ORAL REFERENCE: *ICF1001036OR*

# FAILURE ANALYSIS OF A PARTICULATE COMPOSITE CUTOFF WHEEL WITH FIBER REINFORCING

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## ABSTRACT

A failure analysis was undertaken after an abrasive particulate composite cutoff wheel failed in operation, injuring a worker. Compact tension tests and bend tests were performed on samples cut at various angles from the failed wheel and from unused wheels. Relative fracture toughness values calculated from the compact tension tests showed the dependence of plateau toughness on fiber orientation. Specimens with fibers normal to the crack direction exhibited a higher plateau toughness than those with mis-aligned fibers. Energy absorbed during fracture, calculated from the bend tests, reduced markedly with fiber orientation. Specimens with fibers parallel to the loading direction absorbed more energy during failure than those with mis-aligned fibers. It was determined that the catastrophic nature of this failure could be attributed to reduced fracture toughness resulting from the unfortuitous fiber orientation. In addition, the accident need not have been so severe had reasonable safety procedures been followed.

## KEYWORDS

Failure analysis, composite, fracture toughness, brittle fracture, fiber bridging

## INTRODUCTION

An abrasive cut-off wheel, used for cutting bronze bar into lengths, fractured during operation, seriously injuring a worker. A failure analysis was conducted to determine the contributory causes of failure. The emphasis of the discussion in this paper is on the mechanism of failure in a particulate composite with fiber reinforcing, and the implications for improved design of abrasive cutoff wheels. However, the failure analysis also showed that the severity of the incident was exacerbated by unsafe operating conditions. While this paper will not dwell on the issue of safety, it is important to note that, had reasonable safety procedures been in place, the failure need not have resulted in a serious accident.

### *Standards*
The standard for the use and care of abrasive wheels [1] recognizes that abrasive wheels are easily damaged and liable to fail during operation, and recommends procedures to ensure that such failures should not cause injuries. These procedures are largely the responsibility of the operator of the equipment. Where relevant, the regulations are mentioned in the discussion following. There are no standards relating to the use of fiber reinforcing on abrasive wheels, or specifying the procedures which should be followed in the manufacture of a particulate composite abrasive wheel. For reasons that can only invite speculation, abrasive wheel manufacturers have not shown great willingness to develop fabrication standards.

### *Abrasive Cutoff Wheel Specification*
The cut-off wheel in question is a 30” diameter abrasive wheel, ¼” thick, with a central arbor hole 1¾” in diameter. It is manufactured of particles of aluminum oxide embedded in a matrix of phenolic resin. This mixture is pressed between layers of loosely woven glass fiber cloth, resulting in a composite sandwich with one layer of glass cloth at the top and one at the bottom of the disk. The cloth is a 0°/90° weave with thicker fiber bundles in the warp direction than in the weft direction. The two glass fiber cloths are oriented at some random angle with respect to each other. The composite is subjected to a high pressure for a short time, and then cured for 48 hours at 170°C. Disks are speed-tested to 20% above the maximum rated speed before being shipped, as required by the standard [1].

### *Operation*
The abrasive cut-off wheel was used to cut bronze bars into lengths in a continuous casting operation. Cartridge brass bar drops vertically through the cutting station and the wheel is hand-fed through the bar. Since the bar is moving while the wheel makes the cut, some amount of bending load is generated in the wheel during the cutting process.

The cut-off wheel is mounted horizontally over the motor shaft. A cupped mounting flange is placed on either side of the wheel, clamping the wheel along an annulus with an outer diameter of roughly 4”. The ANSI standard [1] recommends, but does not require, that a compliant blotter be used between the mounting flange and the wheel to alleviate stress concentrations at the flange/wheel contact. A blotter was not used on the wheel that failed. A nut is used to securely clamp the wheel between the mounting flanges. Since there is no established tightening torque, the nut is tightened at the discretion of the individual mounting the wheel. Prior to and after mounting, the user is expected to conduct a subjective ‘ring’ test: the wheel is lightly tapped to excite vibrations. A skilled user is said to hear the difference between an undamaged and damaged wheel. When the user is satisfied with the ‘sound’ of the wheel, the wheel is put into use. This procedure was not followed in the present case.

To allow ease of manual cutting the cut-off wheel is mounted at about waist height. Unfortunately, this also enables a dangerous envelope for debris in the event of a wheel failure, with fragments flying horizontally at waist height. To reduce the threat posed by wheel fragments, a safety guard is required by the standard [1]. The guard in this case was designed to encircle the wheel, apart from an opening of 80°, allowing bar stock of diameter 10” to be cut. The subject manufacturer had ‘modified’ the guard to accommodate larger diameter bars, by increasing the opening. Additionally, the rotational speed of the wheel had been increased from the design speed of 1800 rpm.

### *The Failure Event*
In the present failure, the wheel had been used for roughly one hour some time prior to the failure. Immediately before the failure the operator started the saw motor and allowed the wheel to come up to speed. The operator had initiated a cut when a ‘popping’ sound was heard, followed by wheel fragmentation. Unfortunately, an employee walking across the room, some 3 meters distant, was struck in the thigh by one of the wheel fragments, causing severe injury.

## EXAMINATION AND ANALYSIS

***Visual Examination of Failed Wheel***

The fragments of the fractured disk were pieced together, as shown in the schematic diagram of Figure 1. Some key features are immediately visible.

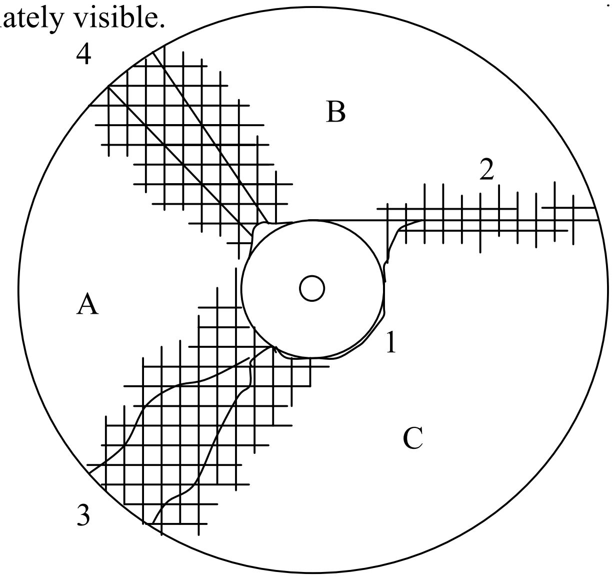


**Figure 1:** Schematic of the failed wheel.

There are four large cracks in the fractured disk. A circumferential crack (labeled "1" in Figure 3) runs completely round the disk along the circumferential footprint of the clamping washer. The fibers are cleanly broken. The other three cracks are radial cracks. Crack "2" runs at 90° to one fiber direction. The bridging fibers are cleanly broken along the length of the crack. Cracks "3" and "4" run at 45° to the fiber directions. They are characterized by large areas of fiber delamination and by considerable loss of the abrasive material. Crack "3" initiates in a non-radial direction, but changes direction to become a radial crack. As expected, therefore, all cracks show a preference for propagating in one of the directions of principal stress, that is, the radial or circumferential direction. The injury was caused by fragment "B".

***Material Testing***

Compact tension specimens and bend beams were fabricated from samples of the failed cut-off wheel as well as from two exemplar cut-off wheels. These samples were used to determine fracture toughness of the matrix material and the bending strength, taking into account the contribution of the fiber mats, and the effect of fiber orientation.

Samples were cut from each wheel at 0°, 45° and 90° with respect to the warp direction of the fiber weave pattern on the top surface of the disk. The relative orientations of the fiber patterns on either surface of the disk varied for each wheel. The fibers on the top and bottom surface of the failed wheel were nearly aligned with each other (relative angle ~6°) while those on the exemplar wheels where not aligned (relative angles ~25° and 60°). This was a consequence of the manufacturing procedure, which neither specified nor ensured the relative fiber orientation.

*Compact Tension Tests*

Compact tension tests were conducted to determine comparative measures of fracture toughness for the different wheels, and for different fiber orientations. The test sample geometry and dimensions are in accordance with ASTM E399 [2]. Typical load displacement curves from one wheel and specimen orientation are shown in Figure 2. In all cases, cracking initiates in the matrix. The toughness of the matrix itself (given by the initiation toughness) is inferred from these tests and summarized in Table 1. The crack propagates across the entire remaining ligament of the test specimen, leaving an intact fiber-bridging zone behind the crack tip. Since the bridging zone is equal to the remaining width of the test sample, this becomes a problem of large scale bridging that is not properly treated using the concepts of linear elastic fracture mechanics [3,4]. Nonetheless, it is possible to calculate a peak load and an associated apparent (or plateau) toughness that can be used to compare samples of identical dimensions. It was observed that the initiation toughness did not show dependence on the fiber orientation, while the plateau toughness did show some dependence on the fiber orientation. This correlates with our understanding that the brittle matrix dominates crack initiation and propagation, but that final fracture occurs only once the bridging fibers have broken or become debonded. It is well known that the stresses exerted by bridging fibers will depend upon the orientation of those fibers, and that aligned fibers are more effective than mis-aligned fibers [5].

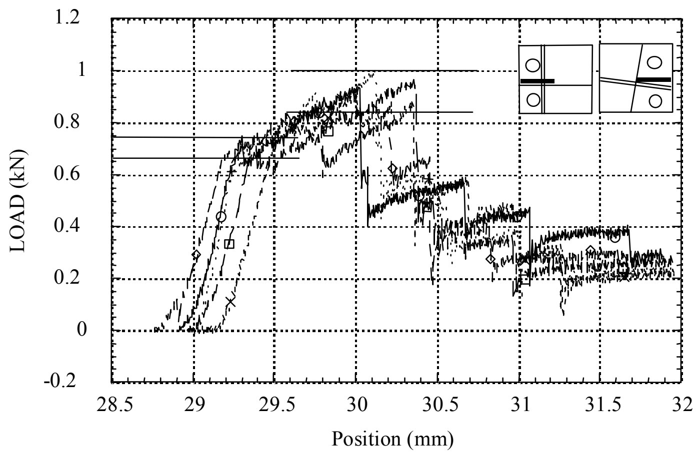


**Figure 2:** Typical results of compact tension tests. Inset shows the relative fiber orientation for these data.

TABLE 1

RESULTS OF COMPACT TENSION TESTS ON THE FAILED WHEEL SAMPLES

| **Wheel** | **Loading Angle** | **Relative Angle** | **Initiation toughness** | **Plateau toughness** |
|---|---|---|---|---|
| | [°] | [°] | [Mpa√m] | [Mpa√m] |
| Failed wheel | 0 | 6 | 3.5 (0.6) | 6.6 (0.4) |
| | 90 | 6 | 3.8 (0.2) | 7.6 (0.5) |
| | 45 | 6 | 3.5 (0.2) | 5.8 (0.4) |

*Bending tests*

Stress-displacement curves obtained from 4-point bending tests were compared for the different specimens and fiber orientations (Figure 3). There is a marked reduction in the amount of energy absorbed through cracking for different fiber orientations. In addition, the energy absorption of the failed wheel was lower than that of the exemplar wheels for all fiber orientations. Examination of the failed specimens showed that those samples with fibers in the loading direction failed by breaking the fibers, while those with fibers at 45° to the load failed by delamination of the fibers from the matrix.

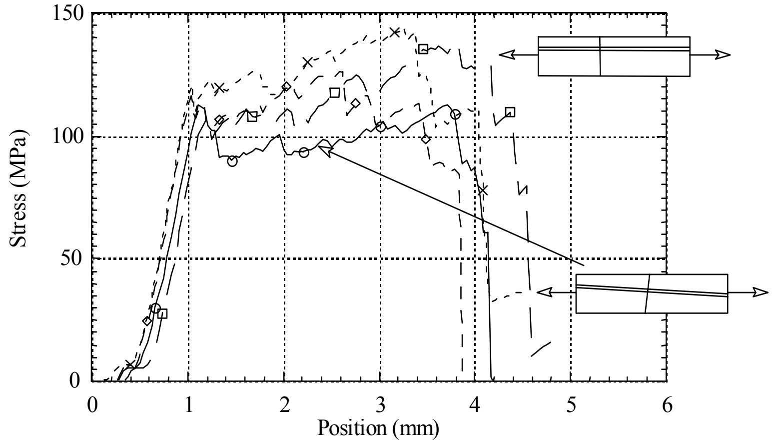


**Figure 3:** Typical results of bending tests. Inset shows the relative fiber orientation for these data.

## DISCUSSION

### *Probable Failure Scenario*

The clean fracture surface as well as the location and geometry of crack “2” support the hypothesis that the wheel fractured along crack 2 under application of a bending load as the wheel was cutting the brass bar. At the edge of the mounting flange, this stress would be concentrated due to sharp or uneven bearing surfaces between the flanges and the wheel. The cracking pattern suggests that failure initiated at the mounting flange and ran circumferentially around the flange. As the crack propagated it branched outward. It is important to emphasize, again, that a blotter pad was not used between the flange and the wheel. The circumferential stress concentration at the mounting flange damaged the fibers underneath the flange. These fibers are essential to the damage tolerance of the wheel, allowing for graceful failure, and large failure strains. In fact, if the fibers are properly utilized, the wheel fragments should hit the safety guard before any fibers have broken. The fibers are intended to pull-out and bridge the cracks in the underling matrix. However, the contact stress generated by the mounting flange damaged the fibers, causing localized fracture at the contact site. As a result, the fibers did not bridge the crack in the wheel and catastrophic failure ensued.

The effectiveness of fiber reinforcing to increase the fracture toughness of a brittle material is demonstrated through the experimental results reported above. The fracture tests presented in Figure 2 and summarized in Table 1 clearly show that the bulk of the toughness comes from fiber bridging stresses. Furthermore, that toughness was shown to depend upon the fiber orientation relative to the crack plane: perpendicular fibers offering the greatest energy absorption. The material testing clearly indicates the effect of fiber orientation on the energy which is absorbed during failure, and show the same trend in the effect of fiber orientation on comparative fracture toughness. The energy required to break fibers which are aligned with the load direction is much greater than that required to delaminate fibers which are at or near 45° to the load direction. If all the cracks in the abrasive wheel had been bridged by transverse fibers, the wheel would have failed, but in a safe manner. This requires redesign of the reinforcing fiber directions to ensure that there are fibers in the principal loading directions of the wheel.

## CONCLUSIONS

### *Most probable cause*

The wheel failed as a result of rapid crack propagation through the matrix, initiated at areas of concentrated stress due to the flanges bearing on the wheel. This failure became catastrophic when the layer of reinforcing fibers which bridged the cracks delaminated on two cracks and broke on a further two.

***Remedial action***

*Redesign*

It is desired that wheels should never fail. However, once they do fail, it is imperative that they should remain safe. Given the finite probability of failure which always exists when using a brittle material, emphasis should be given to damage tolerant design, to reduce the catastrophic effect of failure. In particular, design of cutoff wheels should be appropriate to the hostility of the operating conditions, and should assume a level of mishandling and abuse.

It is recommended that a different weave pattern should be used for the layer of reinforcing fibers on the abrasive wheel. A radial / circumferential weave pattern could be used with minimal increase in manufacture cost, resulting in a more damage tolerant product, with reinforcing fibers perpendicular to both principal loading directions.

*Implement Safety Procedures*

Crack initiation may not have occurred had the bearing surfaces on the flanges been properly maintained, or a blotter or compressible washer been used. Injury could have been prevented even in the case of catastrophic failure if the safety regulations laid down in the relevant standard [1] had been observed. Operators of abrasive wheels should recognize that there is always a risk of failure, and should take appropriate precautions.

## REFERENCES


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