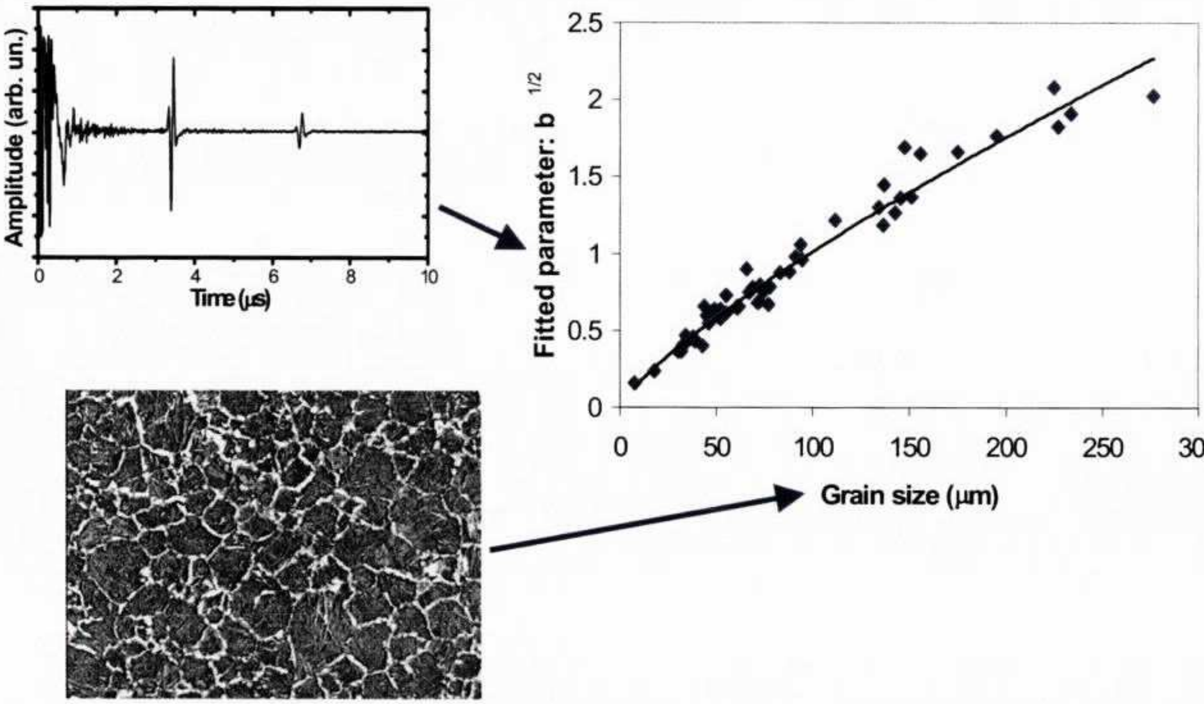

Figure 8. Calibration of the relationship between ultrasonic attenuation and the metallographically measured austenite grain size.

A software was developed to determine the grain size in real-time, based on the described approach. Figure 9 shows the comparison between austenitic grain size measured online by the laser ultrasonic technique and that measured metallographically. Due to the online factors (roughness, diffraction, etc.), the ultrasonic measurements are expected to be less accurate that those performed in ideal conditions in the laboratory. The metallographic values are also less accurate due to the tough challenge of applying, in the production environment, the proper cooling procedure that allows the decoration 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 metallography.

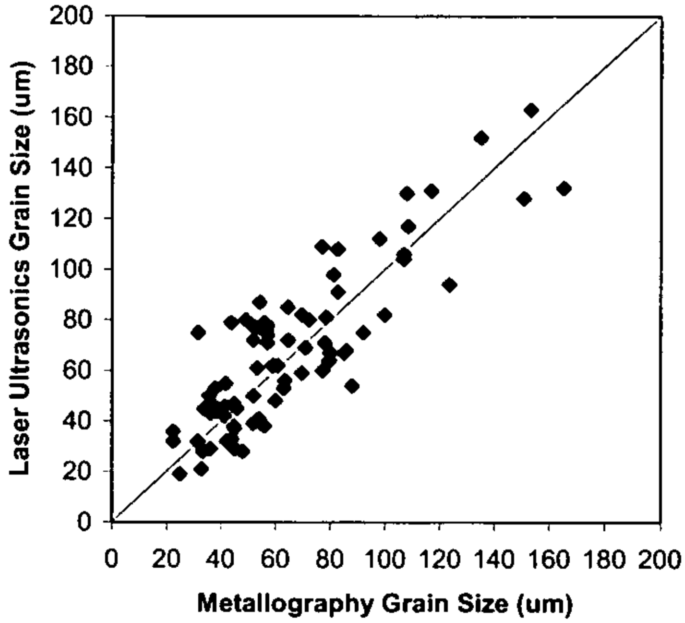

Figure 9. Grain sizes measured on-line by the laser ultrasonic system as a function of those obtained by metallography on the same tubes after proper quenching.

FUTURE OF THE TECHNOLOGY FOR THE METALLURGICAL INDUSTRY

Timken's analysis of the benefits of the technology in the first months of its use has shown clearly that the expected savings of a half million dollars per year were actually surpassed and in 2003 the mill had its low scrap level of its history.

This first successful implementation reported of a permanent laser-ultrasonic system in the metallurgical industry boosted the expectations of its use for other applications related to real-time microstructure monitoring. Laboratory and on-line demonstrations have demonstrated the ability of the technique to monitor texture and phase fraction in addition to the grain size. On-line texture measurements could monitor the efficiency of annealing lines, especially on texture-designed products like IF steels. Phase fraction monitoring should be particularly useful for new generation of high-strength steels like TRIP steels where the residual austenite fraction could be monitored. A new era of sensors for the metal industry could be just starting.

ACKNOWLEDGEMENTS

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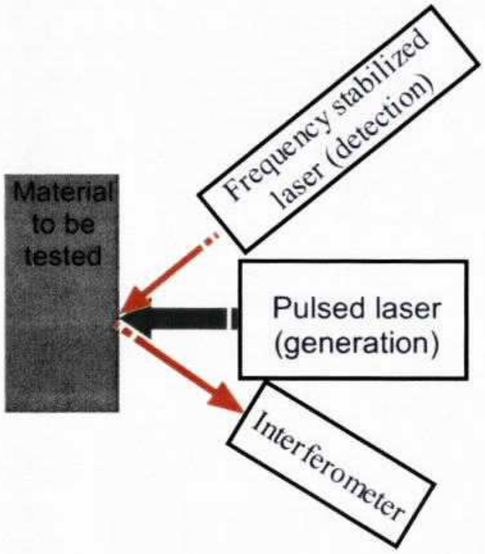
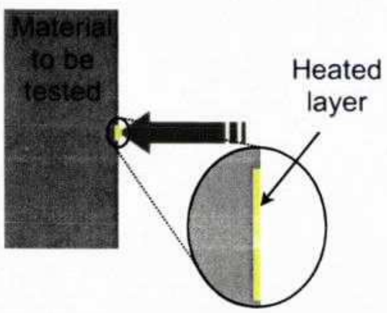
APPENDIX I
HOW DOES LASER-ULTRASONICS WORK

A laser-ultrasonic system is composed of **two** different lasers, one for **generation** and another for **detection** of ultrasonic waves. The detection laser light reflected from the material surface is demodulated by an optical **interferometer**. Figure below illustrates the basic components of a laser-ultrasonic system.



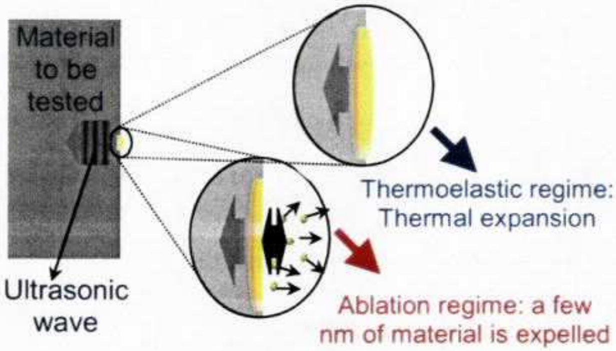
Basic components of a laser-ultrasonic system

The **generation** laser fire a short (< 50ns) and high intensity (order of MW/cm^2) pulse on the material surface. Part of the pulse energy is absorbed by the material and transformed into heat as shown in the figure below.



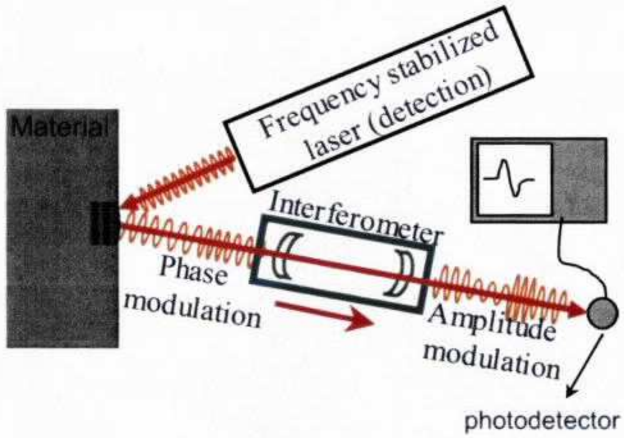
Heated layer on the material surface

The heating causes a sudden **thermal expansion**. Additionally if the laser pulse is sufficiently powerful to heat to a temperature higher than that of vaporization of the material, a small quantity of matter is evaporated or **ablated**. Both phenomena produces strain on the material surface that propagates into the material under the form of an **ultrasonic wave**.



Two mechanisms of ultrasonic generation: thermoelastic and ablation

As the ultrasonic wave propagates through the material it is scattered by discontinuities like flaws, porosities, inclusions, grain boundaries and is eventually reflected at the back wall of the piece (just as piezoelectric generated ultrasound does). The scattered and/or reflected waves arriving on the surface produce a surface movement that modulates the **detection** laser light. This phase modulation is demodulated by an **interferometer**, as illustrated in the figure below.



Laser detection of ultrasonic waves

The amplitude modulated light from the output of the interferometer is transformed in electrical signal by a photodetector and provides a representation of the ultrasonic wave that can be further processed to provide information about the material under study.