A case study of an axial shell edge crack in a Yankee dryer

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Fracture and fatigue mechanics were applied to uncover why the dryer failed as it did.

Cracks in Yankee dryers can present a serious safety hazard, because of the high potential energy within the vessel. Catastrophic failure may cause extensive down-time, high repair and replacement costs, and even injury or fatal injury. A fracture that cannot be detected in time may result in catastrophic failure. Sometimes a temporary repair can be made to a crack, but this approach has not proven satisfactory in general. Fortunately, much has been learned from previous failure studies on Yankee dryers, and continued research should also help reduce future problems.

In a 1985 review of nine dryer failures (*1*), the dryers studied varied in age from new to 31 years old. Five of the dryers failed from a shell edge crack, two exploded, one failed from a shell centerline crack, and one had a cracked head. Additional information from the TAPPI Yankee Dryer Safety Committee reveals that most failures are shell cracks, particularly those initiated at the shell edge.

There are many factors which need to be considered in understanding why dryers fail. Naturally, the design is an important factor. A stress analysis of the design can identify the areas of greatest stress. In most stress analyses, the tensile stresses are found to be largest at the outside surface of the dryer shell at the centerline, acting circumferentially. This pattern would cause cracks to form at the centerline and run axially across the dryer shell.

Unfortunately, most shell cracks occur at the shell edges. This dilemma leaves engineers with interesting questions. Why do dryers fail at the edge? What factors besides the design and the stress analysis are important?

In this case study of an axial shell edge crack, the material properties of the dryer were tested, and a stress analysis was made. Fracture and fatigue mechanics were applied to discover why the dryer failed as it did.

Case study

The dryer measured about 3 m (120 in.) in diameter and 3 m in face length. It was a plain bore Yankee dryer, although spoiler bars had been added at some point. The dryer had been operated for 13 years prior to failure and had a fairly good operating history. The dryer had also been plugged several times but not in the area of the crack. When the dryer cracked, the shell thickness was about 5 cm (2 in.). The crack was repaired by metal-locking, and it operated under normal conditions until a replacement was made one year later.

The features of the dryer's history potentially connected to the edge cracking were:

1. Excessive superheat, up to 38°C (100°F), recorded during the eighth year of operation
2. Steam leaks between the head and the shell during the ninth year of operation.

The leaks were sealed, and these areas were not associated with the area that subsequently cracked.

Visual examination

A 30X scope was used to examine the shell, and only one crack was visible on the edge. A coupon was cut from the dryer, with ample space left around the crack. This coupon was examined with a 100X scope. In the unstressed condition, the crack extended 5 cm in from the shell edge on the outer surface. In the stressed state, the crack extended an additional 0.5 centimeters across the surface. The crack was located radially opposite a bolt hole but did not extend into it.

Dye penetrant examination

A dye penetrant was used to determine the extent of the crack radially inward. The crack did extend below the metal-locking at the edge, but it was not a crack that extended completely through the metal. The total crack depth was 5.5 cm.

Load until break

The sample with the repaired crack was cooled in liquid nitrogen, then was loaded to break open the fracture. The final fraction occurred when the tensile stresses reached approximately 190 MPa (27,500 psi). The initial fracture surface was examined under a high-powered microscope. There was evidence of corrosion that the unfractured and newly fractured surfaces did not have. The fracture

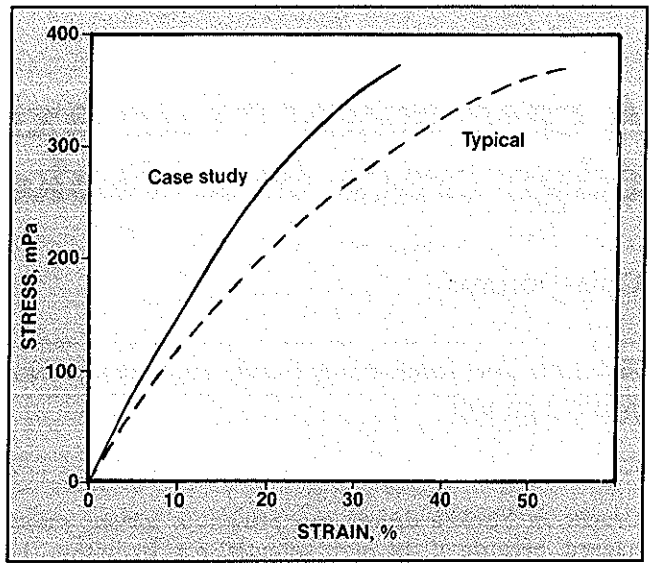
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I. Results for tensile strength and fatigue tests

Tensile strength	
Tangent modulus of elasticity at zero stress, MPa	1.5×10^5
Tensile strength, MPa	370
Strain at failure, %	35
Fatigue	
Fatigue limit in air, MPa	160
Threshold fraction toughness, MPa·m$^{1/2}$	14
Critical fracture toughness, MPa·m$^{1/2}$	26

psi = MPa × 144.9

1. Stress-strain curve



initiation site was located at the outside corner of the shell edge.

Chemical analysis

A piece was removed, and the chemistry was tested. The chemistry was good for a Yankee dryer iron, except for a finding over 0.1% of phosphorous. This percentage is perhaps twice that which might be expected in modern shell chemistry. As the limit of phosphorus solubility in iron is exceeded, the presence of phosphides in the microstructure is indicated.

Microstructural analysis

A piece was removed, polished to 0.05μm, and etched with 2% nital. The microstructure was observed at 100X, 400X, and 1000X. (Classifications are made at 100X.) The microstructure revealed type A graphite, size 3-4, with a fine pearlite matrix and a secondary eutectic. Stead's reagent was used to confirm that the secondary eutectic was a phosphide. The cell size averaged 0.25 cm and was fairly even throughout the shell.

The macrohardness of the dryer tested at 240 Brinell Hardness (BHN). The microhardness tested as 247 BHN equivalent for the pearlite and as 530 BHN equivalent for the phosphide eutectic. The computer image analyzer computed the contents at 16% graphite and 5% phosphides, with the remainder as fine pearlite.

Tensile strength testing

Specimens were cut from the dryer shell for testing tensile strength. The average results are given in **Table I.**

Fatigue testing

Wedge-opening loading specimens were cut from the dryer shell for fatigue testing. This type of specimen has been used to study fracture toughness, fatigue crack initiation and propagation, stress corrosion cracking, and corrosion fatigue cracking of various materials (*2*).

Although S-N fatigue tests are usually made with rotating beam specimens, the fatigue limit is about the same for the wedge-opening loading tests, which measure the fatigue stress limit from zero to the maximum value (*2*). The curve differs at lower cycles, however. The averages of these results are given in Table I.

Examination results

In general, the test results revealed that the Yankee dryer was in good repair. The exceptions were the presence of phosphides and the low percent strain at failure. However, the critical fracture toughness was fairly high. The fatigue limit in air is about 43% of the tensile strength, which is typical for pearlitic irons.

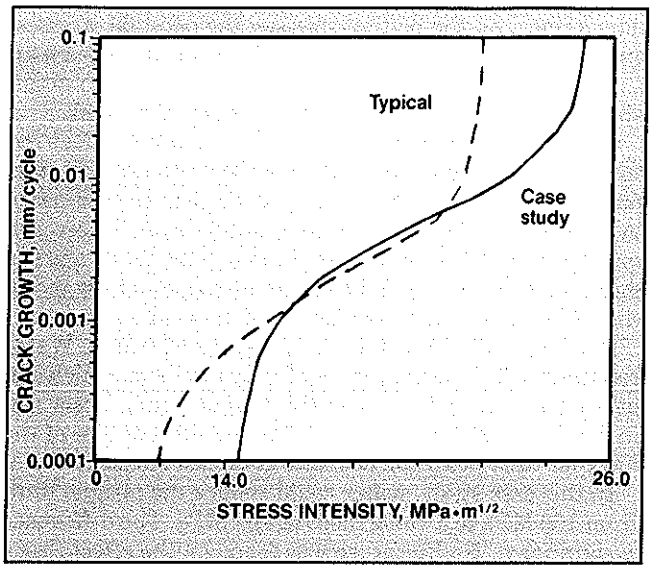
The phosphides are undesirable, because they detract from the toughness of the material (*3*). This drop is best measured by the reduction in area under the stress-strain curve, which is used to compare the relative toughness and the impact resistance of materials (*4*). The area represents the energy absorbed prior to fracture. A comparison with a typical stress-strain curve for the same ultimate tensile strength is useful, as shown in **Fig. 1.**

The difference in area is significant, which underscores the potential value of percentage strain at failure as a criterion for metal quality. The less the area under the curve, the less ability it has to absorb impact loads, and the less tolerant it is of metallurgical and geometric discontinuities.

It is difficult to compare results from the fatigue tests with typical results, because little has been published on fatigue behavior of high-strength, gray cast irons. **Figure 2** shows curves for fatigue crack propagation rate vs. stress for a typical Class 30 iron and the iron in the dryer in the case study. This kind of information can be useful in determining the chance of fracture failure. Given a flaw size, we can calculate the rate at which it is likely to grow to critical size and fail catastrophically. Because some dryers have failed by fracture, it is important to include the fracture toughness information in future designs to prevent other failures.

So far, the testing procedures have not revealed the reason for the failure in the case study. There was no

2. Crack growth vs. stress intensity



evidence of shrinkage or other gross defects in the cracked area. No evidence of thermal fatigue, or crazing, was found. Overall, the metal met all specifications.

The Yankee dryer probably failed by fatigue, possibly assisted by corrosion. Operational procedures contribute to the cyclic nature of the stresses. Every time a change is made—as in a warm-up, cool down, or a sheet change—the stresses also vary and encourage crack growth. Close attention to good operating procedures tends to minimize these effects. The design, the presence of phosphides, the excessive superheat, and corrosion are also likely to contribute to the failure.

Stress analysis

A combination of formulas was used to determine the stress at the shell centerline and edge, including:

- Thin-wall shell theory for pressure vessels
- The thermal stress equations for a constrained plate
- The Donnell equations for the ends of a thin-wall pressure vessel using the procedure presented by Hoff (*5*)
- The Roark equations for press-roll-induced stresses.

The final equations used did not include surface loads or temperature. Alternative equations are available as given by Kraus and Morley for these cases (*5*). The equations used, while not representing exact solutions, are used for a worst-case estimation. There are other formulas to consider, such as for the effects of dead weight and beam bending, but these effects are negligible in comparison. Also, stress patterns will be altered by holes and section size changes, which were apparent in the dryer in the case study.

For this Yankee dryer, a stress analysis for normal conditions was carried out. It was assumed that the area inside the shell was not covered with a film of condensate, though a condensate layer would normally be expected. The treatment here allows a look at the worst case scenario. Furthermore, the stress at the shell edges may be elevated considerably by running excessively wide or wet felts or through applying water directly to the shell flange area. However, this consideration was also not included in the calculations.

Under normal conditions, the maximum centerline stress at the outside surface was found to be 100 MPa. At the edge, the maximum stress was 90 MPa. At the superheating condition of 38°C, the results were 160 MPa for the centerline and 150 MPa at the edge.

For normal conditions, the stresses are well below the fatigue limit, and a crack would not be expected. However, with the worst case, the stresses are near the fatigue limit. A crack may have started during a condition of high stress, whether this stress was caused by superheating or some unknown problem such as improper warm-up.

Fracture mechanics

Theoretical approach

A linear-elastic fracture mechanics (LEFM) approach was used, which is not completely correct since an elastic-plastic method should be used on cast iron. Gray cast iron does not have a linear stress-strain curve, but the LEFM approach does give fair approximations.

One theory for explaining the applicability of LEFM is that the crack moves along the graphite, which deforms quite readily. To fracture the material, the crack must extend across the cells, or across the matrix. In other words, the matrix limits the fracture.

The matrix is basically a steel, which does behave linearly. As the strength of the cast iron is increased, the accuracy of the LEFM method improves. The presence of phosphides decreases the accuracy somewhat because the phosphides crack at low strains, ahead of the crack tip. Voids are formed there, which coalesce as the crack tip extends, increasing the likelihood of cracking.

For a crack to initiate, the stresses must exceed the fatigue limit of the material. As the crack begins to assume its shape, the fracture mechanics formulas are used. If the stress intensity factor, K_I, is above the threshold value, K_{Ith}, then the crack may grow. When the critical value is reached, K_{I_c}, the final rate of fast fracture growth is reached.

It is difficult to apply an exact fracture formula to a Yankee dryer, because the shape and the stress patterns are complex. For simplicity, only the circumferential stresses were considered, and they were assumed to be uniform over the entire crack length. For an elliptical crack with a depth equal to half the length, the formula for the centerline was

$$K_{I_c} = 1.12\,(2/\pi)\sigma\,(\pi\,a)^{1/2} \qquad (1)$$

where

a = the crack length, cm.

The formula for the edge was

$$K_{I_c}\,(\text{edge}) = 1.12 \times K_{I_c}\,(\text{center}) \qquad (2)$$

With the worst case (superheat calculations), this results in K_I values of:

$$K_{I_c}\text{ (center)} = 20.2a^{1/2} \quad (3)$$

$$K_{I_c}\text{ (edge)} = 21.2a^{1/2} \quad (4)$$

From these equations, the edge seems to be more favorable for cracking, although the difference in the numbers is not significant.

Crack growth in the case study

Assuming that a crack-like flaw exists at the edge, would it become larger? For growth, the stress intensity must exceed the threshold value. In the worst case, this means that a flaw size of about 0.44 cm is needed. This size is just short of two cell widths, and it is possible for a flaw of this size to exist. Conversely, at normal stresses, the required flaw size for growth would be about 1.2 cm, which is much more unlikely to exist.

In the case study, a crack probably began during an unusually high load, possibly during the superheated condition. It slowly grew larger, even at reduced stress. Of course, the stresses of shutdowns, sheet removals, and warm-ups would contribute to the crack propagation. The next questions are, when would the crack have become critical, and how safe was the repair by metal-locking?

To explore the first question, the crack size under normal running conditions is compared to the critical fracture toughness value, K_I. For the edge crack, this estimation yields a critical flaw size of 4.2 cm. This critical flaw size is less than the actual fracture size of 5.0 cm. For this to exist, the stresses must be lower at the crack tip than at the shell edge, and a uniform stress field can not be assumed to exist.

This differential was expected from the stress analysis for that area, which has been demonstrated previously (*6*). As an additional safety factor, it is favorable to have the predicted critical fracture size below the actual critical size. However, the crack as first observed was sizable, and it was necessary to repair it.

For the second question, the stress that finally broke the repaired crack is used in the equations to find an equivalent flaw size. This new flaw size is used back in the same equation for normal operating conditions. This procedure results in a K_I value of 12 MPa $m^{1/2}$.

This stress intensity value is below the threshold value, so the repaired crack would not have been expected to grow larger under normal operating conditions. However, the mechanism of fracture of a repaired crack is not well known, so the crack may have grown anyway.

Discussion

In this case study, a crack may have been initiated during a period of excess superheat or from some unknown high loading. The presence of phosphides contributed to this occurrence by reducing the strain to failure, but the phosphides did not cause cracking.

The crack continued to grow by fatigue even at a reduced loading. The cyclic nature of the stresses came both from changes in operation, such as a warm-up or sheet change, and from changes as the dryer rotates. Such changes during rotation occur when the felt hits the dryer and when the sheet leaves the dryer.

At some point, the crack growth may have been assisted by corrosion. More information about such factors as the position of the manhole or of internal equipment, the interference fit, the bolting stresses, the residual stresses, and the warm-up procedures would be helpful in such an analysis. For a full and proper analysis, more information about the dryer design and history would be needed.

Certainly, the known information in this study does not completely account for the cracking problem in this particular dryer. The subsequent repair, however, appears to have been effective on a temporary basis. There are many effects that were not considered, which may answer questions such as why failures occur predominantly at the shell edge, as was the case here, and not at the centerline.

One important factor is the presence of water. Water reduces the fatigue properties of gray cast iron, which can be seen by the reduction in the fatigue limit. Tests run in demineralized water show a fatigue limit of 80% of the limit for tests in air for pearlitic gray cast irons (*4*).

In this case study, water could reduce the fatigue limit from 160 MPa to a value more at 130 MPa. The difference is significant. No literature was found on the effect tissue water would have, but it is likely that the effect would be detrimental.

More must be learned about Yankee dryer iron properties and how iron is affected by its environment and its microconstituents. This knowledge would lead to an even greater understanding of Yankee dryers than we now have. More in-depth studies of future failures should be undertaken to advance our understanding.

Literature cited

1. Ferrari, F. J., 1985 Engineering Conference Proceedings, TAPPI PRESS, Atlanta, p. 385.
2. Barsom, J. M. and Rolfe, S. T., Fracture and fatigue control in structures, 2nd edn., Prentice Hall, N Jersey, Englewood Cliffs, 1987, p. 350.
3. Angus, H. T., Cast iron: physical and engineering properties, Butterworths, 1976, p. 65.
4. Iron castings handbook (Walton, C. F., Ed.), Iron Castings Society, Inc., 1981, p. 255.
5. Gill, S. S., The stress analysis of pressure vessels and pressure vessel components, Pergamon Press, 1970, p. 31.
6. Voll, G. and Fearnside, R. L., 1985 Engineering Conference Proceedings, TAPPI PRESS, Atlanta, p. 407.

The author wishes to thank J. L. Hill, A. E. Carden, and J. T. Berry, University of Alabama, for their help. Special thanks also go to William G. Corboy, chairman of the TAPPI Yankee Dryer Safety Committee.

Received for review June 14, 1988.

Accepted June 24, 1988.

Presented at the 1988 Engineering Conference.