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FRACTURE RESISTANCE - A CRITERION FOR PAPER RUNNABILITY?

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FOR a body containing a crack, the Griffith energy balance criterion for crack growth is—

$$G = -\left(\frac{\partial U}{\partial A}\right)_l \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where G is the strain energy release rate for a fixed length l of the specimen, U is the elastic energy stored in the body and A is the area of the fractured surface. A crack will propagate if the energy that is available equals or exceeds

$$G \geqslant G_c = R \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The two qualities G and G_c (or R) are quite distinct. The former is a function of the geometry of the body, its elastic properties and loading conditions, whereas the latter is the energy absorbed by the material in the process of crack extension and is a material property. G_c (or R) can be used to characterise the fracture resistance of the material.

Failure of paper in the papermaking and converting operations occurs by rapid propagation of a flaw or a crack. This type of failure is best described by a tensile opening mode(1) of crack propagation. Since the fracture resistance depends on the mode of crack propagation, it is imperative that it be measured for paper in the tensile opening mode.

Fracture resistance of various machine-made papers was measured in the tensile opening mode by two different approaches—

1. Considering paper to be a homogeneous orthotropic continuum, the critical strain energy release rate G_c was measured by linear elastic fracture mechanics technique.(2) For a sheet with a crack, G_c was calculated from the fracture stress, the specimen and crack dimensions and the elastic properties of the sheet. Using specimens of suitable width, a value G_c independent of specimen and crack dimensions was obtained.

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2. The work of crack propagation in a sheet was measured directly by using a quasi-static crack propagation technique.[3] The quasi-static condition was achieved by using short specimens and a hard testing machine. Using wide specimens and a suitable ratio of crack length to specimen width, the fracture could be initiated at a load less than the general yield load of the sheet and the work of fracture *R* measured from the load/elongation curve.

Although the two techniques of measurement are quite different, it has been shown theoretically[3] that for linear elastic structures, identical results are expected. The data on G_c and *R* for eight different papers is shown in Fig. 1. In spite of the assumptions made in the calculation of G_c and the experimental limitations, agreement between G_c and *R* is close. It is thus established that a characteristic crack resistance of paper can be measured by either technique, the latter being more amenable to use as a routine method.

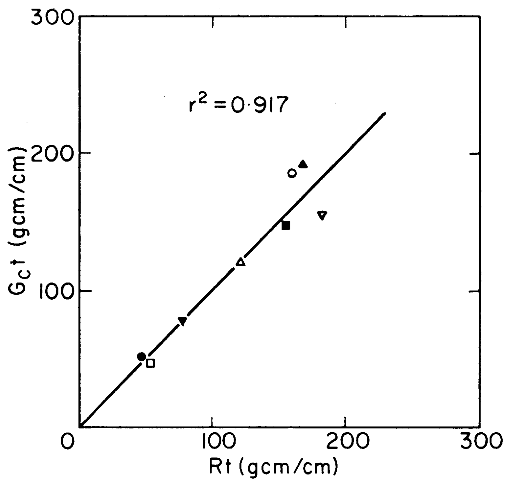

Fig. 1—Equivalence of G_c and *R* for eight different papers

It may be pointed out that in-plane tearing strength does not measure the crack resistance of a paper sheet in the plane stress mode. The tearing forces are applied at an arbitrarily chosen angle of 12°,[4] but the tearing energy changes with tearing angle and we have found a particularly sharp increase in tearing energy for small tearing angles (Fig. 2). As the tearing angle approaches 0°, the in-plane tear approaches the fracture resistance *R* of the specimen.

It is believed that neither the Elmendorf tear nor the in-plane tear (at an arbitrary tearing angle) measure the true fracture resistance of a paper sheet relevant to its runnability and therefore that the fracture resistance G_c or R is a better criterion.

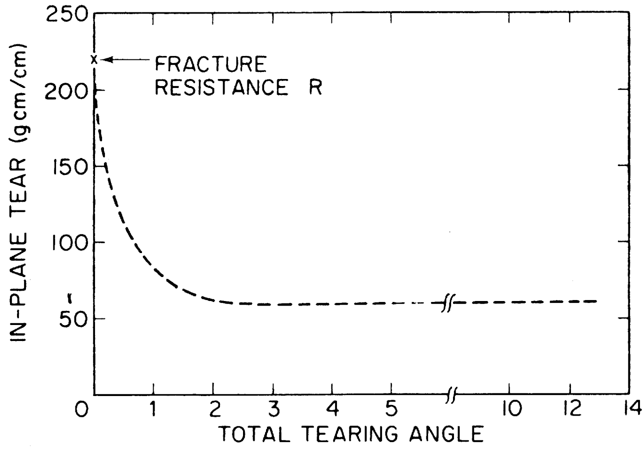

Fig. 2—Variation of in-plane tear with tearing angle

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Transcription of Discussion

Discussion

Mr A. E. Ranger I would like to make two comments on Seth & Page's contribution *Fracture resistance*. Firstly, I think the suggestion that a tensile mode of failure should almost axiomatically be related to poor web runnability bears a little examination. The basic feature of the tensile mode of paper testing is that the stress distribution across the test piece is uniform (except for deliberately induced stress concentration). The failure of paper running through a press is a very rare event; if there is one thing that is probably even more rate, it is the situation in which the stress across the web is uniform and steady with time. Of course, this is a matter of speculation, but I am sure that everyone who has been paper running through a press will agree with me. Whether the pure tensile mode is used or whether the laws are inclined at some angle is a matter for speculation at this stage and certainly needs much further investigation.

My second point is perhaps more crucial to this problem. The first point was essentially concerned with the 'geometry' of simulation, but another aspect to simulation is of course strain rate. The strain rate used in a test for attempting to predict ultimate end use behaviour in such an instance is very important, since the ratio of the number of fibres broken to those pulled out at final fracture increases substantially with increase in strain rate. If one is using a low strain rate test to simulate a high strain rate end use situation, therefore, the very different proportion of fibres broken to those pulled out from the surrounding matrix can produce misleading results. This may explain why the tearing test has had some success in predicting press room runnability in spite of its defects. For any very small area of paper, the strain rate that it sees as the crack advances to it and then ruptures it is very high indeed. To match this strain rate with a tensile mode of testing would require expensive and sophisticated equipment.

This study of the relative number of fibres broken compared with those pulled out and its dependence on the strain rate is one that we have only relatively recently started, but we are already convinced of its vital importance.

With the Chairman's indulgence, may I say how disappointed I was after

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Dr Goring's paper that no one saw fit to congratulate him on an excellent presentation, one that I thoroughly enjoyed. Having lived through (perhaps the word is survived) the last two or three years in the pulp and paper industry, I was comforted to hear David's belief that there will still be paper physicists and chemists around in the year 2001. I was a little disturbed at his suggestion, however, that they might be met on the street and I wondered what they were doing there.