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Discussion

D. K. Felbeck.[5] The apparent ease with which an internally notched disk could fracture at an average tangential stress of less than half the yield stress emphasizes a possibly important difference between fracture initiation in a rotating structure and in a relatively stationary structure. Although it was not discussed in the present paper, there is an additional necessary condition that must be met before brittle fracture will occur, at least in structures such as ships or oil-storage tanks at temperatures well above their purely brittle range. Not only must a flaw be present, but appreciable deformation must occur at the root of a notch before fracture can be initiated. The energy of this deformation per unit area of fracture surface is orders of magnitude greater than the plastic deformation that occurs in the surfaces of a propagating fracture. The gross plastic deformation introduces sufficient triaxiality around the root of the notch to permit an increase of the local yield stress by a factor of two or three. As the load on the structure is increased, the cleavage strength can then be reached at the root of the notch before the yield strength is reached. Fracture is thus initiated, and once the crack is moving at high speed the increase in yield strength associated with high strain rate is sufficient to maintain fracture in the absence of gross plastic deformation. The important difference between material behavior under fast-response loads (as in rotating equipment) and slow-response loads is that the energy available from the fast-response load vastly exceeds the elastic strain energy of a structure under either fast or slow-response loads. Thus it may be anticipated that the authors might find more plastic deformation at the roots of the notches than along the remainder of the fracture surface. This difference in magnitude of plastic deformation cannot be determined by casual observation; the deformation at the surfaces of a running crack may only extend to a depth of order of 0.5 mm, whereas the deformation at the notch root may involve appreciable volume of material and extend entirely through the plate thickness. The former deformations require x-ray methods for determination, while the latter can sometimes be measured as a thickness contraction of a few per cent. The energy for deformation prior to fracture initiation was probably provided very rapidly by the rotational energy of the disk. It is possible that less plastic deformation, if it occurs with sufficient speed, is necessary to cause a fracture to attain running speed in a fast-response load system than in a slow-response system. There have been to date no laboratory examples of slow-loaded notched structures, without either gross prior plastic deformation or large residual stresses, that failed at average applied stresses appreciably below yield. In fact, it is even doubtful whether low-stress service fractures have ever occurred in undeformed material under slow-response load conditions, although the unknown magnitude of residual stress prior to failure prevents precise calculation of the total stress.

The researchers on stationary structures who have been prevented for years from measuring the Griffith-type relation because the relation was masked by the requirement of a higher initiating stress will be happy to see that such a relation can be measured under different conditions of fracture initiation.

G. R. Irwin.[6] Fracture-mechanics analysis along the general lines discussed in this paper is potentially of value to the fracture problems in pressurized-cabin airplanes, gas-transmission lines, large liquid-storage vessels, and welded ships. The development of the topic appropriate to each of these areas is, of course, different. For example, in the case of pressurized-cabin planes emphasis must be placed upon methods of fracture arrest to obtain a fracture fail-safe design. Considerable progress has been made in subjecting fracture tests of large structures to a theoretical fracture-mechanics analysis by several aircraft companies and it is to be hoped their work also will be reported in the technical literature soon.

The present paper represents a commendable accomplishment. The authors and their associates acquired a thorough understanding of fracture-mechanics theory. They collected and presented in this paper experimental information appropriate both to the theory and to their special problem. Table 2 of the paper which gives results from more than thirty spin tests of 24-in-diam cylinders, in particular, is an impressive and valuable collection of data.

Also noteworthy was their careful analysis of these data to indicate those conditions of test which resulted in apparently low G_c values because of extensive plastic strains as well as those which failed to approximate the desired plane-strain conditions.

With regard to constancy of the deformation work per unit of fracture area it should be remembered that the G_c concept for crack extension is like the yield-stress concept for plastic deformation. One can measure and discuss yield-stress values without saying anything about the resistance to deformation beyond initial yielding. Similarly, if one defines G_c as the value of the crack-extension-force, G, for onset of rapid crack extension, this definition does not imply that the fracture work rate remains constant after rapid crack extension begins.

At one point the paper states the utility of the fracture-mechanics analysis "is realized by deriving theoretical formulas for

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G for practical cases." It is hoped this remark did not infer that lack of a theoretical formula necessarily prevents knowing the value of G. It is clear from references (5 and 11) of the paper that several procedures exist for obtaining the relation of G to the applied load by methods of experimental stress analysis. The writer would like to know whether any experimental procedures were used to verify or supplement the theoretical equations for G referred to in the paper.

R. E. Peterson.[7] The present paper, together with the extensive amount of testing, represents a major contribution in the brittle-fracture field as applied to rotors.

As pointed out by the authors, the value of a basic theory is its utility in extending results to other geometries and sizes. In this connection, it is of interest to compare the results of the large (24-in-diam) disks and the small (8 to 11-in-diam) disks made from the same notch-sensitive materials. The G_c values are as follows:

Forging	Large disks	Small disks
TC	102	362
WD (average of 3)	170	305

The small disks were $^1/_2$–$^3/_4$ in. thick and the large disks were 3–6 in. thick. As mentioned in the paper, higher G_c values may be expected in the thin disks due to the shear lip. Had the small disks been thick then the same G_c should be obtained, on the average, for the large and small disks for these notch-sensitive materials, if G_c is a material constant. Perhaps such tests have been made since the paper was written; and, if so, it would be of interest to know the outcome. It is the writer's belief that a brittle failure should be expected for such tests, since in rotor-burst tests made at Westinghouse last May–August, brittle fractures were obtained with a $7^3/_4$-in-diam rotor, 4 and $8^1/_2$ in. long (see Fig. 17). The material was the same alloy steel as used in previously reported rotor tests. The 50-per-cent shear transition temperature was 90 C (194 F). Since our test rotors have a notch on one side only, it is not clear how G_c should be computed, but it is interesting that calculations made according to two different approximate methods result in G_c values which fall within the scatter band of Fig. 12.

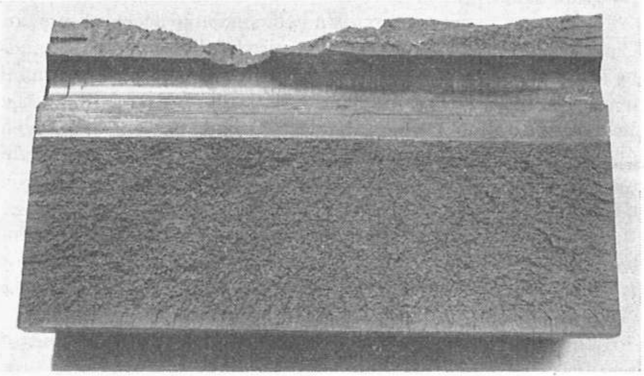

Fig. 17 Brittle fracture of $7^3/_4$-in. diam rotor

The effect of size of defect is one of the main considerations in connection with brittle fracture. For the same G_c and the same stress level, a 4-in. bore with 1-in. notches in a 24-in. disk should, according to crack-propagation theory, correspond to a disk-shaped notch of $11^1/_4$ in. diam in an infinite body or in the middle of a large rotor (Equations [23] and [7]). Since such large defects are not to be expected in rotors, the effect of smaller defects must be either obtained from tests of smaller notches or estimated on the basis of constant G_c, and variation of fracture stress inversely as the square root of the notch diameter. For the G_c values in Table 2, it can be seen from Fig. 5 that a disk-shaped notch of, say, $^1/_2$-in. diam would not be expected to result in brittle failure at the stress levels used in rotor design (including overspeed). Rather large defects of the order of 2 in. are indicated and, in fact, service failures have involved defects of this magnitude. This does not mean that we can tolerate cracks of $^1/_2$ in. diam, because we must consider other possible types of failure, namely fatigue, due to cycles of starting and stopping, and creep-rupture for the elevated temperatures of turbine rotors. Questions concerned with long-time service deserve intensive study and, in fact, such studies and tests are in progress.

The authors have presented a wealth of material concisely and clearly. Those of us who have been concerned with rotor testing appreciate the magnitude of the work. The authors are to be congratulated for a very valuable paper.

Ernest L. Robinson.[8] This paper is, in this discusser's opinion, one of the important papers of the decade. It describes accomplishments which all designers of high-speed rotating machines have been seeking for a generation.

Three years ago, the writer made a 1-page summary of each of 37 reports then available on the subject of rotor bursting and then made a second two-page digest of those. Average bursting strength indicated in these reports ranged from 7 to 118 per cent of nominal tensile strength.

For *sound* disks of *good* material, it has been the writer's opinion for some time that the nominal tensile strength itself is the best index of average bursting strength and the most suitable figure to use for determining an appropriate "factor of safety."

The authors place the average bursting strength as at least equal to the yield strength and generally larger and usually less than tensile strength, and occasionally equal to it. In Table 1, the following values of bursting strength relative to tensile strength are given: 1.00; 1.00; 1.00; 1.02; 1.14; 1.18, or, in other words, 6 out of 22 values equal to or above unity. Certainly 27 per cent of the entries is more than occasional. With good design and good material in particular, the bursting strength may occasionally be generously above the nominal tensile strength.

What has plagued the operators of high-speed machines has been the rare but serious case where a generous factor of safety has not sufficed to assure 100-per-cent safe operation. The risks have been fully insurable but we have wanted for a long time to reduce the risks.

The authors develop the concept of an *effectively notched disk*, by which they seem to mean a *disk so notched as effectively to represent a defective disk*. They find that such disks either show a middling good bursting strength in spite of the notch—if the material is good—or a rather poor bursting strength—if the material is not so good.

For many years, the writer has advocated the use of a model disk-bursting test for acceptance of rotor materials but without getting any converts because most disks show good strength regardless of quality.

Here is an *effectively notched disk* that distinguishes between the good and what is a poor risk.

And what is more, the authors rationalize the whole business by determining a material property which they call the *fracture toughness*—inch-pounds of energy per square-inch of surface—by means of which they can describe results. They even claim they can determine the fracture toughness in a notch bend test

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and use that to predict the strength of their effectively notched disks.

Having arrived at this great achievement, let's use the effectively notched disk in a bursting test to determine bursting strength, and not try to cut corners by using a slow bend test for such an important determination.

Readers should be cautioned against drawing any wrong conclusions from this paper. It deserves careful and painstaking study.

One contrary-to-fact aspect of this paper which should not mislead any careful reader should be pointed out. More than 30 years ago a number of turbine wheels burst at sharp-cornered keyways. When sharp-cornered keyways were discontinued that type of burst was eliminated.

The authors show that an effectively notched disk—worse than a sharp-cornered keyway—is good for the determination of material quality. Let no one conclude that such a detail of design would be used on a modern machine.

Let us remember that, if we make an intentionally defective test disk quite differently from a real rotor, then the intentionally defective disk will be much weaker than any real rotor except a really defective one.

In other words, the test of the intentionally defective disk is contrary to fact in 99 out of 100 times (or 999 out of 1000). But it is *true* in the 1 case in 100 (or 1 in a 1000) where it is important to have it true. And *this is the important point.*

A. A. Wells.[9] In the study of crack propagation in engineering materials the paper under discussion is of great importance not only for its wealth of experimental data but also because of the systematic planning of the experiments and analysis of the results. It is evident from the latter that a strength analysis based on stresses alone cannot explain the results, and that the approach based on strain-energy release rate and fracture toughness correlates more closely with observation even when notch depths are varied by a ratio as much as 5 to 1. Such an unequivocal result does not emerge from all notch-brittleness tests, and it is helpful to set down some of the features of the present tests in relation to others.

The disk-bursting tests appear to be characterized by: (*a*) Use of alloy steels which, for reasons associated with the large forgings, have in many cases fracture-appearance transition temperatures much above the testing temperature, (*b*) large absolute size of specimens.

Conversely, many other investigations, even on a large scale, have been concerned with uniaxial tension on plain low-carbon steels in plate form, where transition temperatures have seldom been more than the order of 100 F above test temperatures. In the discusser's experience extending over a hundred or more notched wide-plate tensile tests in his own laboratory and elsewhere, such plates always show general yield before failure, if the presence of cold sheared edges and notched and welded joints is excluded. By way of comparison with the present tests K_{ys} would always be equal to or greater than unity.

The existence of the general yield condition is a complicating feature in the successful application of strain-energy release-rate fracture-toughness treatments, since it introduces an ambiguity as to whether a fracture is prevented: (*a*) Because it cannot be initiated, or (*b*) because it cannot be propagated. On the other hand the authors have demonstrated cases where the parent material is sufficiently brittle and where the specimen and notch size are sufficient for condition *a* to be removed.

The over-all situation may be alternatively summarized by examination of the results of geometrically similar notched bend tests of the type performed by Docherty[10] using the same material and test temperature over a large range of absolute specimen size:

				G_c	
	Specimen size	Fracture type	K_{ys}	Minimum	From notch bend test
	small	ductile	>1	large	large
	medium	brittle	>1	small	small
	large	brittle	>1	small	increasing
Authors' experiments	large	brittle	<1	small	small

In such cases, once the critical size for brittle failure has been exceeded, fracture toughness, at the given temperatures, as determined by the authors' method, increases with specimen size. With Docherty's specimens this situation existed with a low carbon steel, even up to a 4 × 4-in. cross section. It can only be inferred under these circumstances that the real G_c at the temperature in question, is the minimum value obtained with specimens at the critical size for a ductile brittle transition. By using specimens of similar size but in an alloy steel of much higher transition temperature, tested at room temperature, the authors appear to have avoided this anomaly, and there should be no hindrance in the application of their treatment within the limits of the materials and loading conditions which they have specified. Furthermore, it has been the discusser's experience that notches formed from arrested brittle or fatigue cracks in large plate-type specimens are no more severe, as far as brittle fracture initiation is concerned, than the sharp-ended slots which the authors have used, so that their results should be equally valuable in assessing the influence of natural cracks in forgings.

Although the paper is generally well supplied with supporting data, it would be helpful in making comparisons with other work if actual or specification chemical compositions could be given for the forged materials with brief notes on microstructure.

Authors' Closure

The authors wish to express their appreciation to the discussers for the interesting points that have been brought out. Their comments indicate the importance of such fracture studies.

Mr. Felbeck points out the importance of velocity effect so ably described by him in (14). In this connection it is pertinent to mention that the bursting test of a large disk lasts between 15 and 30 minutes from start-up to actual burst. The following qualitative analysis of events during the disk bursting test may help to amplify Mr. Felbeck's discussion. This analysis, although plausible, is, however, almost purely conjectural.

While the speed is gradually increasing, the intensity of the stress field near the notches is increasing with the square of the speed. At a certain speed a preliminary plastic flow phase, which is a necessary prerequisite to fracture, is initiated. This plastic flow causes a gradual building-up of stresses which results in a maximum stress due to "plastic constraint" (14) of the order of 3 times the yield strength. This stress occurs along the notch axis, a number of radii of curvature away from the apex of the notch (43).[11]

As a result of local plastic deformation within the grains, some of them cleave and cracks are formed ahead of the notch apex. These cracks soon break down the bridge formed by plastically deformed grains, and a continuous crack is formed. The disk speed at which incipient cracking occurs is a function of the physical condition of the steel just below the notch,

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[9] British Welding Research Association, Abington, Cambridge, England.

[10] J. G. Docherty, *Engineering*, vol. 133, 1932, pp. 232, 645, and vol. 139, 1935, p. 211.

[11] Numbers in parentheses from (43) to (46) designate Additional References at end of closure.

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since the cleavage strength depends on the degree of plastic deformation.

Since the notch is at least 2 or 3 inches long, the point of initiation occurs at a location which is most favorable for fracturing. Variation in the amount of cold work at the notch root caused by machining may contribute to this preference for fracture initiation at a certain location.

It must be remembered that the bursting tests were performed on heat-treated alloy steels and not on hot rolled or normalized low-carbon steel plates. There is practically no "thumbnail" area evident and gross plastic deformation at the initiation point is not discernible. The so-called "mirror surface" is very small and almost all surface from the notch bottom to the outside consists of ridges of varying roughness indicating high crack velocity.

The mechanical notch was designed to be a very effective discontinuity, and it appears that as soon as an incipient crack is initiated at the bottom of the notch, it propagates rapidly. The notched disk-bursting test apparently succeeds in combining effectively the crack initiation and propagation phases into an instantaneous event.

It should be pointed out that there have been a few laboratory examples of slow-loaded notched specimens of rotor forging steels which failed at average or nominal maximum stresses well below the yield strength. Reference (36) reports results of slow notched-bend tests in which the strength of a nine-inch square bar with a 0.001-in. notch radius was only about 40,000 psi, or half the material yield strength. Not reported in the literature, but also tested at the authors' company, was an internally notched plate 9 in. wide and only $^3/_8$ in. thick which failed in tension at an average stress just over half the yield strength. Two disks identical to WD2T in Table 3 were fractured by a spreading force applied across the bore hole by means of a split collar and wedge. The disks broke into two pieces at average stresses approximately $^1/_4$ of the yield strength. None of these specimens exhibited any gross plastic deformation.

The authors would like to draw Mr. Felbeck's attention to tests performed by A. B. Bagsar (44) and N. A. Kahn (45). In these tests, called "cleavage tear" tests, a notched tensile-bend type coupon is used. If tested below transition temperature, the net average tension stress in the notched section is less than one half of the yield strength. The disk bursting test is somewhat similar because the intensity of the mean stress field near the notch is considerably higher than the net average tangential stress.

Dr. Irwin points out that the fracture work rate does not remain constant after rapid crack extension begins. However, the authors have not been able to discover this variation experimentally and would appreciate information which will elucidate this point.

The authors and their associates are making efforts to obtain, both theoretically and experimentally, valid formulas for G for additional configurations different from the ones described, e.g., for a round notched bar in tension. No experiments have yet been performed to verify the theoretical expression for G for the notched beam in bending.

The authors appreciate the complimentary remarks and excellent discussion offered by Mr. Peterson. In respect to the behavior of small cylinders the following comments may be made. Whether a notched cylinder or disk bursts in a brittle manner in consequence of rapid crack propagation may be judged by the relative magnitude of the net average tangential stress $\bar{S}_{bn}$ at bursting speed. Namely, $\bar{S}_{bn}$ must be limited to a fraction of the yield strength, defined by the geometry of the disk. Only under such conditions will the correct G_c be obtained. In a certain sense notch brittleness is not a distinct property which a material may or may not possess; it is a mode of behavior which is dependent upon the size and geometry of the specimen and its discontinuities.

Tests to evaluate the effect of increasing thickness on disks with a small diameter have not been performed. However, 24-in-diam disks ranging from $^3/_4$ to 6 in. thick have been burst. These showed a rather small increase in strength as the disk thickness was decreased from 6 inches to $^3/_4$ in. It is not expected that the small disks would show any greater increase. Some of the difference in G_c values between the small and large disks may be due to radial variation of properties within the forging, since the large disks were machined concentric with the forging, while the small disks were removed between the bore and outer diameter.

The problem of predicting bursting speeds of rotors containing discontinuities of various shapes and sizes is not yet completely solved. However, rapid strides are being made which are leading to a better understanding of this complex phenomenon.

Mr. Robinson is very cognizant of the results obtained. The authors agree with him in his pertinent analysis of our findings. We have been able to burst properly designed notched disks at stresses close to those encountered in bursts of large rotors. This agreement is a prerequisite of a satisfactory testing procedure.

From our point of view, a sharp cornered keyway is effectively a crack at the center, whose length is somewhat less than the over-all combined length of bore and keyway depth. See Fig. 6, case B versus case A. Fatigue may have provided the necessary initiation in the case of the turbine wheel failures, and as soon as the critical crack length for the material fracture toughness was reached, the crack propagated.

Dr. Wells correctly points out that in some of our tests the mean stress field near the notch is less than the yield strength, which is required to initiate cracks in mild steel. For instance, in Table 2, Ni-Mo-V disks WD7A and WD1A burst with K_{ys} ratios equal to 0.28. Therefore because the tangential stress in the region of the notch is less than twice the average stress, the mean stress near the notch is only about one half of the yield strength. It is reassuring that Dr. Wells's experience indicates that natural cracks do not appear more severe than our mechanically produced notches with 5-mils radius.

It is difficult to understand why Docherty's notched-bend tests of small specimens, resulting in ductile fractures, yield large values of G_c. Our tests showed that when the specimen size was too small to permit a brittle fracture, the G_c-value calculated from such a test was fictitiously low. This result appears to be confirmed by the Griffith-Irwin theory.

The authors would like to draw attention to the theoretical and experimental work pertaining to fracture of sheet specimens which was performed in England by the British Welding Research Association (46). This work came to our attention just recently. It enlarges upon the plastic behavior of ductile sheets during the process of rapid crack propagation.

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