LASER ULTRASONIC SENSOR FOR ON-LINE SEAMLESS STEEL TUBING PROCESS CONTROL

G. Jeskey[1], R. Kolarik II[2], E. Damm[2], J.-P. Monchalin[3], G. Lamouche[3], S. E. Kruger[3], and M. Choquet[4]
[1]Jeskey Consulting, North Canton, Ohio, USA; [2]The Timken Company, Canton, Ohio, USA; [3]Industrial Materials Institute, Boucherville, Quebec, Canada; [4]Tecnar Automation Ltd., St. Bruno, Quebec, Canada.

Abstract: Numerous mechanical components such as bearings and gears are manufactured from seamless steel tubing, which offers superior mechanical properties. 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. 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. A laser-ultrasonic system was installed immediately after the final operation in seamless tube making. The system consists of generation and detection lasers and an interferometer located in a cabin outside the tube mill, and a fiber coupled inspection head located above the process line. Tube wall thickness and temperature measurements are used to guide mill adjustments to achieve the desired tolerances. Nearly 1,000,000 tubes were inspected in the first two years of operation. In a separate effort, additional functionality was added using the same signals that measure the tube wall thickness to sense the size of the austenitic grains. The austenitic grain size of carbon and alloy steel is of high importance due to the impact on mechanical properties of the final product. The time delay between the back wall reflections is a function of the wall thickness, while the attenuation between these same signals is related to the grain size. The target austenitic grain size is achieved by controlling the deformation and thermal process parameters operation in seamless tube making.

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 tube making process begins with heated cylindrical billets that are formed into hollows by cross rolling over a piercing plug (see Fig. 1 for a sketch of the process used at The Timken Company). The hollows are elongated into shells by cross rolling over a mandrel bar and formed into the final tube size in a reducing mill. The piercing process can cause wall thickness variations, which often follow a helical pattern.

The need of a thickness measurement sensor follows not only from the requirement of controlling the wall thickness to specification, but also from the desire for improved process control to increase yield and reduce scrap and rework. Although penetrating radiation (γ-rays) techniques have been developed and used for thickness gauging tubes, they have various limitations and, in particular, they cannot measure tubes with a mandrel inside. For cold tubes, ultrasonic techniques are widely used to measure thickness along tubes based on the time delay between successive echoes combined with the material velocity. The ultrasonic waves are usually generated and detected by piezoelectric or EMAT transducers and coupled to the inspected part either by direct contact (or a few millimeters distance in the case of EMATs) or through a water bath or a water jet. For hot tubes during the production, these ultrasonic techniques are not applicable, firstly because of the relatively high tube temperature (in the range of 1000 °C) and secondly, because the tube is not very precisely guided.

Laser ultrasonics [1], which uses lasers for the generation and detection of ultrasound at a distance (typically several tens of centimeters to one meter and even more), does not have such limitations and 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 time a system is continuously used in production. The austenite grain size is well known to be a microstructural parameter that determines to a great extent 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], as the normal practice for steel products is to do the hot-rolling in that phase. Continuous inline monitoring of grain size facilitates a controlled process that leads to an optimized microstructure, avoiding post-production modifications usually performed through costly heat treatments. This paper describes the laser ultrasonic system that has been running at The Timken Company in Ohio, USA, for more than two years and reports its performance in the continuous monitoring of both wall thickness and austenitic grain size.

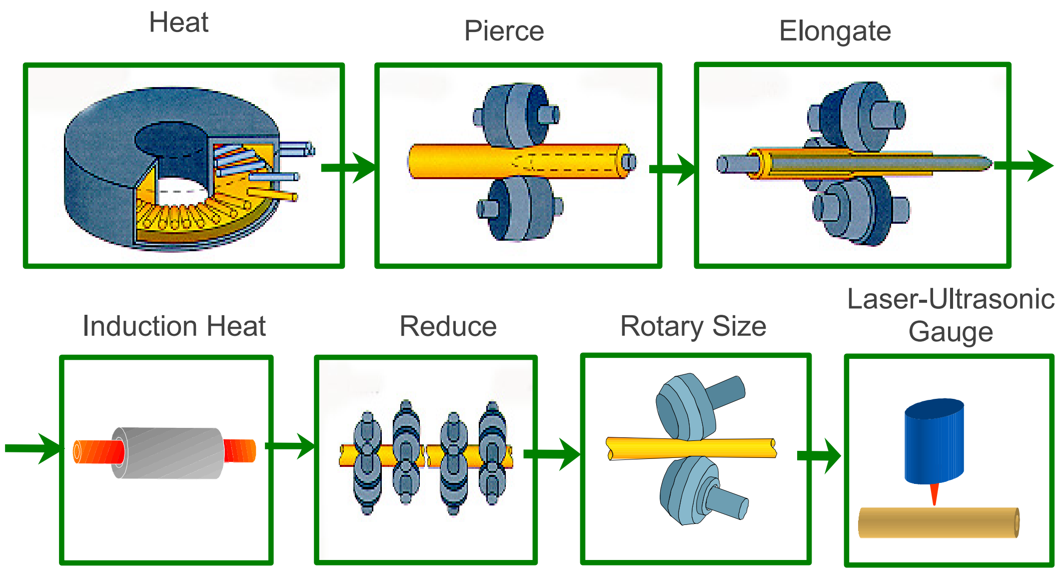

Figure 1. Stages of a seamless tube producing process.

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 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 on-line. Specially designed Doppler velocimeters (translation and rotation) and two-color pyrometer allow the measurement of the position and temperature of the measurement location (see Ref. 6 for details).

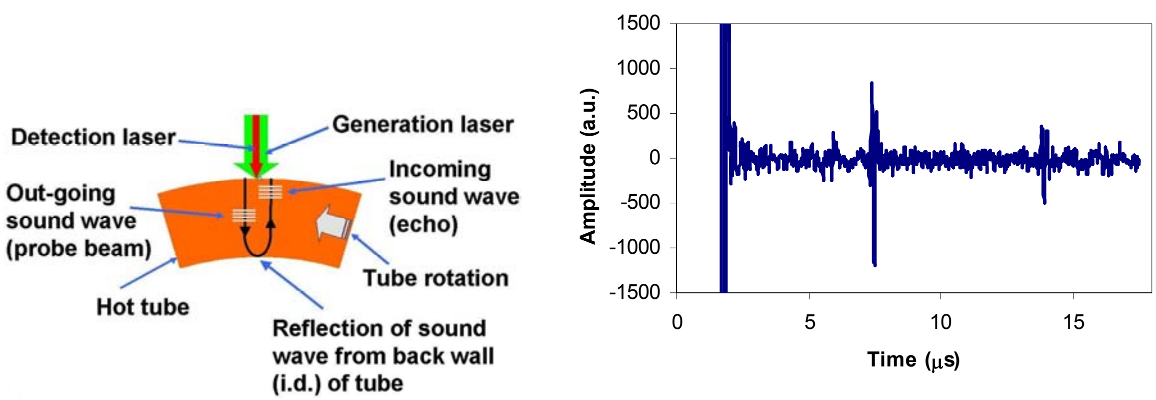

Figure 3. (a) Principle of laser ultrasonic generation and detection in a tube and (b) signal acquired on-line for a 16 mm thick tube at 940 °C.

Figure 4 depicts the laser-ultrasonic system where all delicate equipments (lasers, interferometer, etc.) are housed with other delicate sub-systems in the clean air-conditioned environment of an off-line cabin. The light beams for the three functions (laser-ultrasonics, pyrometry and velocimetry) are transmitted by optical fibers to a front coupling head located right on the line. For additional mobility of the system, this cabin is mobile and is built in a truck trailer. The lasers include the generation Q-switched Nd-YAG laser operating at 1.064 µm and the detection laser, which is long pulse (50 µs) and high stability and also operates at the same wavelength. The repetition rate is 100 Hz, which gives, depending upon the processing conditions and the tube diameter, 5 to 15 data points around the tube circumference. The demodulator used is a confocal Fabry-Perot interferometer and its unit is also located inside the cabin. The demodulator unit also includes the pyrometer with its electronics and the velocimeter detector and electronics. The velocimeters use a fraction of the power of the cw Nd-YAG laser used to seed the detection laser.

The umbilical cord that includes fibers for transmitting the generation beam, the detection beam, the scattered light beam phase modulated by ultrasound, the illumination beams for the velocimeters, the scattered light from the velocimeters beams and the infrared emission from the tube for the pyrometer is about 25 m long. The cabin also houses data acquisition electronics, several computers for processing the various signals, calculating time-of-flight and attenuation between echoes and providing thickness, austenitic grain size, eccentricity, measurement position, and temperature. The cabin also includes a monitor from which all the information provided by the system is displayed as numerical values, chart or maps. Information that is the most useful to the production line operators, i.e. thickness and temperature profiles along the tube are available on a remote console near the line and at various locations in the plant through additional monitors (not represented in Fig. 4). All relevant information is also immediately available for computers connected to the company network.

The inspection head includes appropriate focusing optics for laser ultrasonic probing and Doppler velocimetry. The head rests upon a mechanical part, the laser light shield, through which the tube passes, whose function is both to hold the inspection head above the tube and to provide laser light shielding. The section encircling the tube is sufficiently long for blocking scattered light, so the amount of light that can escape in the worst case is negligible, thus ensuring eye safe operation. The inspection head is moved on top of the laser shield by an overhead crane as shown in Fig. 4. The head has its own cooling unit and its temperature is monitored. The head has an output window that is protected from water splash and fumes deposits by a strong airflow. It was found convenient to have an eye-safe enclosure near the line for calibration purposes. This enclosure, the calibration box, is a metal box that rests on the plant floor and can hold the inspection head. Pieces of tubes and a black body source can be measured in it for verification and calibration purposes.

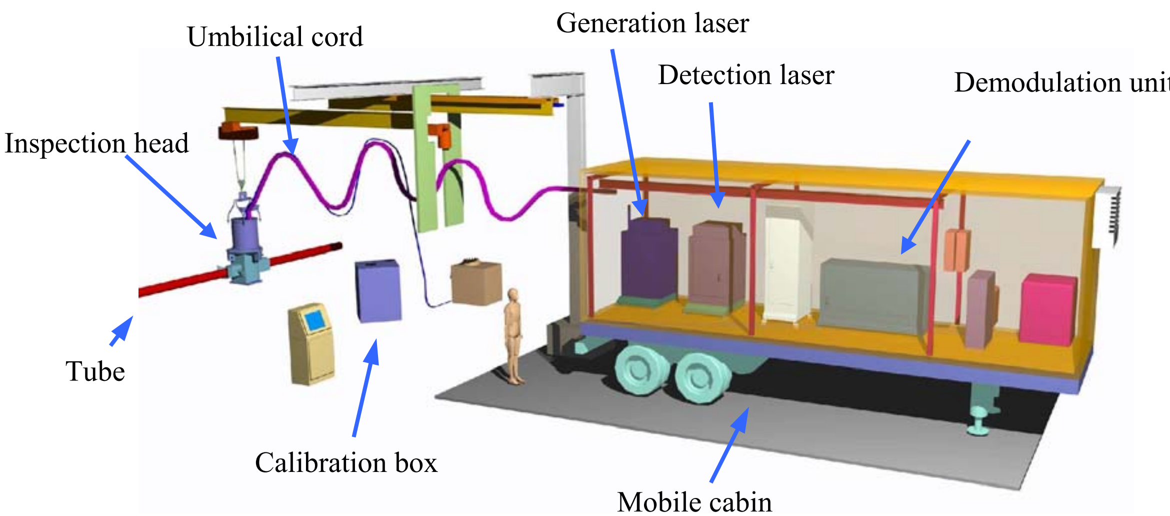

Figure 4. Overview of the laser ultrasonic system.

Results and Performance of the System for wall thickness: 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 +/- 0.5%). The system providing in real time wall thickness information over the whole tube length allows adjustment of the mill machinery to get a 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-specifications products.
The first one shows a case where high eccentricity was observed and corrected afterwards. The second one shows the case of 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 measuring them, such defective tubes would have been processed unnoticed, resulting in additional costs for additional machining.

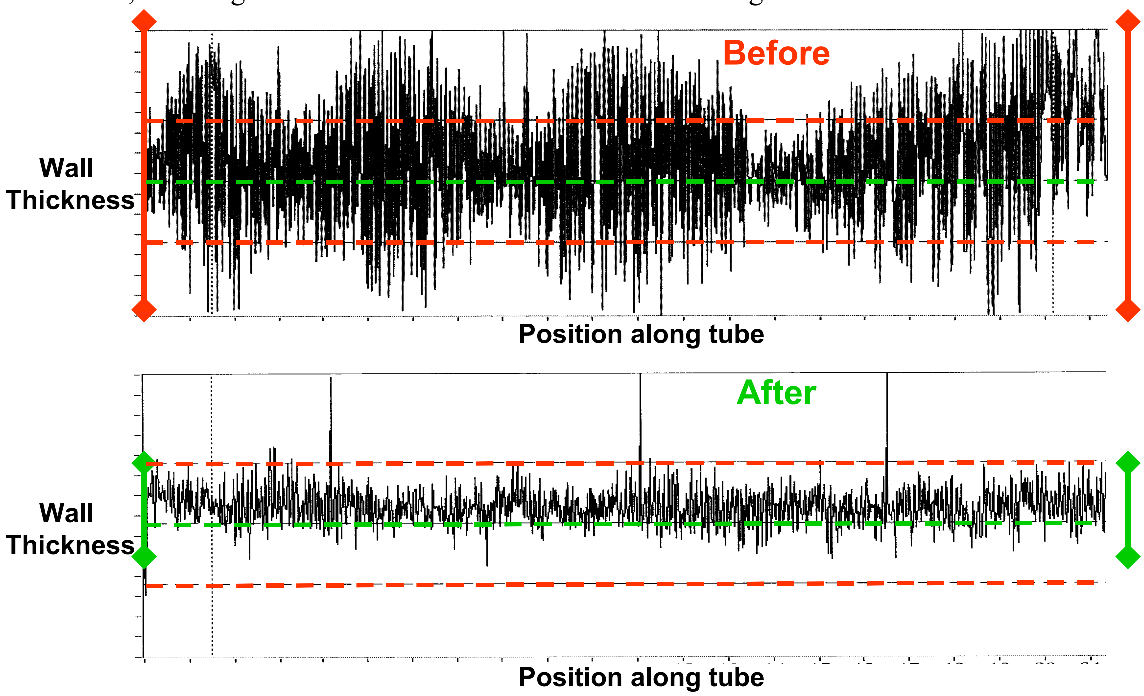

Figure 5. Example of a tube detected with high eccentricity exceeding specification and then, after corrective measures brought to the line, the next tube produced within specification.

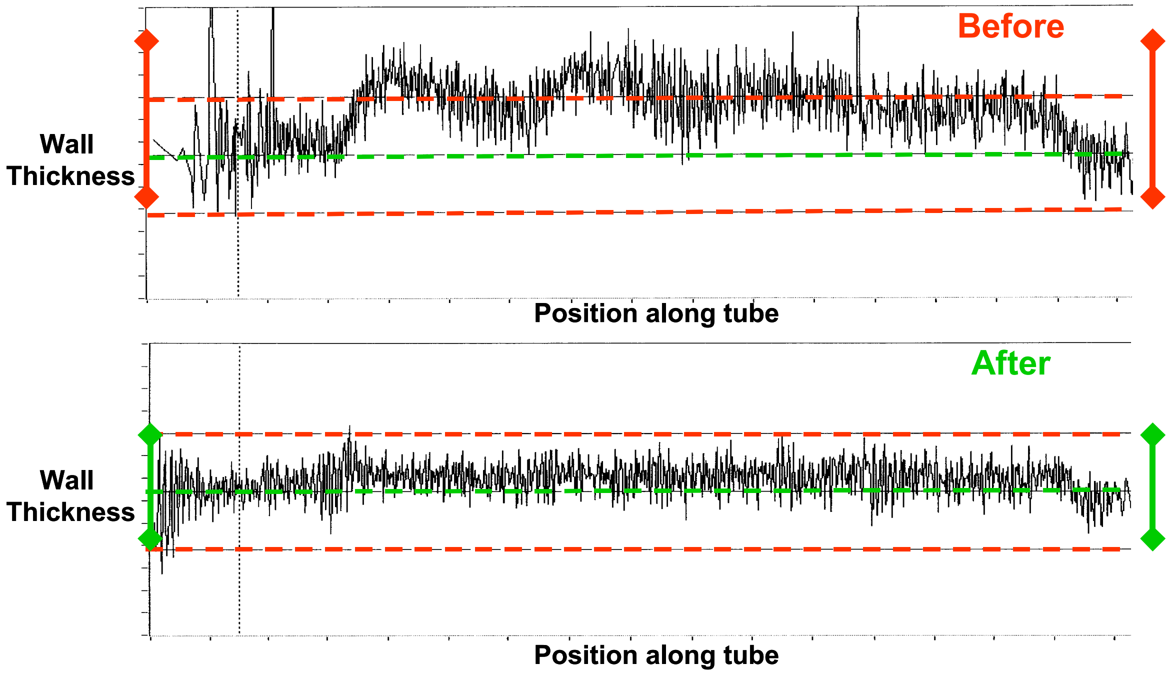

Figure 6. Example of a tube detected within specification only at its very ends and then, after corrective measures, the next tube produced within specification along the entire length.

Results and Performance for Austenitic Grain Size Measurements: Ultrasonic attenuation variation on grain size is a well-known phenomenon. It has been recently demonstrated that this concept can be applied successfully at high temperature for steels at the austenitic phase [5]. 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 determine experimentally 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 and 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 6 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 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 on the measured ultrasonic attenuation has been determined theoretically and experimentally and was found negligible for signals averaged over many positions along the circumference of the tube and over the range of eccentricity found in normal operating conditions. The roughness effect was studied theoretically and experimentally and conclusions are that it should have an impact on the measured attenuation, but it appears that its effect is closely coupled to the diffraction effect and was thus not considered independently. The diffraction has a major effect on the measured attenuation and correction is made based on tube thickness and temperature. This correction was determined experimentally with tubes of various thicknesses.

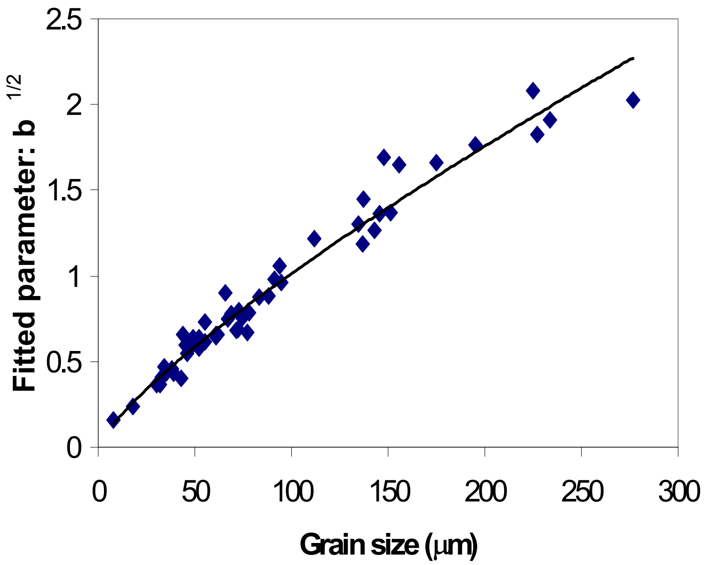

Figure 6. Calibration of the fitted attenuation parameter 'b' and metallographic measured austenitic grain size.

Software was developed to determine in real-time the grain size, based on the described approach. Figure 7 shows the comparison between the laser-ultrasonic and austenitic grain sizes measured metallographically. Due to the on-line factors (roughness, diffraction, etc.), the ultrasonic measurements are expected to be less accurate that those performed in ideal conditions in the laboratory to determine the calibration curves. 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.

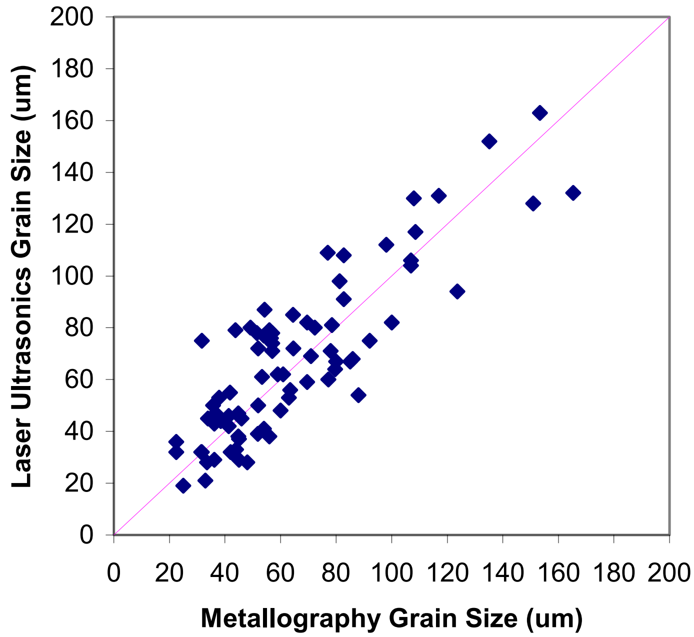

Figure 7. Grain sizes measured on-line by the laser ultrasonic system as a function of those obtained by metallography on the same tubes after proper quenching.

Discussion: The estimates developed for the proposal of this project claimed a potential for $0.50 million in annual savings through the implementation of the laser ultrasonic wall thickness measurement gage at one Timken mill. That included $0.26 million for manpower costs through improved productivity, $0.18 million in material savings through reduced scrap and rework, and $0.06 million in reduced energy consumption.

Plant engineers were asked to estimate the savings after about three months of the deployment of the gage. Having the customer conduct the analysis in itself insured that claimed savings would not be overstated. Confidence in numbers was buoyed by the fact that actual cost tracking numbers were used to develop the estimates. Those estimates included savings for reduced time to get size on the mill, savings for reduced downtime because of improved decision making, savings due to fewer samples taken from production and savings because of reduced scrap and rework.

The annualized savings estimate totaled $0.53 million – 5% greater than claimed. The largest savings came from the time savings and the wall scrap reduction, each being 47% of the total. Rework was 3%, decision making 2%, and sample savings was 1% of the total. It is interesting to note that the savings due to reduced scrap levels may even be higher as recent trends in wall scrap have shown reductions to be 1/3 higher than projected.

The energy savings realized from the implementation of the laser ultrasonic wall measurement gage were estimated by noting that energy costs are roughly 1/3 of the total hourly costs to operate the tubing mill. The time savings noted above would translate into a 5% fuel savings based on 2001 data. The tube mill uses 6.54 million BTU's to produce a ton of steel tubing. That savings applied to the tons produced would suggest 2.3×10^{10} BTU's saved annually.

Conclusions: A laser ultrasonic system was developed and implemented to gauge thickness and determine the austenitic grain size on-line in a seamless tube production plant. 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. It allows very quick and reliably better mill adjustments, thus reducing out-of-tolerance products (less scrap and rework) and troubleshooting time. The real-time determination of the austenitic grain size provides an extraordinary tool towards controlling microstructure by a closed loop controlled thermo-mechanical processing. With nearly 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. The technology has been licensed and made commercially available. Such a system, although specially designed for thickness gauging of hot tubes, could also be used elsewhere in the steel and metals industry, and eventually in other industries, for various tasks in material testing and characterization. Depending upon the application, this may require some modifications but those will be essentially limited to the inspection head.

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References:

1. Scruby, C.B. and Drain, L.E. *Laser-Ultrasonics :Techniques and Applications* (Adam Hilger, Bristol, UK,1990).
2. Monchalin, J.-P., Néron, C., Bussière, J.F., Bouchard, P., Padioleau, C., Héon, R., Choquet, M., Aussel, J.-D., Carnois, C., Roy, P., Durou, G., Nilson, J.A., "Laser-ultrasonics: from the laboratory to the shop floor", *Advanced Performance Materials*, **5**, 7-23 (1998).
3. Paul, M., Hoffman, A., Deppe, G.J., Oesterlein, L., "Laser ultrasonics in industry", in *7th European Conference on Nondestructive Testing,* Copenhagen, May 26-29, pp. 2134-2141, 1998.
4. Keck, R., Kruger, B., Coen, G. and Hasing, W. ‘Wandickenmeassung an 1230C heissen Rohrluppen mit enem neuartigen Laser-Ultrashall-System’ *Stahl und Eisen*, 107, 1987, pp. 1057-1060.
5. M. Dubois, M. Militzer, A. Moreau and J. Bussiere ‘A New Technique for the Quantitative Real-time of Austenite Grain Growth in Steel’ *Scripta Materialia* 42, pp. 867-874, 2000.
6. J.-P. Monchalin, M. Choquet, C. Padioleau, C. Néron, D. Lévesque, A. Blouin , C. Corbeil, R. Talbot, A. Bendada, M. Lamontagne, R. V. Kolarik II, G. V. Jeskey, E. D. Dominik, L. J. Duly, K. J. Samblanet, S. E. Agger, K. J. Roush, M. L. Mester ‘Laser Ultrasonic System for On-Line Steel Tube Gauging’ *Review of Progress in Quantitative NDE*, Vol. 22, eds. D. O. Thompson and D. E. Chimenti, AIP: New York, pp. 264-272, 2003.