Determination of tensile strength in old paper machine dryers

Algis P. Mockaitis

Proper evaluation of shell thickness and tensile strength for old paper machine dryers may indicate that they can be operated safely at pressures higher than the 13,000-psi criterion established by insurance underwriters.

Many older paper machine dryers are still in operation in paper mills in the United States. Some of these dryers date back to the last century. Unfortunately, failures have occurred, some of them catastrophic ruptures that have caused injuries and prolonged machine outages. These incidents have prompted TAPPI to publish guidelines for inspection of paper machine dryers (*1*). Such inspections involve visual examination, ultrasonic thickness measurements of the shell, magnetic particle inspections of the heads, and examination of bolts for cracking.

All paper machine dryers can be placed into one of two categories: (a) dryers manufactured prior to adoption of the American Society of Mechanical Engineers (ASME) Code for which material properties are not known, and (b) dryers that are ASME Code-rated with material properties determined from test bars cast at the same time as the shells and heads. The Code-rated dryers are hydrostatically tested, and a data report is filed by the authorized inspector with the National Board of Boiler and Pressure Vessel Inspectors.

It is the non-Code dryers that present a problem. Shell thickness can be determined to a high degree of accuracy by ultrasonic test equipment using proper procedures, but material properties are unknown. Destructive testing of older dryer rolls conducted in the 1950s revealed that the cast iron tensile strength in some was as low as 12,500 psi (*2*). Our experiences support these findings of the existence of low strength cast iron in some old dryers.

The insurance industry calculates maximum allowable working pressure (MAWP) based on a 13,000-psi tensile strength for all non-Code dryers for which material strength is not known. Since many older dryers are stronger, typically above 20,000 psi, the strict application of this criterion can result in unnecessary lowering of operating steam pressures on many machines, with resulting production losses.

Mockaitis is director, mechanical engineering, for Stone Container Corp., 8170 S. Madison St., Burr Ridge, Ill. 60521.

To integrate the need for safety and productivity, Stone Container undertook a program to determine nondestructive techniques that could predict the tensile strength of cast iron in paper machine dryers. An important goal was to develop a technique that would allow sufficient test data for characterizing the material in a dryer to be obtained during the time typically available for an operational machine, i.e., an annual outage of 5-7 days. The program evolved over a number of years and was based on cast iron samples obtained from dryers that were hydrostatically tested to destruction or that were removed from machines due to physical damage. These samples were tested to determine hardness, tensile strength, chemical composition, and microstructure. Correlations between tensile strength and the other properties were investigated. Hardness proved to be the best single predictor of tensile strength.

Factors that determine properties of cast iron

The mechanical properties of a gray iron casting, from which most paper machine dryers are made, are determined by a number of factors. These include (a) chemical composition, (b) the effects of solidification and cooling rate, and (c) casting design. Due to the interactions between these factors, their individual effects on mechanical properties cannot be isolated, but certain trends and interrelations can be established. Unfortunately, when these old dryers were cast, there were no standardized requirements for quality control. Documentation is lacking, and wide variations in strength are encountered. An observed trend is that material properties did improve over the decades and, on the average, there is some correlation between tensile strength and the casting date.

Standard test bar to establish tensile strength

The importance of the cooling rate of a casting was recognized in the early 1920s, when a recommendation was made that standard test bars be cast in small, medium, and large diameters to represent castings of corresponding thickness (*3*). The standard arbitration test bar represents the metal in the ladle and not the metal in the casting. Differences in cooling rates between test bars and the casting result in different tensile strengths. The rate at which gray iron solidifies has a direct influence on its graphite structure. Faster solidification rates result in a finer graphite structure, which also produces a casting of higher tensile strength.

Chemical composition to predict tensile strength

Various investigators have searched for correlations between tensile strength, chemical composition, and other measurable properties, such as Brinell hardness (*4–6*). Many of the attempts to produce such a formula centered around the chemical composition of the iron carbon eutectic. The amount of eutectic is a measure of the quantity of graphite formed during solidification. The tensile strength of gray iron is known to increase as the eutectic cell size decreases. A limit of 4.3% carbon produces 100% eutectic. The percentage of carbon is affected by other elements such as silicon and phosphorus. Accounting for these has resulted in a variety of relationships. The most commonly accepted relationship for North American irons is:

$$C_e = C_{tot} + (A_{Si} + A_P)/3 \quad (1)$$

where

C_e = the carbon equivalent

C_{tot} = total carbon percentage (graphite and iron carbide)

A_{Si} = silicon percentage

A_P = phosphorous percentage.

A correlation of the carbon equivalent value and tensile strength was explored by Barlow and Lorig (*4*) in 1946. Later work by Schneidewind and MeElwee (*6*) in 1950 derived an equation for the best-fit line to correlate carbon equivalent and tensile strength, S_T:

$$S_T = 10{,}000(11.5 - 2C_e) \quad (2)$$

This equation was derived from data for 1.2-in.-diam. test bars and applies strictly to that size casting only. Correlation to account for section size resulted in a modification to the equation to give:

$$S_T = 10{,}000(11.68 - 2C_e - \log D_e) \quad (3)$$

Here D_e is the equivalent diameter. Equations 2 and 3 become the same for a value of $D_e = 1.2$.

This correlation of tensile strength and chemical composition is of most value to the foundry, which can adjust the composition to obtain the desired properties. An increase in the carbon equivalent value results in a decrease in the tensile strength. Similar mechanical properties can be obtained from irons of different composition.

Our interest is in the determination of the tensile strength of irons that may have low tensile strength. Unfortunately, the published references generally do not contain data below 20,000 psi. This prompted an independent search for correlations between chemical composition, microstructure, and tensile strength. The samples of iron studied were obtained from old dryers. Several samples had tensile strengths below 12,000 psi. Samples that were above 30,000 psi were not used. These stronger irons are typically representative of newer dryers that were manufactured to Code specifications.

No positive correlations were obtained from attempts to predict the tensile strength from the carbon equivalent number. Although the expected trends were obtained, there appeared a need to adjust the equivalent diameter, D_e, in Eq. 3 to match tensile test data. This adjustment varied for different dryers, and the prediction equation is very sensitive to minor changes in the value of D_e. This suggests that the differences in foundry practices and cooling rates are too great. Correlations that included combined multiple variable regression statistics with chemical composition and microstructure also were not fruitful.

Correlation of tensile strength and Brinell hardness

The correlation of hardness and tensile strength for steel alloys has been long established. Similar correlations have also been sought for cast iron but with mixed success in defining a straightforward relationship for the full range of cast irons. The most extensive work that investigated the relationship between tensile strength and Brinell hardness of cast iron was done by MacKenzie in 1946 (*7*). It included over 1550 sets of data and is shown in **Fig. 1**.

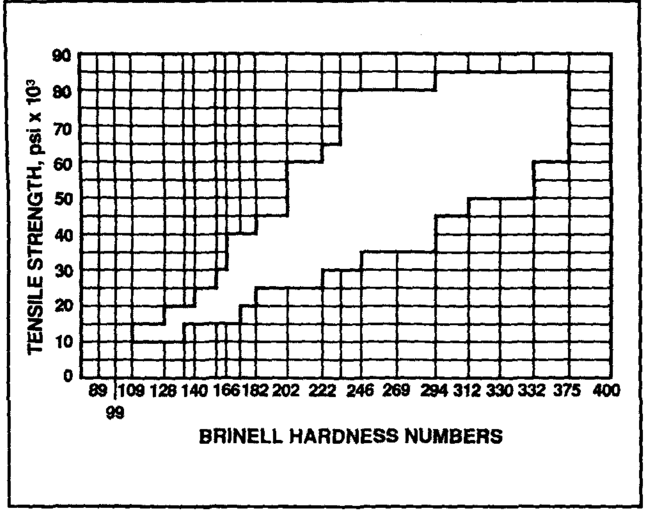
MacKenzie showed that Brinell hardness could be used to classify cast iron into low strength and high strength categories. However, considerable scatter is seen in his data. The hardness test procedures, such as location on the casting at which hardness readings were to be taken, were not clearly established prior to the test program and contributed to some of the scatter. A standardized test procedure is an important prerequisite for establishing a correlation with minimum scatter.

MacKenzie also sought mathematical formulations to correlate tensile strength and hardness. He investigated the least-square best-fit straight line, hyperbolic, and parabolic equations to predict tensile strength from Brinell hardness data. All of these equations gave reasonable predictions for cast iron above 25,000 psi. For cast iron below 25,000 psi, these equations predicted tensile strengths that were either too high or too low.

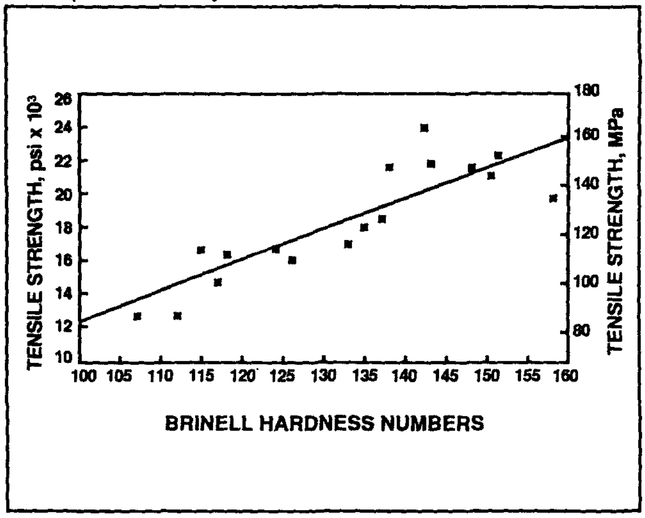
A review of the data from which MacKenzie's graph was prepared shows that very few data are available in the low strength range. Only seven data points are represented in the region below 20,000 psi strength range for test bars under 2-in. diameter. This lack of data for low strength cast iron prompted an independent investigation. The governing consideration in this investigation was to determine if adequate information could be obtained from a dryer in a paper machine to determine its tensile strength. The overriding concern was operating safety. Low strength dryers, with a low operating safety factor, must be removed from service to eliminate the risk of a catastrophic failure.

The investigation involved a correlation of tensile strength and Brinell hardness obtained from samples removed from old cast iron dryers. A standard procedure

1. *Relationship between Brinell hardness and tensile strength determined by MacKenzie from over 1550 sets of data*



2. Relationship between tensile strength and Brinell hardness for cast iron below 25,000 psi tensile strength. Data points represent tests made on samples from old dryers.



was established with Brinell hardness data to be taken on the outside surface of a dryer shell and tensile strength data to be taken at the same location. Much of the data was also taken in the region of the dryer where the maximum operating stresses occurred to provide critical information on the strength of the dryer (*8*). Dryers manufactured between 1903 and 1946 were included in the study. The results are shown in **Fig. 2**. The best-fit straight line through the data for predicting tensile strength from Brinell hardness number, *B*, is:

$$S_T = 184B - 6215 \quad (4)$$

The correlation is based on a standardized test procedure in which Brinell hardness readings were taken on the surface of dryer shells and tensile test bars were machined adjacent to the hardness test sites.

Most of the published data deal with correlations of Brinell hardness and tensile strength for test bars. For large castings, which are representative of paper machine dryers, the test bars will have tensile strengths that are greater than the actual castings. Brinell hardness readings made on Code-rated dryers have been compared with tensile strengths of their test bars. Actual tensile strength data at the site of the hardness readings are not known, and the correlation of test bar data with local hardness readings is poor.

Brinell hardness test procedures

The standard Brinell hardness test consists of applying a hydraulically controlled load of 3000 kg on a 10-mm-diam. ball for at least 10 s. The diameter of the impression is measured with a microscope containing an ocular scale. Tables are available to convert the observed diameter of impression to the Brinell hardness number. The Brinell hardness test is actually a specialized compression test and measures the combined effect of matrix hardness, graphite configuration, and volume of graphite (*9*).

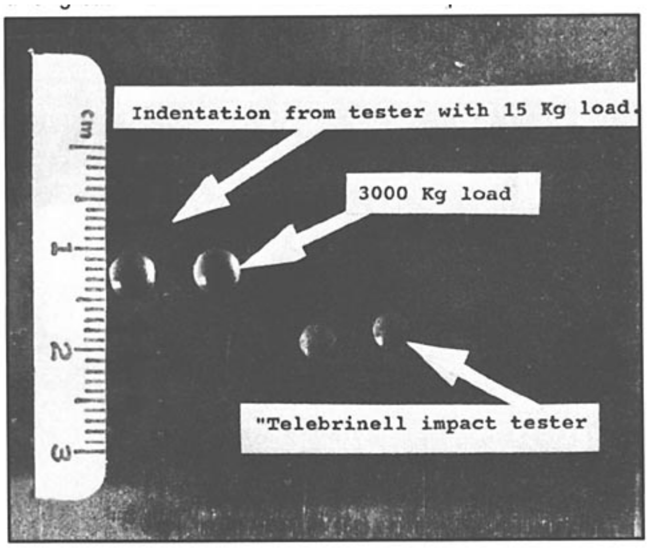
The microstructure of cast iron requires that a relatively large area be measured when conducting a hardness test. This eliminates many of the simple, portable, hardness test instruments, such as the scleroscope, which measures the rebound of a hard ball from the surface and which is sensitive to the microstructure at the point of measurement. Other portable instruments are available which apply a load of approximately 15 kg to a diamond indenter through preloaded springs and thus measure only a relatively small area. These instruments also are sensitive to the local microstructure, as well as to the surface finish at the point of measurement. They are intended for higher quality castings and finer surface finishes than are typically encountered in old dryers.

One portable Brinell tester, the King tester, applies a hydraulic load to make a standard Brinell test and can be mounted on a dryer. However, attaching the test head to a dryer to resist the 3000-kg load requires a large chain and careful alignment to obtain an accurate reading. The tester frequently does not fit in the available space, and its application has been too time consuming for it to be practical.

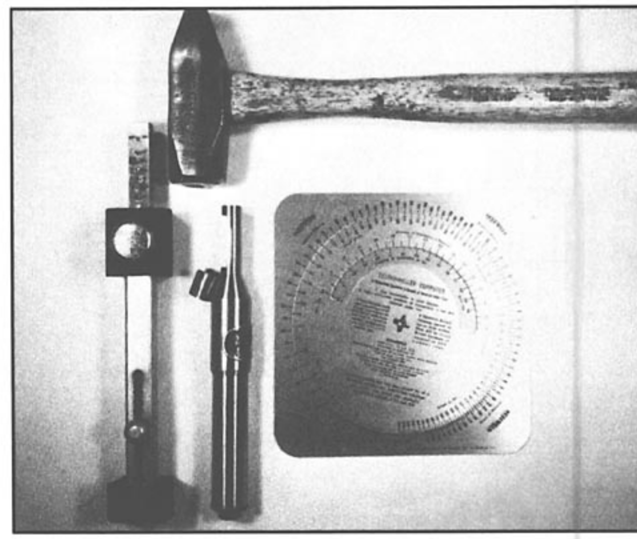
Another portable Brinell impact tester, the Telebrinell tester, compares the indentations made by a 10-mm steel ball in the test specimen and a standard bar. To conduct a test, the head of the instrument is struck a sharp blow with a hammer and indentations are made in the standard bar and the test specimen at the same time. The ratio of these diameters is used to determine the Brinell hardness of the dryer. The diameter of the resulting indentation is comparable to that produced by the standard 3000-kg load, as shown in **Fig. 3**. It is the test instrument that most nearly reproduces the test conditions obtainable in the laboratory with a 3000-kg load.

The Telebrinell instrument has proven to be easy to use. Multiple hardness readings can be obtained on both the tending and drive sides of all dryers in a paper machine during a typical annual maintenance outage. Even dryers where accessibility is difficult, such as the drive side of open gear machines, can be tested with this instrument. The test equipment necessary to obtain hardness readings is shown in **Fig. 4**.

3. Comparison of indentations made by a standard Brinell tester using a 3000 kg load, the Telebrinell impact tester, and a portable tester using a 15 kg load. The Brinell hardness of the test sample was 160.



4. Telebrinell test equipment used to determine Brinell hardness of dryer shells



Determination of allowable working pressure

The maximum allowable working pressure (MAWP) is determined by the ASME Code through a combination of design stress values, material test data, and hydrostatic burst tests to prove the design. For older dryers these criteria are not applicable, and indeed this information is not available. However, the Code hoop stress formula is often used as the basis for calculation of the MAWP. The maximum allowable working pressure, P, is then obtained from:

$$P = SEt/(R_i + 0.6t) \qquad (5)$$

where

S = the maximum allowable stress value

E = joint efficiency

t = shell thickness

R_i = the inside radius.

For typical dryer dimensions, where the radius R_i is greater than 24 in. and the shell thickness is close to 1 in., dropping the $0.6t$ term from the denominator introduces an error less than 3%. Then the formula becomes (with the joint efficiency $E = 1.0$ for a casting):

$$P = St/R_i \qquad (6)$$

Several factors are considered in the application of this equation. The equation is accurate only in computation of shell hoop stresses away from the shell-to-head intersection (*2*, *8*). However, a detailed analysis of the shell that accounts for the head and shell geometry, material elastic constants, and tensile strength is usually prohibitive. It is recognized that the juncture of the head and the shell produces the maximum discontinuity stresses (*8*). The maximum tensile stress in this region is the result of bending loads. The transverse bending strength of the cast iron becomes the governing criterion, rather than the tensile strength alone. However, while the calculated tensile stress in this region is higher, so is the transverse bending strength. This is a result of the compressive strength being much higher than the tensile strength, which produces an effective shift of the neutral axis and lowers the true tensile stresses on the surface.

The ratio of transverse to bending tensile strength for cast iron varies from 1.5 to 2.4. The good news is that the low tensile strength iron has the proportionately higher bending strength. Thus, after a consideration of the actual stress distribution, the stiffening influence of the head, and the transverse bending strength of cast iron, Eq. 6 represents the best available equation to determine MAWP for the shell. A separate analysis has to be considered if the heads are recognized as the weak link in the dryer design, as occurs in some old dryers.

The critical factor in the operating pressure determination is the tensile strength of the cast iron. The allowable stress is defined to be 0.1 of the tensile strength. This figure accounts for the sins of imperfect castings, fatigue influence, and the effects of higher stresses at the head and shell juncture that cannot be accurately calculated. A method to predict reliably the tensile strength of the shell can eliminate the need to assume a safe value of only 13,000 psi for tensile strength of old cast iron of unknown class. Assumption of only a 1300 allowable hoop stress would frequently result in a MAWP that is below current operating requirements, with a consequent loss of production.

Variation of material properties within dryers

The need to evaluate the tensile strength of paper machine dryers is usually part of a program to assure safe and reliable operation of old dryers. The program typically involves thickness testing of the shells and magnetic particle testing of the heads. A complete Brinell hardness survey may also be required if data on material strength are lacking.

The tensile strength of the cast iron within a dryer varies due to the influences reviewed earlier, with the cooling rate within the mold probably being the most significant factor. Analyses of samples taken at different locations within the same shell showed that one end of the shell can have 35% higher tensile strength than the other end. For most medium quality cast irons, the variations were found to be less than 15%. The variations around the circumference (e.g., 180° apart) on one end of a dryer can also be as high as 30%.

The Brinell hardness readings will similarly vary. Thus an evaluation of a dryer requires that Brinell hardness readings be taken on both ends of a dryer at locations approximately 180° apart. To assure that data are reliable and repeatable, at least three hardness measurements are required at each location.

Summary

Safe operation of old paper machine dryers requires that a maximum allowable working pressure be determined on the basis of shell thickness and tensile strength of the shell. Ultrasonic thickness measurements can determine shell thickness, but tensile strength of the cast iron is usually an unknown. Tensile test specimens taken from old dryers revealed that some old dryers can have tensile strengths as low as 12,500 psi. With this information, insurance underwriters established a criterion of allowing a maximum of 13,000 psi as the tensile strength for unknown dryers. Application of this criterion can result in a calculated MAWP that is below the operating steam pressure requirements. To maintain safe operation and avoid production penalties, the MAWP must be calculated on the actual tensile strength of a dryer.

A program was carried out to examine the factors that are influential in determining tensile strength and to determine the correlation between these factors and tensile strength. Chemical composition provides a good correlation with tensile strength but only for test bars of the same size. Brinell hardness and tensile strength were found to have the best correlation for dryers. The regression equation to predict tensile strength from hardness data taken on the outer surface of a dryer shell is given. The Brinell hardness test procedures and instruments for testing dryers are reviewed. Tensile strength and hardness variability found in individual dryers are also reviewed.□

Literature cited

1. Guidelines for the Inspection and Nondestructive Examination of Paper Machine Dryers, TIS 0402-16, TAPPI PRESS, Atlanta, 1988.
2. McGee, T., Tappi J. 68(9): 134(1985).
3. Committee Reports, Proc. American Society for Testing and Materials, 24(Part I): 215(1924).
4. Barlow, T. E. and Lorig, C. H., Trans. American Foundrymen's Society, 54: 545(1946).
5. Angus, H. T., Dunn, F., and Marles, D., Trans. American Foundrymen's Society, 57: 21(1949).
6. Schneidewind, R. and McElwee, R. G., Trans. American Foundrymen's Society 58: 312(1950).
7. MacKenzie, J. T., Proc. American Society for Testing and Materials, 46: 1025(1946).
8. Mockaitis, A. P., Tappi J., 69: 68(1986).
9. Gray, Ductile, and Malleable Iron Castings—Current Capabilities, Special Publication 455, American Society for Testing and Materials, Philadelphia, 1968, p. 12.

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