Design and Implementation of a Tube Wall Thickness Measurement System

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Abstract

This paper describes the design and implementation of a gage for measuring the wall thickness of hot rolled steel tubing at an actual production facility. The design is based upon a statistical analysis of the tube samples, and upon the economic realities of mill operating conditions. Issues relating to time constraints, uneven sample preparation, a mill operating environment, and differences between gage operators are addressed. The gage records more data from the tubes than could be taken manually, and therefore allows the accompanying software to apply unique algorithms for the calculation of hexing and eccentricity in each sample. All results are recorded and stored in a database for continuous use in statistical process control.

Introduction

This paper explains the design of a device for measuring the wall thickness of steel tubing. In order to understand the context of this problem, an overview of a steel tubing production facility is important. The steel arrives at the plant in large rolls, referred to as master coils. These are slit into smaller widths, formed into a circle, and welded in order to form a *mother tube*. Forming and welding mother tubes of different diameters requires extensive equipment changes, and therefore considerable downtime. Therefore, a more specialized machine, the *stretch-reduce mill* (SRM), is used to produce a large number of different tube sizes from the few standard mother tubes.

In the SRM, induction heaters raise the temperature of the mother tube immediately before it is gripped by a bank of rollers. The rollers are arranged in sets of three, and each set is offset 60° from the previous one. This arrangement causes the tube characteristic referred to as *hexing*, which is described in greater detail later in this paper. Figure 1 shows a single set of

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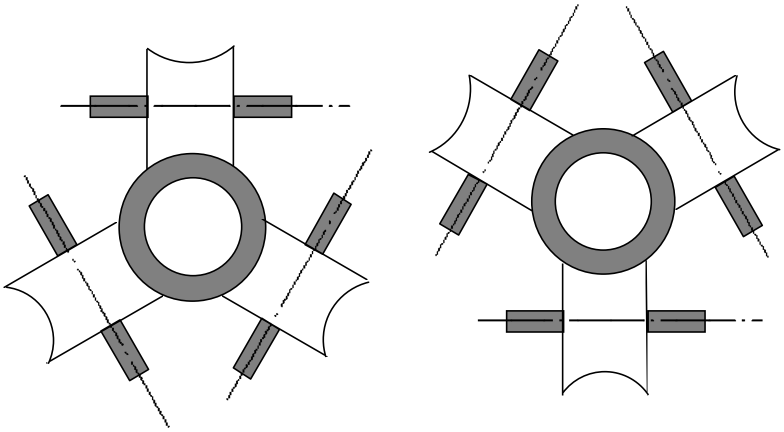
rollers, uniformly spaced 120° around the circumference. These sets are arranged in order of increasing roller diameter, and they act radially to squeeze the mother tube down to a smaller size. In addition, the rollers are driven and grip the outer surface of the tube. By changing the relative speed between the sets of rollers, the tube can either be stretched or compressed. Therefore, by inserting or removing different sized rollers, and by changing the roller speeds, a large variety of tube sizes are manufactured from a single mother tube size.



(a) N_{th} set (b) $N+1_{th}$ set, phased 60°.

Figure 1. Roller Arrangement in the Stretch Reduce Mill.

An undesirable characteristic of the SRM is that the roller speed settings are not repeatable enough to produce tubing within customer specifications. Instead, the operator must stop the mill to manually check the thickness at the beginning of each run, and periodically throughout each run. If necessary, the operator changes the roller speed settings and repeats the process until achieving an acceptable wall thickness. Prior to the introduction of the wall thickness gage, the operator based his decision upon manual micrometer readings. After cutting, cooling, and deburring a sample, he measures it at six locations around the circumference. Finally, he transcribes those readings to a log book containing measurements from prior runs and decides if changes to the SRM settings are required. The main problem with this method is the tube characteristic referred to as *hexing*. The arrangement of rollers (each set of three rollers is phased at 60° apart in the SRM, Figure 1) produces a series of six peaks and valleys in the circumferential wall thickness. The level of hexing varies from measurably imperceptible to that which can be detected by unaided visual inspection. A detailed measurement of tube samples revealed that the hexing exhibited wall thickness variations large enough to require over two hundred measurements be taken on a typical sample to meet the target 6σ accuracy of ±0.001

inches for the mean wall thickness. The method of taking six measurements with a micrometer is statistically incapable of meeting this level of accuracy, and resulted in a measurement system that neither the management of the company nor the operators of the mill were confident in using.

A method that the company investigated prior to the start of this project was to measure the wall thickness on-line with a variation of an x-ray machine. However, the high cost (over $1 million) led to the abandoning of this idea. Another possible on-line method considered for thickness measurement was the use of ultrasonic transducers. The largest obstacle associated with ultrasonic probes is the requirement of keeping a fluidic coupling between the hot tube and the probe tip. In addition, the probe tips must be changed for each different tube outside diameter, and the system requires recalibration for each different grade of steel. A more fundamental problem exists with on-line measurement. The probe is generally fixed, and therefore only measures deviations along the length of the tube. Such a measurement generates the wall thickness' *axial* distribution. However, the sample analysis had shown that hexing causes significant variation in the *circumferential* distribution. Thus a single probe tip could ride in a peak or valley of the hexing and produce an inaccurate reading of the average wall thickness. Multiple probes around the circumference, rotating probes, or a combination of the two add to the complexity and cost of a system. Economic rationale dictates that the wall thickness measurements should to continue to be taken off-line.

Requirements

With economic issues in mind, several criteria were established for the design of the wall thickness gage. The most critical one is that measurement time be kept comparable to the existing six minutes (including sample preparation time). This is critical because the mill is not producing while the results of the measurement are pending. The developed design criteria contains several corollaries. The first is that the gage cannot require a precisely prepared sample. Out-of-square end-cuts and small burrs on both the inside and outside diameters are to be expected. The second requirement is that the system be capable of withstanding the harsh mill conditions. Taking the sample to a controlled environment for inspection requires too much time. The third requirement is that the gage require little or no maintenance. The mill operates around the clock, based upon the readings given by the gage, so any amount of gage downtime would be considered unacceptable. Fourth, the gage should be able to measure all of the tube sizes produced in the mill without requiring adjustments. Several different tube sizes are produced every shift, and so the time lost in preparing the machine to accept each of them would again be significant. Finally, the gage must be easy to use and generate results that are operator independent. Different operators with widely varying skills will be required to use it with little or no previous instruction.

Other requirements relate to the capabilities of the gage. It must be able to read the wall thickness around one tube sample and predict whether the thickness throughout the entire run will fall within the customer specifications. This is typically ±10% of nominal for a hot-rolled product. Additional samples are always preferable from a statistical standpoint, but each sample costs both time and an otherwise salable section of tube. After calculating this prediction, the operator should be presented with a simple "GO" or "NO GO" indicator. This helps to lessen differences from one operator to the next, and to prevent endless adjustment in search of an exact thickness.

Gage Design

The gage design allows the operators to take measurements on sample tubes with no special preparation beyond that which was previously done. A photograph of the first prototype gage is shown in Figure 2, and a cross-sectional diagram with the one roller removed is depicted in Figure 3. Two rollers at the top of the gage support a tube sample. Generally, the samples are about 8-inches long. Shorter or longer samples can be measured, but an 8-inch size is comfortable for an operator to handle during cutting and deburring operations. One roller is driven, and rotates at approximately 15 RPM. It is important to note that these rollers only provide support and rotational motion to the sample. Measurements are not referenced to them. Because of this, burrs on the sample (provided they are not large enough to prevent rotation) will not affect the accuracy of the gage.

A linear variable differential transformer (LVDT) is used to generate the thickness measurement. The gage head is mounted in an assembly that is constrained to move only in the z-direction through the use of V-wheels and track. This assembly is visible in the right of Figure 3. (Note: the first prototype of Figure 2 had twin linear shafts and two pillow blocks instead of the V-wheels.) The top of the structure contains a downward pointing carbide roller tip. In operation, this tip rests on the inside of the tube sample. Directly below it is the spring-loaded LVDT. Its tip rests on the outside of the tube sample, and so a measure of the thickness at one particular point is generated. By keeping the measurement device in line with the wall thickness, the Abbe' principle (Bryan, 1989, Slocum, 1992) is obeyed and angular offset errors are eliminated. In order to measure the wall thickness around the entire sample, the motor activates and rotates the tube. The entire LVDT assembly follows the contours of the inner surface, and the LVDT itself follows changes in the outer surface relative to it.

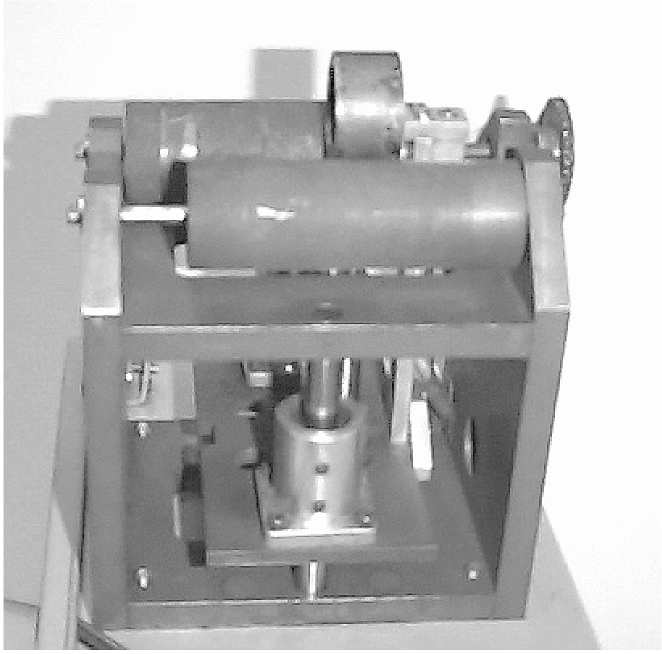


Figure 2. Tube Wall Thickness Measuring Gage.

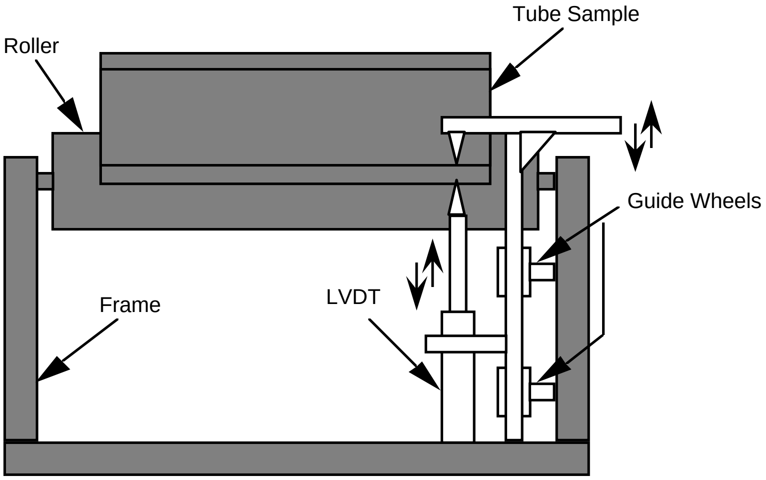


Figure 3. Cross Section of Tube Wall Thickness Gage.

An alternating current LVDT is used in order to minimize the effects of electrical noise in the mill environment on the thickness reading. A voltage module circuit creates the AC signal (2.5 kHz), and converts the return signal from the LVDT into a ±10V DC signal that is proportional to the tip displacement. A low pass filter further lessens the effect of electrical noise, and prevents aliasing. Finally, a 12-bit analog-to-digital conversion board, located in an Intel™ 486-based personal computer, converts the electrical signal to an integer value. A schematic diagram of the circuitry is shown in Figure 4. Dividing the 0.5-inch range of the LVDT by the 4096 (2^{12}) available counts on the board gives a resolution of 122-μin. In order to achieve a statistically significant measure of the average wall thickness without recording extraneous amounts of data, we selected a sampling frequency of 100 Hz. The final component of the circuitry is an amplifier that controls the operation of the roller motor based upon an analog voltage from the signal converter board in the PC.

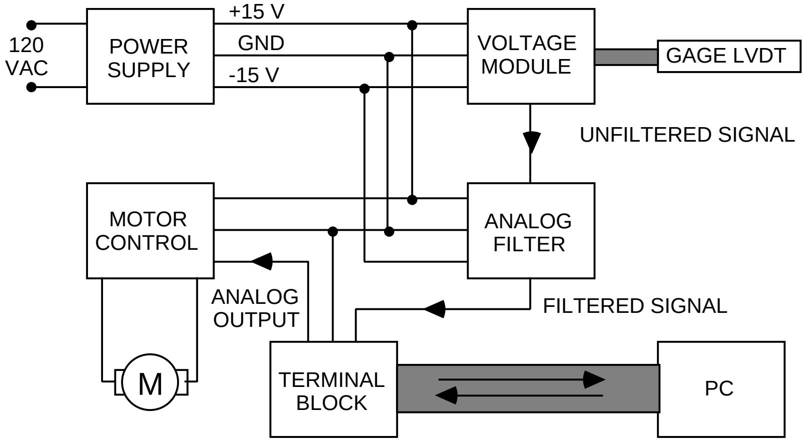


Figure 4. Schematic Diagram of Tube Wall Gage Circuitry.

The final attribute of the design is the accompanying software, written using LabVIEW™ for Windows™, a development package by National Instruments. The main benefit of using this software is the ability to easily develop a graphical user control panel. On-screen "switches" are used to set the customer specifications, and the measurement process begins when the operator presses an on-screen "START" button. The remainder of the measurement process is automated. After the computer records the measurements, they are displayed for the user in graphical form. The software generates an estimate of the overall limits of the run thickness and compares it to the customer specifications. The result is either a red "STOP" light or a green "GO" light indicating whether the SRM settings are acceptable.

Estimation of Hexing and Eccentricity

Until the development of this gage, hexing in hot-rolled steel tubing had been addressed in only a qualitative manner. However, the gathering of large numbers of data points allows a numerical value to be assigned to it. Obtaining a metric for the measure of hexing is important since much of the tubing is further worked through a cold-drawing process. With a numerical value for the hexing, the operator of the cold-draw bench can decide whether the machine can remove the hexing in a single pass, or if multiple forming passes are required.

A characteristic that cannot be removed through the cold drawing process is eccentricity; since the draw bench cannot move the amount of steel required to align the centers of a heavily eccentric tube. Eccentricity is defined as the distance between the centers of the two circles formed by the inner and outer tube surfaces. To perform an exact measure of eccentricity, (x, y) data points are required on both the inner and outer surfaces. However, provided the assumption that the outer surface is circular remains valid, an approximation for the eccentricity in steel tubing can be derived from only the wall thickness values. Figure 5 shows an exaggerated cross section of an eccentric tube sample.

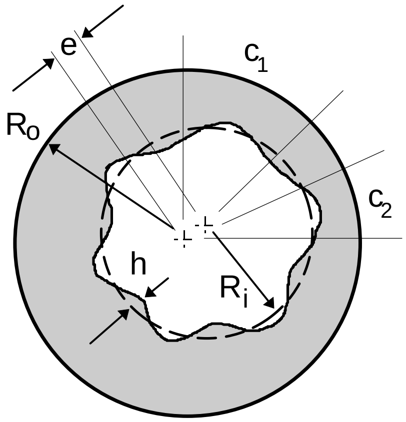


Figure 5. Exaggerated Cross-Section of a Typical Tube Sample.

When the thickness values are plotted for a single revolution of a tube, hexing appears as six undulations per revolution, while eccentricity appears as one superimposed on it. Therefore, a sinusoidal curve fit to the data is performed. Eccentricity (e) and hexing (h) are calculated by fitting the thickness values (T) to the following equation.

$$T(\theta) = \overline{T} + e\sin(\theta + c_1) + h\sin(6\theta + c_2) \tag{1}$$

The value $\overline{T}$ represents the average wall thickness, and c_1 and c_2 are phase angles. This approach is similar to that of Jayaraman and Raja (1994). The phase angles will change depending upon where along the circumference the operator starts the measurement from, and have not been found to be of any practical use. Equation (1) is an unwieldy expression to work with because the phase angles enter the relationship nonlinearly. Eccentricity and hexing are therefore calculated from a least squares curve fit of the measured thickness values to equation (2).

$$T = A + B\sin\theta + C\cos\theta + D\sin 6\theta + E\cos 6\theta \tag{2}$$

Equation (2) is mathematically identical to equation (1) provided that the relationships between the constants are defined through equations (3) through (5).

$$\overline{T} = A \tag{3}$$

$$e = \sqrt{B^2 + C^2} \tag{4}$$

$$h = \sqrt{D^2 + E^2} \tag{5}$$

Hexing is a non-standard term, and so we were free to apply our own definition of it as the variable h in equation (1). However, eccentricity has an accepted definition which is only approximated by the sinusoidal fit. This approximation makes sense from an intuitive standpoint (imagine the profile of an eccentric tube that has been sliced open and laid flat), but it can also be proven mathematically. The mathematical proof of the approximation proceeds as follows, and the constants are the same as in Figure 5. First, begin with the Cartesian equations for the outer (6) and inner (7) circles.

$$x_o^2 + y_o^2 = R_o^2 \tag{6}$$

$$\left(x_i - e\sin(c_1)\right)^2 + \left(y_i - e\cos(c_1)\right)^2 = \left(R_i - h\sin(6\theta + c_2)\right)^2 \tag{7}$$

Next, substitute polar notation for the Cartesian coordinates.

$$r_o^2 = R_o^2 \tag{8}$$

$$\left(r_i\cos\theta - e\sin(c_1)\right)^2 + \left(r_i\sin\theta - e\cos(c_1)\right)^2 = \left(R_i - h\sin(6\theta + c_2)\right)^2 \tag{9}$$

Wall thickness is the difference between the inner and outer radii as measured in polar coordinates. Therefore, the r_i term must be extracted from equation (9). This is done by expanding the left side of equation (9) and simplifying with trigonometric identities to form equation (10).

$$r_i^2 - 2er_i\sin(\theta + c_1) + e^2 - \left(R_i - h\sin(6\theta + c_2)\right)^2 = 0 \tag{10}$$

This quadratic equation can be solved for the positive root, which is given by equation (11).

$$r_i = e\sin(\theta + c_1) + \left[\left(R_i - h\sin(6\theta + c_2)\right)^2 + e^2\sin^2(\theta + c_1) - e^2\right]^{1/2} \tag{11}$$

This exression can be simplified using the Binomial Theorem[1] since $R_i^2 >> e^2$ and $h << R_i$.

$$r_i = R_i - e\sin(\theta + C_1) - h\sin(6\theta + c_2) + O(e^2) \qquad (12)$$

The term $O(e^2)$ contains the higher order terms of the Binomial Expansion. Equation (12) can now be subtracted from the outer radius R_o to generate our model of the wall thickness.

$$T = R_o - R_i + e\sin(\theta + C_1) + h\sin(\theta + c_2) + error \qquad (13)$$

The magnitude of this error depends upon the values of the inner radius, hexing, and eccentricity. If nominal values seen in the mill for these quantities are used (R_i=1-in, e=0.005-in, and h=0.005-in), the magnitude of the error is only about 25-µin, which is well below the sensor resolution in this application.

To further compare eccentricity as calculated by the sine fit to the true eccentricity, thickness data for tubes with various inner radii and eccentricity were generated mathematically. The true eccentricity is, therefore, known and can be compared to the value predicted using a least squares curve fit to equation (1). The percentage error between the true eccentricity and the eccentricity calculated by the sinusoidal curve fit was determined for the range of tubes produced (inner radius of 0.2-in to 2.0-in) for several typical values of eccentricity (0.010-in to 0.002-in). Although the error slightly increases with the ratio of eccentricity to inner radius and decreases with the tube inside radius, the maximum error magnitude for all cases examined is extremely small (under 4×10^{-8} percent) and can be neglected.

As a final practical comparison, we measured eight tube samples of different sizes on a coordinate measuring machine (CMM), and recorded one hundred points around both the inner and outer circumferences. Eccentricity was then calculated from these data points using both a circle fit and the proposed sinusoidal fit. Finally, the identical tubes were measured again for eccentricity on the tube wall thickness gage. The results of this comparison are displayed in Figure 6. It is also interesting to compare the differences times required for the obtaining measurements. The time required by the CMM to programmatically measure 100-points of thickness is 10 minutes, while the time required by the gage was 30 seconds. Clearly there is a significant time advantage to the gage.

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[1] Binomial Theorem: $(a+b)^k = \sum_{n=0}^{k} \begin{pmatrix} n \\ k \end{pmatrix} a^{k-n} b^n$

As a result of these three different proofs: mathematical, with mathematically generated data, and with actual tube sample data, we concluded that the sinusoidal curve fit provides an accurate estimate of eccentricity without the need for a CMM when the tube radius is large in comparison with the eccentricity being measured. Since this is the case for the samples expected to be measured through the use of this method, inaccuracies are too small to be consequential.

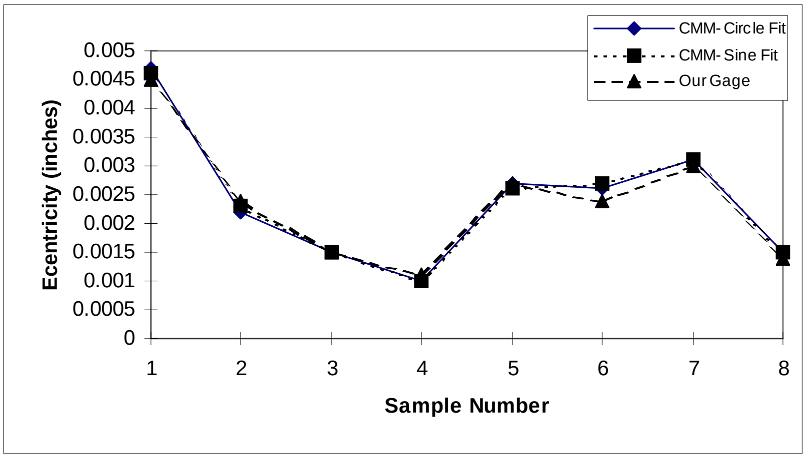
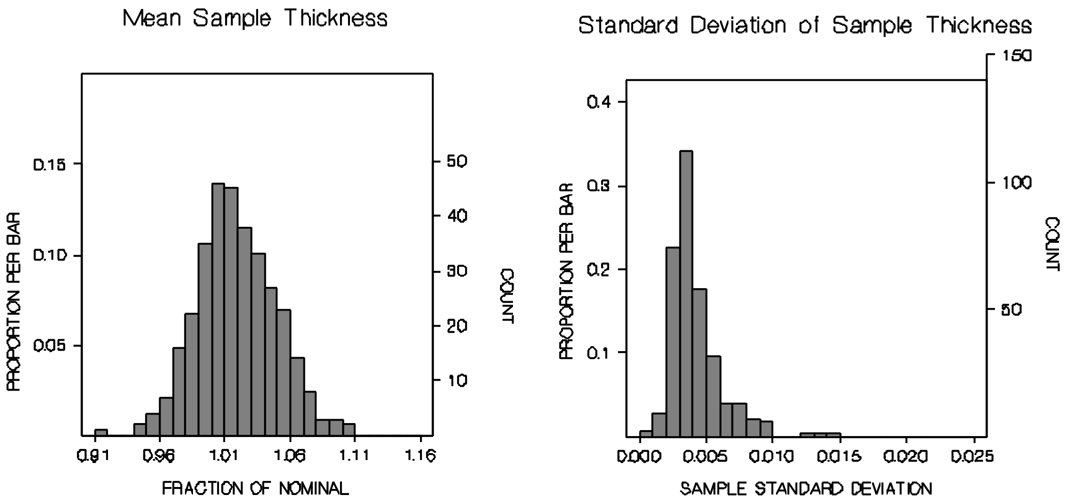


Figure 6. A Comparison of Eccentricity Measured Through Three Different Methods.

Statistical Uses of the Gage

An immediate benefit of the use of the gage is the ease of data gathering for statistical purposes. All data are archived to the hard drive of the personal computer in a text format. It can be downloaded at any time for further analysis. As an example, two histograms are reproduced below. The first shows the distribution of the sample wall thickness as a percentage of the desired wall thickness. The distribution appears fairly normal. The other shows the standard deviation of the thicknesses in sample pieces. Tracking these distributions over time will indicate changes in the overall manufacturing process.



Figures 7(a) and 7(b). Histograms of Percentage Deviation From Desired Wall Thickness (a) and Sample Standard Deviation (b).

Conclusion

The wall thickness gage design is superior to hand measurements with respect to accuracy, repeatability, and fitting data to appropriate models. The gage is also superior to CMMs in terms of its cost, ruggedness, data collection and analysis functions. It is also important to note that CMMs will not measure annual thickness directly as is done in the tube wall thickness gage. The hexing and eccentricity measurement error from the underlying mathematical simplifications are smaller than the resolution of the signal converter board and significantly smaller than typical resolution and errors in CMMs.

A wall thickness gage was designed and constructed to meet the requirements of a steel tube production company. The gage was installed and used in the tube mill. After some initial concerns about its ability to withstand to a mill environment, and some unfamiliarity with using a personal computer, the gage was accepted by the mill operators into routine operation. During the initial field trial, we intended that the gage be used as a backup while SRM process settings were still based on manual micrometer readings. From the first use, however, it became apparent that just the opposite was true. The operators relegated the micrometer to a confirming role.

The benefits of a rugged and economical metrology system that provides a repeatable indication of the true tube size, collects information for further statistical analysis, and that eliminates subjective operator measurement errors in SRM settings, are readily accepted.

Future plans include the possible development of a plant controller to determine SRM setpoints based on historical data and settings.

References

Bryan, J. B., "The Abbe Principle Revisited-An Updated Interpretation," *Precision Engineering*, Vol. 1, No. 3, pp. 129-132, 1989.

Devor, R. E., Chang, T., and Sutherland, J. W., *Statistical Quality Design and Control*, Macmillan Publishing Company, New York, NY, 1992.

Dorf, R. C., *Modern Control Engineering*, Addison-Wesley Publishing Company, Inc., Reading, MA, 6th. Ed., 1992.

Hoffman, J. D., *Numerical Methods for Engineers and Scientists*, McGraw-Hill Publishing Company, Inc., New York, NY, 1992.

Slocum, A. H., *Precision Machine Design*, Prentice Hall, Englewood Cliffs, NJ, 1992.

Smith, R. J., and Dorf, R. C., *Circuits, Devices, and Systems*, John Wiley and Sons, Inc., New York, NY, 5th. Ed., 1992.

Jayaraman, V., Raja, J., " A Simple and Effective Method to Account for Tilt and Eccentricity in Roundness Measurements" *Proceedings of American Society for Precision Engineering 1994 Annual Meeting*, pp. 141-4, 1994.